# Variety of the drift pumice clasts from the 2021 Fukutoku-Oka-no-Ba eruption, Japan.

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## Abstract

Pumice rafts that arrived at the Nansei Islands, Japan, provided a unique opportunity to investigate the Fukutoku-Oka-no-Ba (FOB) eruption of August 2021. Despite drifting for two months for ~1300 km, the drift pumice raft had a large volume and contained a variety of pumice clasts, some of which were deposited during a high tide in a typhoon, while others were washed up on a sandy beach. Most of the drift pumice clasts are gray in color, vesicular, and have a groundmass containing black enclaves. Rare black pumice and the main gray pumice components have similar trachytic compositions, with $SiO_2$ = 61–62 mass% and total alkalis = 8.6–10 mass% (on an anhydrous basis). Both pumice types contain clinopyroxene, plagioclase, and rare olivine phenocrysts. Thin-section observations show that the gray pumice has more elongated vesicles as compared with the black pumice that has spherical vesicles, even where the two types of pumice are in the same clast. The glass in the black pumice is transparent and brown in color, while that in the gray pumice is colorless. No micro or nano-crystals were observed during electron and optical microscopy. Raman spectra of the brown-colored glass exhibit a clear magnetite peak, suggesting magnetite nanolites cause the brown color. High-Mg olivine in the black pumice has an equilibrium temperature of 1240 °C and a rim diffusion profile indicative of re-equilibration with the surrounding melt over a period of hours to days.

The textural relationships between the gray and black pumice suggest that the black pumice had become black and viscous before the two types of pumice mixed. Therefore, crystallization of magnetite nanolites and a corresponding increase in melt viscosity were important in the eruption preparation process, which then resulted in a large-scale Plinian eruption.

Keywords: Fukutoku-Oka-no-Ba, Izu-Bonin-Mariana arc, Plinian eruption, drift pumice, nanolite

## 1. Introduction

Fukutoku-Oka-no-Ba (FOB) volcano is located at 24°17.1’N/141°28.9’E, ~5 km north-east to Minami-Ioto Island, south of mainland Japan (Fig. 1a). Five eruptions have been recorded in 1904-05, 1914, 1986, 2005, and 2010 (https://www1.kaiho.mlit.go.jp/GIJUTSUKOKUSAI/kaiikiDB/kaiyo24-2.htm), and discoloration of the sea surface has been occasionally observed (e.g., Furukawa, 1995). Geochemical analyses and petrographical observations have been conducted on pumice erupted in 1904, 1914, and 1986 (Tsuya, 1937; Yoshida et al., 1987; Kato, 1988; Nakano & Kawanabe, 1992). Major element composition the FOB pumices are trachyte similar to the nearby Ioto volcano, which magma type is rare in the Izu-Ogasawara arc. In contrast, FOB pumices are isotopically distinct from the products of the Ioto, but similar to the Hiyoshi Volcanic Complex to the south of the FOB (Sun et al., 1998).

Detailed topography and preliminary geophysical observations of the relevant area show that there exists a large volcanic complex, which has a size of 15 and 30 km for EW and NW direction, respectively, and rises 2000–2200 m above the surrounding ocean floor (Fig. 1b). This complex consists of Kita-Fukutoku-Tai, Kita-Fukutoku caldera, and Minami-Ioto volcanoes, from north to south (Ito et al., 2011). The Kita-Fukutoku Caldera has east-west and north-south length of 10 and 16 km, respectively (Fig. 1b). The seismic basement of the caldera has a mortar shape, which is filled by low velocity and low density materials (Onodera et al., 2003). Nishizawa et al. (2002) suggested the existence of partial melts below the caldera at >1.5–2 km beneath the sea level. FOB is a central cone of the Kita-Fukutoku caldera, which have ~2 km in diameter at the bottom and the height is ~200 m. The summit of FOB had an oval shape elongated NE-SW, with the length of 1.5 km and 1 km, respectively, and was flat at the depth of ~30 m below sea level before the eruption (Ito et al., 2011).

The 2021 FOB Plinian eruption occurred from 04:30 (JST) on 13 August, reported by a local fisherman, to the morning of 16 August (Japan Meteorological Agency, 2021). The eruption column reached 16 km in height, the tropopause of the relevant area. The total volume of the erupted pumices was estimated to be 100–500 × $10^6$ $m^3$ (Oikawa et al., 2021). These pumices were ejected high in the air, fell on the ocean surface and started floating. A large pumice raft was observed by satellite images at 08:00, 3–4 h after the eruption started (Ikegami, 2021). After the eruption, two small islands were observed as "( )" shape, then eastern one disappeared within a month (Geospatial Information Authority of Japan, 2021).

Pumice rafting is typically observed once a decade worldwide (e.g., Bryan et al., 2012), where silicic magma erupted explosively beneath the ocean. The 1986 FOB eruption also generated pumice rafts, and large amounts of drift pumice clasts arrived at numerous locations, including the Nansei Islands, to where the pumice clasts were transported for ~1300 km by the Kuroshio Counter-current after a duration of >4 months (Fig. 1a; Yoshida et al., 1987; Kato, 1988; Mori et al., 1992). Ocean bottom observatory instruments also drift from the Izu–Bonin arc towards the Nansei Islands, which are ~ 1700 km apart (Tada et al., 2021). Ocean current simulations indicate that the drift from the Izu–Bonin arc to the Nansei Islands takes <6 months, but depends on the seasonal current and wind conditions (Tada et al., 2021).

The 2021 FOB pumice rafts travelled westward after the eruption. The RV *Keifu-Maru* of the Japan Meteorological Agency collected samples of floating pumices at 25°30.3'N/138°53.3'E on 22 August 2021 (Japan Meteorological Agency, 2021). Subsequently, the drift pumice rafts arrived at the Nansei Islands in early October, ~2 months after the eruption. The 2021 pumice raft drifted twice as fast as the 1986 FOB pumice raft, possibly due to the seasonal change of the Kuroshio Counter-current that is thought to be weakened in the winter season (Uchiyama et al., 2016). We undertook comprehensive analyses of the *Keifu-Maru* samples and drift pumice clasts collected from several locations on the Nansei Islands. Petrographic observations revealed a variety of pumice types originated from the 2021 eruption. In the present paper, we describe the textural and geochemical characteristics of the collected pumice clasts, and discuss the mechanisms of the 2021 FOB eruption.

## 2. Methods

Mineral compositions were determined with a field emission gun electron microprobe (EPM) analyzer equipped with five wavelength-dispersive X-ray detectors (JXA-8500F; JEOL) at Japan Agency for Marine-Earth Science and Technology (JAMSTEC; Yokosuka, Japan). Natural and synthetic standards were used to calibrate the quantitative analyses. The analytical conditions were 15 kV and 10 nA for the accelerating voltage and beam current, respectively, except for the olivine analyses. For olivine, we used an accelerating voltage of 20 kV and beam current of 25 nA.

Raman spectra were obtained with a Raman spectrophotometer (RAMANtouch VIS-HP-MAST; Nanophoton) equipped with a 532 nm semiconductor green laser at JAMSTEC. The laser power on the sample surface was ~2 mW, and data were acquired in 2 × 20 s cycles. The spectrometer was calibrated to the Raman peak of a Si wafer (520.7 $cm^{-1}$).

Whole-rock major element compositions of the pumice clasts were determined by X-ray fluorescence (XRF) spectrometry (Rigaku ZSX Primus II) following the analytical procedure of Tani et al. (2006) and sample preparation methods of Sato et al. (2020). Prior to analysis, the pumice samples were crushed to pebble size (5-10 mm) and soaked in hot water (~40 °C) for 0–3 days. The clasts were then repeatedly boiled in Milli-Q water in a microwave oven until addition of a $AgNO_3$ solution showed that precipitation of AgCl did not occur. After desalinization, all samples were washed with Milli-Q water and acetone in an ultrasonic bath, and powdered in an agate mortar or with a Multi-beads Shocker pulverizer. Finally, a mixture of 0.4 g of sample powder and 4 g of $Li_2B_4O_7$ was fused and made into a glass bead for XRF analysis. Accuracy and reproducibility of the major element data are better than ±1% and ±2 % (relative standard deviations), respectively. We also analyzed trace element composition of whole-rock using solution mode ICP-MS (iCAP Qc, ThermoFisher Scientific). Rock powder was digested by acids of HF, HClO4, and HNO3.

Trace elements of selected melt inclusions and glass in vesiculated groundmass were determined by LA-ICP-MS which is a sector-field type inductively coupled plasma-mass spectrometer (Element XR, ThermoFisher Scientific) combined with femto-second laser ablation (FsLA: OK-Fs2000K, OK Lab.) installed at JAMSTEC (Kimura and Chang, 2012). Ablated spot is 30 μm in diameter and ~20 μm in depth. BCR-2G (basalt standard glass issued by the United States Geological Survey) was used as external calibration standard. Any contaminations from surface and proximal phases were checked by the time-resolving profiles of the signal and turned out to be negligible. During the analysis, 100% normalized major element compositions are also obtained.

The mass-normalized susceptibility of the pumice clasts was measured with a kappabridge (KLY-4;

AGICO).

## 3. Field occurrence of the drift pumice clasts

Pumice clasts that had drifted to the Nansei Islands were first reported from Kita-daito Island by local residents via Twitter (https://twitter.com/ufuagari_jima/status/1445317054043602945) on 5 October 2021. The drift pumice clasts were reported on Kikai Island on 10 October, and they continued to other islands located farther west, finally the arrival were reported from Izu Islands and Boso Peninsula on Mid November (Fig. 1a). The first identification of the drift pumice clasts on Kita-daito Island was on 5 October, because it was the first day that a ban on coastal access due to high waves caused by a typhoon was lifted. An interview with the local residents suggests that the pumice raft was offshore on 30 September, the day of the typhoon attack (Fig. 1a). On Minami-daido Island, a large amount of drift pumice clasts was also deposited in a coastal area (i.e., Kaigunbo pool). At Kaigunbo pool, some pumice clasts became trapped in crevices up to 1 m above sea level during a normal high tide (Fig. 2a-b). Other occurrences of pumice clasts include those collected on a rocky beach a short distance from the shoreline which was not tide-related (Fig. 2c). These occurrences suggest that the pumice on Minami-daito Island was washed onshore by storm waves (Goto et al., 2011) and were then protected from the rising tide. The samples from Kita- and Minami-daito islands are relatively small in size (up to 5-10 cm).

In contrast, the pumice clasts on Kikai Island and islands farther west were deposited as “moraine-like” features on the shorelines of sandy beaches at high tide (Fig. 2d). At low tide, there were rocks and mudflats on the seaward side of the pumice moraines, but almost no pumice. The amount of pumice deposited varied greatly from beach to beach, possibly due to the orientation of the beach and the direction of waves and winds on the days around when the pumice was deposited. The pumice clasts deposited on the sandy beach are occasionally large (>10 cm).

The differences in pumice depositional patterns reflect variations in coastal topography. Given that the coasts of Kita- and Minami-daito islands have steep cliffs and no sandy beaches, almost no pumice was deposited these islands. Kikai Island and islands farther west generally have sandy beaches, and drifting materials are easily beached (and subsequently carried away) depending on the direction of the wind and tide.

The drift pumice clasts described below were collected from Kita- and Minami-daito islands and sandy beaches of Kikai Island, Amami Oshima, and Okinawa Island (Fig. 1a).

## 4. Pumice classification

The pumice clasts collected from the drifting pumice raft by the RV *Keifu-Maru* (samples 15, 18, and

19 provided by the JMA, herein referred to as FOB-JMA-15, -18, and -19, respectively) have similar characteristics to the drift pumice clasts collected from the Nansei Islands. Notably, the large FOB-JMA-18 sample has a highly vesiculated interior (Fig. 3a-b), whereas such highly vesiculated pumice was rarely observed in the drift pumice clasts collected from the Nansei Islands. Regardless of the deposited locations, the characteristics of drift pumice clasts are similar and they can be classified into six types, based on color and texture: gray, black, brown, pale gray, amber, and streaky (Fig. 3c). The details of each type are described below.

**Gray type**: This is the most abundant pumice type (>90%). The drift pumice clasts collected by the RV *Keifu-Maru* (samples FOB-JMA-15, 18, and 19) are also classified as this type. The pumice consists mainly of gray-colored vesicular glass, containing dark-colored fragments (Fig. 3a and c) that are termed as black xenoliths (Kato, 1988) or mafic inclusions (Sun et al., 1998), whose appearance is sometimes compared to “chocolate-chip cookie.” The fragments are a few millimeters to 1 cm in size. Hereafter, we refer to these as black enclaves. The vesicles in the groundmass are occasionally elongate.

**Black type**: This type occurs as either independent black pumice clasts or sub-clasts within the gray pumice (Fig. 3c). The independent black pumice clasts are not common, and the sub-clasts in the gray pumice are more common. Most black pumice clasts do not contain elongate vesicles or evidence for ductile deformation.

**Brown type**: This pumice type occurs occasionally as a transitional form of the gray pumice. The brown pumice bands are parallel to the elongate groundmass texture.

**Pale gray type**: The pale gray pumice has a groundmass that is a much darker gray color as compared with the gray type. This type is transitional with the gray pumice.

**Amber type**: The amber type pumice has an amber-colored vesicular groundmass that contains coarse bubbles (up to several millimeters) and is harder than the other types of pumice.

**Streaky type**: This type of pumice consists of banded gray and black pumice. The bands of black pumice (up to 5 mm wide) are generally thinner than those of the gray pumice.

In addition to the above six pumice types, some pumice clasts have blocky and glassy surfaces that possibly formed by quenching.

## 5. Petrography and Geochemistry

### 5.1 Petrography and mineral chemistry

The pumice clasts consist mainly of clinopyroxene (Cpx), plagioclase (Pl), rare olivine (Ol), and a groundmass of vesiculated glass and minor amounts of apatite and opaque minerals (Fig. 4a). Representative mineral and glass analyses are listed in Tables 1–3, and whole-rock compositions determined by XRF spectrometry are listed in Table 4.

Two generations of Ol, Cpx, and Pl were recognized based on optical and electron microscopic observations.

Olivine occurs in two populations. One is phenocrysts or inclusions in Pl phenocrysts in the vesiculated groundmass of the gray pumice, with Mg# values (Mg/[Mg+Fe] × 100) of ~65 and almost free of NiO. The other type occurs as euhedral phenocrysts in the vesiculated groundmass of black, and has Mg# = 92 (Fig. 4c and g), NiO (up to 0.17 mass%), and $Al_2O_3$ (~0.019 mass%). This high-Mg Ol has a low-Mg rim with Mg# = ~80 and, towards the rim, a clear diffusion profile is ~20 μm thick (Fig. 4g). High-Mg Ol also occurs in the pale gray pumice, with lower Mg# values of up to 87. A few Ol micro-crystals were observed in the glassy groundmass of the black pumice, which are up to ~5 μm in diameter and have a similar composition as the low-Mg Ol (Mg# = ~65).

Clinopyroxene occurs as phenocrysts in all pumice types. The Cpx has a diopside (Di) to augite (Aug) composition (Fig. 4e), with Di cores with higher Mg# values (~95) and Aug rims with lower Mg# values (~75). Cpx also occurs as micro-crystals in the glassy groundmass of the black and gray pumice, and is Aug with Mg# values of ~75.

Plagioclase occurs as phenocrysts (up to 5 mm in size) in the groundmass of gray pumice, and is andesine with Ca-rich cores ($An_{45}$) and Na-rich rims ($An_{33}$) (Fig. 4d). Pl in the black pumice is fine-grained (<300 μm) and homogeneous, with $An_{40–45}$. Some Pl that occurs as white-colored enclaves and micro-crystals in the black enclaves has an anorthite composition with $An_{89–95}$. Rare amphibole coexists with the anorthitic plagioclase (Fig. 4f), and dendritic crystals within melt inclusions in high-Mg Ol.

The opaque minerals are generally Ti-bearing magnetite (Mag), while those occurring as inclusions in Pl and Cpx are rarely Fe-sulfide. High-Mg type Ol occasionally contained chromian spinel (Cr-Spl).

Plagioclase occasionally contains abundant brown-colored melt inclusions (Fig. 4a). Melt inclusions in low-Mg Ol are brown-colored, while those in high-Mg Ol are colorless (Fig. 4b).

Black enclaves have two types of occurrences, called type-1 and type-2. Type-1 black enclaves have a dense and fine-grained groundmass consisting mainly of Pl, Cpx, and intergranular glass with phenocrysts of Cpx and Ol (Fig. 5a). Type-2 black enclave have an equigranular texture and consist of Cpx, Ol, and Pl, with minor amounts of magnetite and intergranular glass (Fig. 5b). Ol phenocrysts in type-1 black enclaves are high-Mg and have NiO contents up to 0.12 mass%. Cpx phenocryst in type-1 black enclaves is diopside composition with Mg# values of 92–95 that decrease to 83 in the rims. Pl occurs as fine-grained crystals in the groundmass of type-1 black enclaves, and has high anorthite contents of up to $An_{87}$. In contrast, type-2 black enclaves contain Cpx, Ol, and Pl that have similar compositions as those in the vesicular groundmass of the gray pumice, except for the cores of zoned Pl. Pl in type-2 black enclaves exhibited decrease in anorthite content from core ($An_{82}$) to rim ($An_{32}$) (Fig. 5d and e).

## 5.2 Glass and whole-rock geochemical compositions

The texture of vesicles vary in the different types of pumice. Gray pumice comprises colorless glass with the elongate vesicles, whereas black pumice has a relatively undeformed vesicle texture and brown-colored glass (Fig. 6a–c). Amber pumice has a completely different texture, comprising large bubbles and relatively high glass connectivity (Fig. 6d), resulting in its relatively high hardness.

Vesicular glass in the groundmass is transparent and brown in the black and brown pumices, whereas that in the gray pumice is colorless (Fig. 6a–b). Glass in the pale gray pumice is also colorless, but contains abundant micro-crystals (nanolites) visible under microscope, which are either rectangular or circular in shape (Fig. e–f). These black nanolites were identified as magnetite by Raman microscopy (Fig. 6g). Brown-colored glass in the pale gray pumice only occurs around or inclusions in phenocrysts.

Textural characteristics also vary amongst the different types of pumice. Figure 6c shows a scanning electron microscopy (SEM) image of the contact between black and gray pumice. The gray pumice domain contains highly elongate vesicles as compared with the adjacent black pumice that has a bubble aspect ratio of ~1.

Differences in the brown-colored and colorless glass were further investigated by Raman spectroscopy. The Raman spectrum of the brown-colored glass shows a clear peak at 663 $cm^{-1}$ that is attributed to magnetite (Fig. 6g), even though no micro-crystals were visible under the microscope. In contrast, the 663 $cm^{-1}$ peak did not appear in the spectra of the colorless glass in gray and pale gray pumices.

The glass compositions determined by EMP analyses exhibit trachytic compositions, regardless of the pumice type (Fig. 7a). In particular, the black and gray pumices have very similar compositions, while the amber pumice is relatively enriched in CaO, MgO, and total FeO (Fig. 7b).

Intragranular melt in type-1 black enclaves has lower $SiO_2$ contents as compared with the vesiculated glass, whereas intragranular melt in type-2 black enclaves has similar compositions to vesiculated glass.

Melt inclusions in Pl, augitic Cpx, and low-Mg Ol have similar compositions as the groundmass glass, whereas those in diopsidic Cpx and high-Mg Ol have low $SiO_2$ contents ($SiO_2$ = 50–55 mass%) and are basaltic to basaltic-andesitic in composition (Fig. 7a). Basaltic melt inclusions occasionally contain dendritic minerals, which are difficult to analyze. The most $SiO_2$-rich melt inclusion was discovered in a Aug-Cpx enclosed in Pl (Fig. 4a), and had a rhyolitic composition with $SiO_2$ = 68–69 mass% (Fig. 7a).

Whole-rock compositions of the gray, black, and amber pumice clasts were determined by XRF spectrometry, and all had trachytic compositions regardless of pumice type (Fig. 7a). Pale gray and brown pumice grade into gray pumice, and we did not undertake separate whole-rock analyses of these types.

Selected mafic melt inclusions in type-1 back enclaves and vesicular (trachytic) glass of gray pumice are analyzed and shown in spider diagram (Fig. 7c). Groundmass of type-1 black enclave was also measured as the mixture of intergrain melt and groundmass minerals. Figure 7c also shows whole-rock trace element compositions of gray pumice (FOB-JMA-15, 18, 19). The whole-rock composition and the trachytic glass of gray pumice showed similar trace element patterns to that of the 1986 eruption. In contrast, mafic melt inclusions exhibited different patterns such as positive anomaly of Sr, negative anomaly of Pr, Zr, and Hr. Although measured as mixtures, groundmass of type-1 BI exhibited intermediate compositions between trachytic glass and mafic inclusions.

Mass-normalized magnetic susceptibility was determined on the black and gray pumices (Table 5). The black pumice had a higher magnetic susceptibility than the gray pumice.

# 6. *P*–*T* calculation

Table 6 summarizes the coexisting mineral and melt assemblages observed in the drift pumice clasts. At least two generations can be clearly identified: (1) those associated with mafic melt, including high-Mg Ol and diopsidic Cpx; and (2) those associated with trachytic melt, including low-Mg Ol, augitic Cpx, Mag, and Pl ($An_{44–33}$).

Given that the high-Mg Ol in the black pumice contains Cr-Spl, we applied the Al-in-Ol thermometer (Coogan, 2014). The compositional pair of an Ol core (Mg# = 92) and Cr-Spl of the black pumice (KGB-1) yielded a temperature of 1242 °C.

Growth conditions of the augitic Cpx were estimated using the magnetite geothermometer (Canil and Lacourse, 2020) for Mag inclusions in Cpx (Fig. 4e) and the Cpx single mineral geobarometer (Petrelli et al., 2020) for associated Cpx. Mag in augitic Cpx (FSD-1) yielded ~930°C while pressures for associated Cpx is ~250 MPa.

The Cpx single mineral geobarometer applied to Cpx containing a rhyolitic melt inclusion (Fig. 4a) yielded a pressure of 409 MPa, which is slightly higher than that obtained from the augitic Cpx containing trachytic melts.

# 7. Discussion

## 7.1 Different color types of the drift pumice clasts

Despite the different colors of the pumice clasts, whole-rock compositions of the 2021 FOB pumice are similar. The drift pumice clasts from the 1986 eruption also included gray and black (described as dark-gray in the literature) pumice with similar whole-rock compositions including the $Fe_2O_3$/FeO ratio (Kato, 1988). Raman spectroscopy revealed that the brown-colored glass contained magnetite, although no micro-crystals were observed under the microscope (Fig. 6g). Such a Raman signature is known to originate from sub-microscopic magnetite nanoparticles (Di Genova et al., 2017; Lerner et al., 2021). Based on transmitted electron microscope (TEM) observations of volcanic glass that revealed a crystal size gap of crystalline nanoparticles between <30 nm and >1 μm, Mujin et al. (2017) defined the term "ultrananolite" for grains smaller than <30 nm and the term "nanolite" for a grain size of 30–1000 nm. We did not perform TEM observations and only detected Mag nanoparticles based on Raman spectroscopy. As such, we here use the term nanolite to describe the sub-microscopic Mag in our glass samples. The precipitation of Mag nanolites is consistent with the higher magnetic susceptibility of the black pumice as compared with the gray pumice.

Paulick and Franz (1997) documented very similar characteristics for trachytic pumice in the Meidob volcanic field, Sudan. They measured the $Fe_2O_3$/FeO ratios and magnetic susceptibility for the pumice erupted at 5 ka, which revealed a weak positive correlation between whole-rock $Fe_2O_3$ contents and magnetic susceptibility. In their study, glass in dark gray pumice was also transparent and brown, and they concluded that the brown color was caused by sub-microscopic Mag precipitation in the glass. Schlinger et al. (1986, 1988) identified nano-crystals of Fe oxides in volcanic glasses by TEM observations. In samples from southern Nevada, the size of the Fe oxide grains was up to 140 nm for a quenched sample, and greater in the sample that was more slowly cooled (up to 800 nm; Schlinger et al., 1988). Schlinger et al. (1986) performed heating experiments on colorless, precipitate-free, glass shards at 950°C for 5 min, which resulted in darkening of the glass and precipitates forming on the scale of TEM analysis.

A recent experimental study by Di Genova et al. (2020) revealed that nanolite precipitation is a transient phenomenon that is preserved at a high cooling rate of 10–20°C/s, whereas slow cooling allowed microlites to form. Di Genova et al. (2020) suggested that a small amount (~ 4 vol.%) of nanoparticles and a shear rate of 3.5 $s^{-1}$ would increase the viscosity by a factor of $10^2$ within 100 s of nanolite formation. Given that the brown-colored glass of the present study contains nanolites and that this increased its viscosity, this can explain the less deformed texture of the black pumice as compared with the gray pumice (Fig. 6c).

### 7.2 Timescales of magma mixing

High-Mg Ol found in type-1 black enclaves and black pumice indicated that the mafic magma injection involved in the 2021 FOB explosive eruption. Black pumice clasts are the evidence of heating by the mafic magma of >1200°C and the clear diffusion profile at the rim recorded the timescales of the magma mixing.

To assess the timescales of the mafic magma injection, diffusion modeling of Fe–Mg zoning in Ol was undertaken following the methods of Costa and Dungan (2005) and Viccaro et al. (2016). Diffusion coefficients for Fe–Mg in Ol along *c*-axis were calculated following Costa and Chakraborty (2004):

$$D_c^{\mathrm{Fe-Mg}} = 5380 \times \left(\frac{f_{\mathrm{O2}}}{10^{-12}}\right)^{1/6} \times 10^{3\left(\frac{86-\mathrm{Fo}}{100}\right)} exp\left(\frac{-226000}{8.314 \times T(\mathrm{K})}\right) \quad (1)$$

where the diffusion coefficients for the other axis are assumed to be:

$$D_c^{\text{Fe-Mg}} \sim 6D_a^{\text{Fe-Mg}} \sim 6D_b^{\text{Fe-Mg}} \quad (2)$$

Therefore, the pressure dependence of the diffusion coefficients was ignored. The following form of Fick's second law (in one dimension) with concentration-dependent diffusion coefficients was used for the diffusion modelling:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) \quad (3)$$

Given that the high-Mg Ol had a plateau core composition of Mg# = 92 (Fig. 4g), we used this as the initial value. The rim composition of Mg# = 81 (point A in Fig. 4b) was regarded as the boundary condition at the rim for the calculation (i.e., we used a time-invariant constant composition at the rim). Given that the diffusion rim is very narrow, point B yielded a higher Mg# due to a small mis location of the analytical site. We fitted between point A and corresponding side.

In the present study, the crystal orientation was not determined, and thus diffusional anisotropy was not strictly evaluated. The diffusion modeling was performed assuming a direction parallel to the *c*-axis and the calculated time could be up to 36 times larger than that determined. Diffusion coefficients were calculated at T = 1242°C (derived from Ol–Cr-Spl thermometry) and $f_{O_2}$ values varying from QFM+1 to +3 following the calibration of Myers and Eugster (1983), although 1242 °C is slightly out of the calibration range.

Figure 4g shows the best-fit model and Figure 7d shows the relationship between the calculated time and $f_{O_2}$ values. Assuming that diffusion occurred parallel to the *c*-axis, the calculated time varies from 11 to 24 hours for the $f_{O_2}$ range from QFM+1 to +3. Depending on the crystal orientation, the estimated time becomes as long as 50 d.

### 7.3 Variable pumice types and their role during the explosive eruption

Based on textural and geochemical characteristics, different types of pumice had different roles in the explosive eruption of FOB in 2021. Mitchell et al. (2021) suggested that the pumice clasts form a floating raft and those that suddenly sink to the seafloor have distinct micro-textures (i.e., the floating pumice has a higher vesicle number density and lower pore space connectivity). This could bias the pumice clasts that were sampled. However, the range of drift pumice clasts sampled does partly represent the nature of the 2021 FOB eruption.

The main gray pumice represents the magma reservoir of the FOB. The texture of type-2 black enclaves suggests an origin from a highly crystalized part of the magma reservoir, such as crystal mush. In contrast, type-1 black enclaves and high-Mg olivine in black and pale gray pumice record mafic magma involvement. As groundmass of type-1 black enclaves shows intermediate composition between trachytic and mafic melts (Fig. 7c), type-1 black enclaves represent the mixing nature of the ascending mafic magma and trachytic magma reservoir (Fig. 8). Mafic melt inclusions in both diopsidic Cpx and high-Mg Ol indicate that mafic magma triggered the eruption. Explosive eruption of silicic magma can be triggered by the cryptic mafic magma injection (e.g., Tamura et al., 2003; Shukuno et al., 2006; Tamura et al., 2009). Such involvement are sometimes recognized as co-occurrence of bimodal mafic and silicic clastic materials, although drift pumice clasts in this study all yielded trachytic compositions.

In the present case, black pumice could have been heated by injected mafic magma; however, the whole-rock composition does not change and the high-Mg Ol and Di-Cpx phenocrysts (should be called as xenocrysts) only recorded it. Transport process of xenocrysts from the mafic magma to trachytic magma without changing whole-rock compositions remains unclear. When hydrous mafic magma injected into resident felsic crystal-rich mushes, mafic magma dramatically crystallizes due to the water escape into the felsic magma and corresponding change in liquidus temperature (Pistone et al., 2017). The solidification of hot mafic magma essentially releases the latent heat that can enhance the rejuvenation of the crystal mush. Injected mafic magma would either (1) get highly solidified and could not ejected by the eruption, or (2) sink suddenly around the FOB and we cannot obtain such samples from the drift pumice raft.

Despite the similar whole-rock geochemical compositions of the gray and black pumice, we rarely observed a gradual transition between them. Adjacent gray and black pumice generally have clear boundaries and distinct textures (Fig. 6c), indicating the black pumice magma was highly viscous prior to mingling and that the eruption occurred soon after mingling. The diffusion modeling of Ol also showed a short timescale of black pumice activity, from hours to days (Fig. 7d). Fe oxide nanolites are considered to form due to cooling and/or diffusive $H_2O$ loss (Danyushevsky et al., 2002; Di Genova et al., 2017, 2018), also indicating short timescales. The presence of magmatic nanolites can enhance heterogeneous bubble nucleation and lead to an explosive eruption of silicic magma (Ceseres et al., 2020).

Although the detailed mechanisms of the 2021 FOB Plinian eruption remain unclear, the common and co-occurrence of the nanolite-bearing black pumice within gray pumice might record an important process involved in the explosive eruption. To sum up, ascending mafic magma evidenced by the melt inclusions in high-Mg Ol and diopsidic Cpx heated certain amount of trachytic magma reservoir under FOB, triggering the 2021 explosive eruption (Fig. 8). More detailed micro-textural observations of the mingled black and gray pumice clasts and/or streaky pumice might provide further insights into the magmatic systems of the FOB and neighboring volcanoes in the Mariana arc.

## Supplementary Materials

Trace element analysis data of vesiculated glass, mafic melt inclusions, and whole-rock are available from the online depository materials.

## Acknowledgements

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## Figure Caption

Figure 1.

(a) Index map of the Fukutoku-Oka-no-Ba (FOB) located near the Ioto Island, south of mainland Japan. Summary of the arrival reports of drift pumice are shown. The track of the pumice raft originated from 1986's eruption is also shown. Arrival date are based on Twitter posts for 2021 eruption summarized in https://togetter.com/li/1762225, while those of 1986 eruption are taken from Yoshida et al. (1987), Kato (1988), and Mori et al. (1992). Specific events arranged in chronological order is also summarized. The course of typhoon 16 passed along Japanese Islands on the end of September and should have affected on pumice drifting is also shown (sourced from Japan Meteorological Agency database, https://www.data.jma.go.jp/yoho/typhoon/route_map/bstv2021.html). (b) Topographic map around FOB after Ito et al. (2011).

Figure 2.

Field occurrence of the unloaded drift pumice. (a) Kaigunbo artificial pool at the Minami-daito Island. Small drift pumice clasts were observed on the rugged rock on the road, up to approximately 1m height. Pumice clasts on the road were almost removed. (b) Closed view of the orange rectangle of (a), showing remained pumice clasts in the rock crevices. (c) Rocky beach near the Kaigunbo pool. Large number of pumice clasts were collected in the topographic low. The pumice-pooled area was isolated from the sea by a wall-like topographic high of the coastal rocks. (d) Drift pumice clasts unloaded on the sandy beach of the Amami-Oshima Island. Pumice clasts comprised a “pumice moraine” at the high tide shoreline, while clasts did not remain at more seaward rocky area.

Figure 3

Photo of the typical drift pumice clasts. (a) The large sample collected by JMA RV *Keifu-Maru* (FOB-JMA-18). Compared with the drift sample from the Nansei Islands, rugged surface was preserved. (b) Inside of FOB-JMA-18. Central part is highly vesicular compared to the outer part. (c) Variety of pumice clasts collected from the Nansei Islands. Details are described in the text.

Figure 4.

Photomicrograph and SEM images of the phenocryst minerals in the studied pumice. (a) Cpx and brown-colored melt in Pl phenocryst in brown pumice. Brown-colored melt also surrounded the Pl grain. (b) Colorless mafic melt inclusion in high-Mg Ol occurred in pale-gray pumice. Ol was surrounded by trachytic melt. (c) Euhedral high-Mg Ol occurred in black pumice. Outer-most part show decrease in Mg#. Cr-Spl is included. A-B line indicates the line-profile measurement shown in

Figure 4g. (d) Pl + Cpx phenocryst clot occurred in gray pumice. Pl exhibited $An_{\sim44}$ core and $An_{\sim35}$ rim. (e) Cpx phenocryst showing a clear zonation from the diopsidic core to augitic rim. Abundant Mag and melt inclusions were observed in the rim. (f) Amphibole associated with anorthite rich Pl ($An_{\sim95}$) occurring together with Cpx phenocryst in the gray pumice. (g) Mg# line-profile of the high-Mg Ol. (h) Representative Cpx compositions in Ca-Mg-Fe ternary diagram.

Figure 5.

Back-scattered electron images of two-types of black enclave observed in the studied pumice. (a) Type-1 black enclave exhibiting Cpx phenocrysts embedded in a dense groundmass composed of Pl, Cpx, opaque minerals, and intergranular melt. (b) Type-2 black enclave exhibiting equigranular texture of Cpx, Pl, and Ol, filled with intergranular melt. (c) Closed photo of (a) showing fine grains of Cpx, Pl, and opaque minerals. (d) Zoned Pl occurred in type-2 black enclave, showing rim-ward decrease in An content. A-B line indicates the position of the line profile shown in (e). (e) A-B line profile of An content.

Figure 6

(a) Photomicrograph of the vesicular glass in gray pumice, almost free from microcrystals. (b) Vesicular glass of black pumice exhibits brown color with fine sticky microcrystals of Cpx and rare Ol. (c) Boundary of the black and gray pumice in BSE image. Gray pumice exhibits extensive elongation. (d) Vesicular glass of amber pumice, exhibiting large size bubbles (>500 μm in diameter), and almost colorless. (e) Vesicular glass of pale gray pumice. Abundant nanolites of sticky-shape and small spot are observed (arrowed). (f) BSE image of the glass of pale gray pumice, showing abundant nanolites in the glass. (g) Typical Raman spectra of the black nanoliter in the pale gray pumice and other glasses. The brown-colored glass of black pumice shows the magnetite peak at 663 $cm^{-1}$ although no crystal is visible under microscope observation.

Figure 7.

(a) Total alkali vs $SiO_2$ diagram of the vesiculated glass and whole-rock of the studied pumice clasts. Also whole-rock analyses of previous studies are shown. (b) MgO-CaO binary diagram of the vesiculated glass of the studied sample. Legends are similar to those of (a). (c) Spider diagram showing trace element compositions of the whole-rock gray pumice (FOB-JMA-15, 18, and 19) determined by solution ICP-MS, and vesiculated glass and selected mafic melt inclusions in FOB-JMA-18 determined by LA-ICP-MS. N-MORB data are sourced from Sun and McDonough (1989). (d) Relationship between the time calculated from the diffusion modelling and applied $f_{O2}$ relative to QFM buffer.

Figure 8.

Schematic picture of the FOB 2021 eruption from the preparing stage (A) to the explosive eruption stage (C). Details are in text.

## Tables

Table 1. Representative chemical composition of olivine and clinopyroxene.

Footnote

FeO*: total iron as FeO. $Fe^{3+}/Fe^{2+}$ for clinopyroxene were calculated so that total cation =4 (O=6 basis). B.E.: Black enclave

Table 2. Representative chemical composition of plagioclase and opaque minerals.

Footnote

FeO*: total iron as FeO. $Fe^{3+}/Fe^{2+}$ for opaque minerals were calculated so that sum of $Fe^{2+}$, Mn, and Mg to be 1 (O=4 basis). Calculations of the Pl endmember were as follows: An = Ca/(Ca+Na+K) ×100, Ab = Na/(Ca+Na+K) ×100, Or = K/(Ca+Na+K) ×100. B.E.: Black enclave

Table 3. Representative chemical composition of volcanic glass determined by EMP analyses.

Footnote

FeO*: total iron as FeO. B.E.: Black enclave

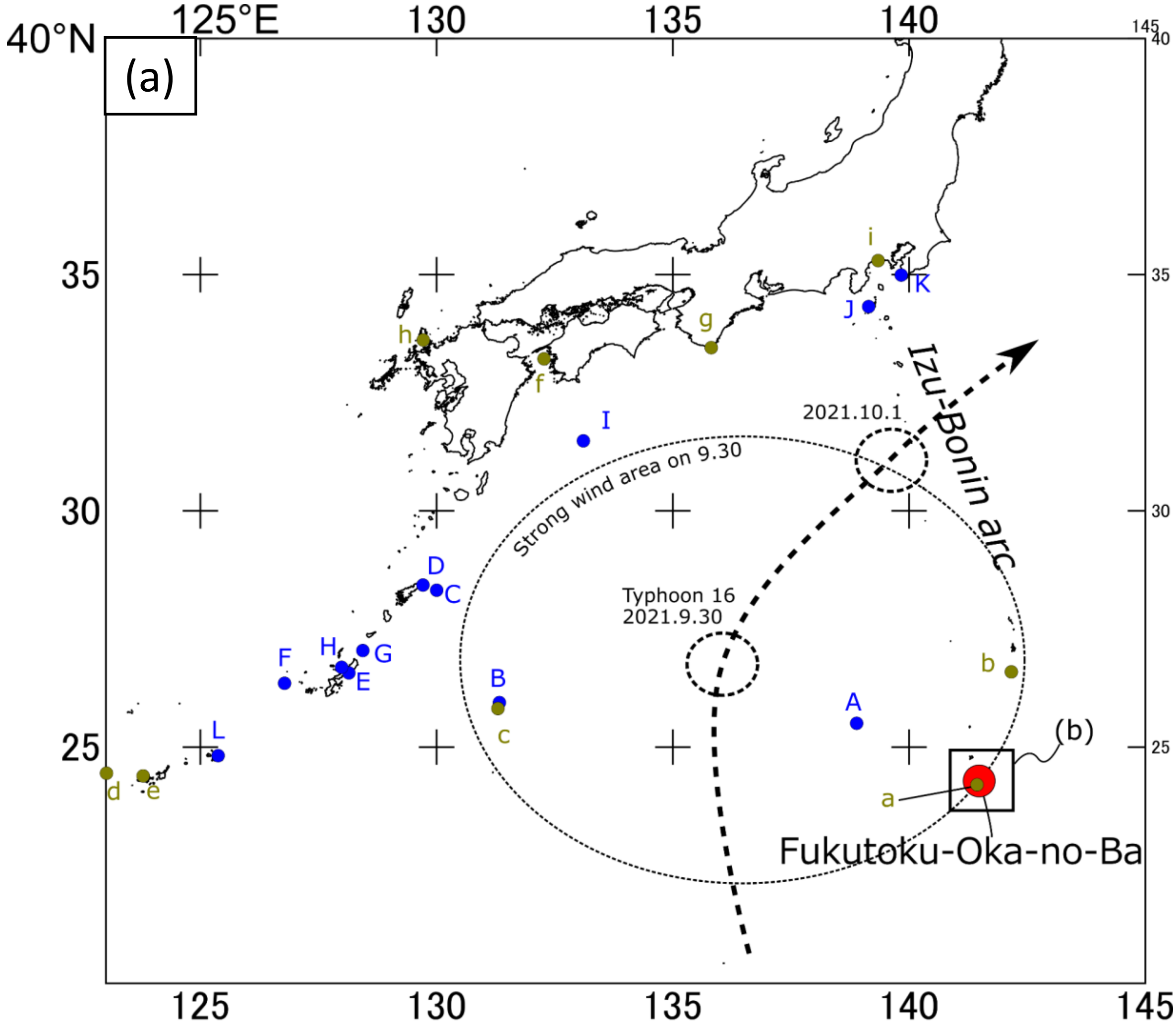
Table 4. XRF whole-rock analyses of the selected pumice samples.

Table 5. Mass-normalized susceptibility of gray and black pumice samples.

Table 6. Summary of the coexisting mineral and melt assemblages.

Table S1. Trace element analyses of glass of inclusions and groundmass, in addition to XRF whole-rock analyses.

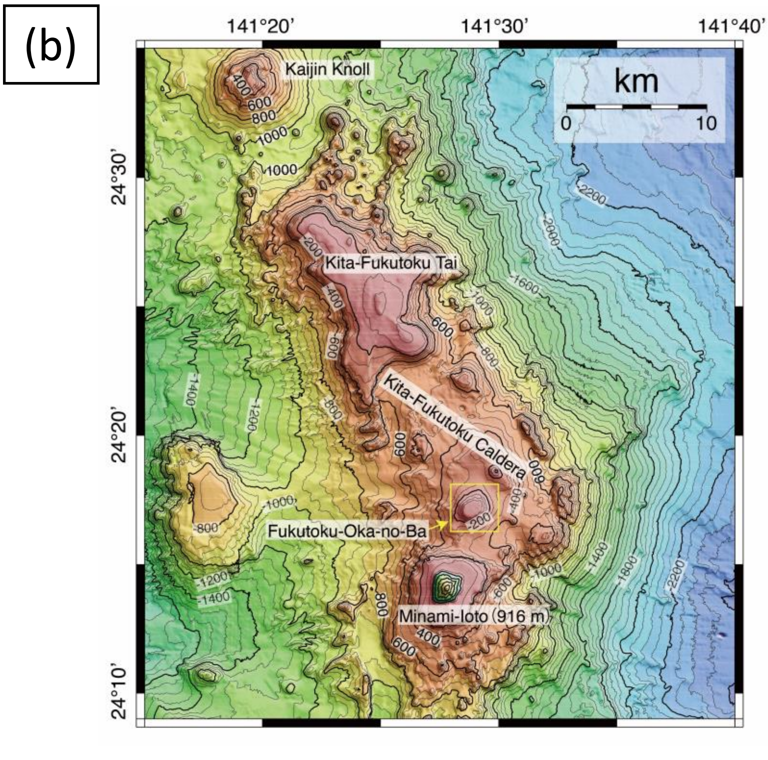
# Figure 1




## Timeline

2021 Aug. 13 eruption
A: Aug 22 Sampling by RV *Keifu-Maru*
B: Oct. 5 Twitter report from Kita-daito Isl.
C: Oct. 10 Kikai Isl.
D: Oct. 12 Amami-oshima Isl.
E: Oct. 13 Okinawa Main Isl. East coast
F: Oct. 13 Kume Isl.
G: Oct. 14 Yoron Isl.
H: Oct. 18 Okinawa Main Isl. West coast
I:Oct. 30 Aircraft observation of the raft
J: Nov. 10 Shikine Isl.
K: Nov. 15 South Boso Peninsula
L: Nov. 19 Miyako Isl.

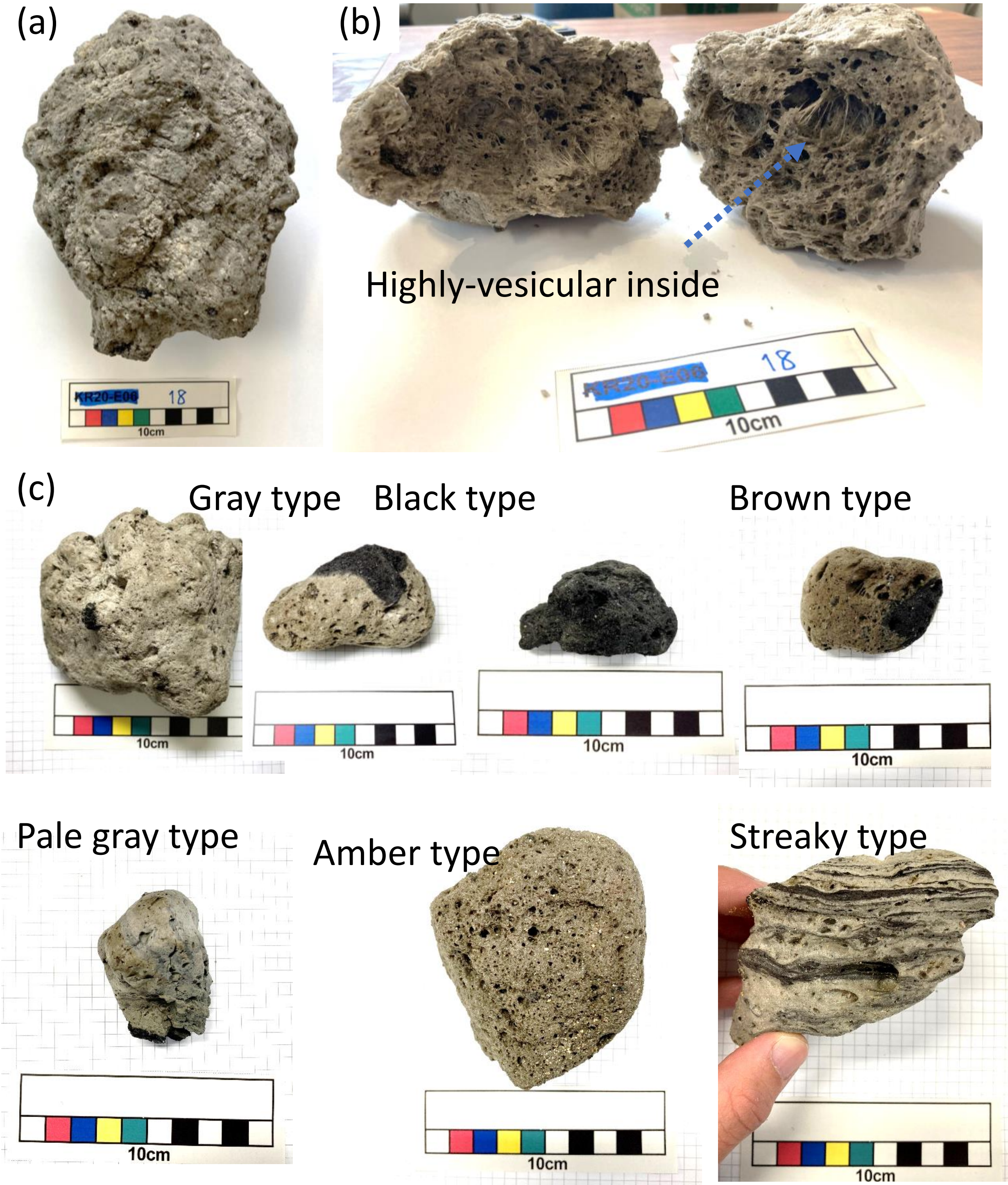
1986 Jan. 18th eruption
a. Jan. 20 Sampling by RV *Takuyo*
b. Mar. 15 Hahajima Isl.
c. Late May Minami-daito Isl.
d. Late May Yonaguni Isl.
e. <June 15 Iriomote Isl.
f. June 26 Ehime Pref. Uwaumi
g. Aug. Wakayama Pref. Kushimoto
h. Oct. Genkai-nada
i. 1991. Sept. Sagami Bay



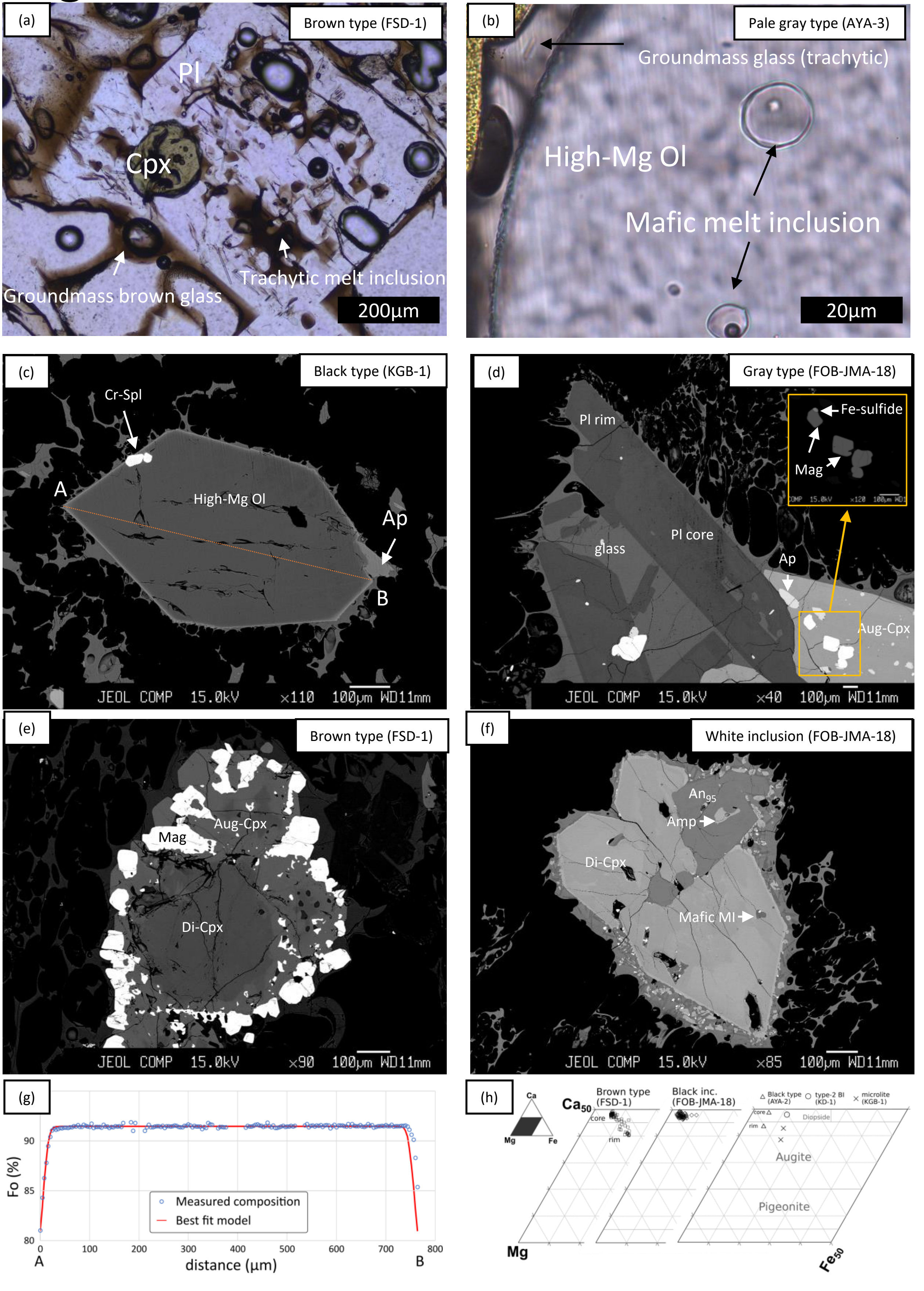
# Figure 2

(a)
Maximum height of the Drifted pumice observed
~1m
sea
(b)
Remained pumice in the rock crevices
5cm
(c)
sea
Topographic high wall
Pumice collected in the rocky beach
50cm
(d)
No pumice remained on the rocky beach
sea
"Pumice Moraine"

Figure 3

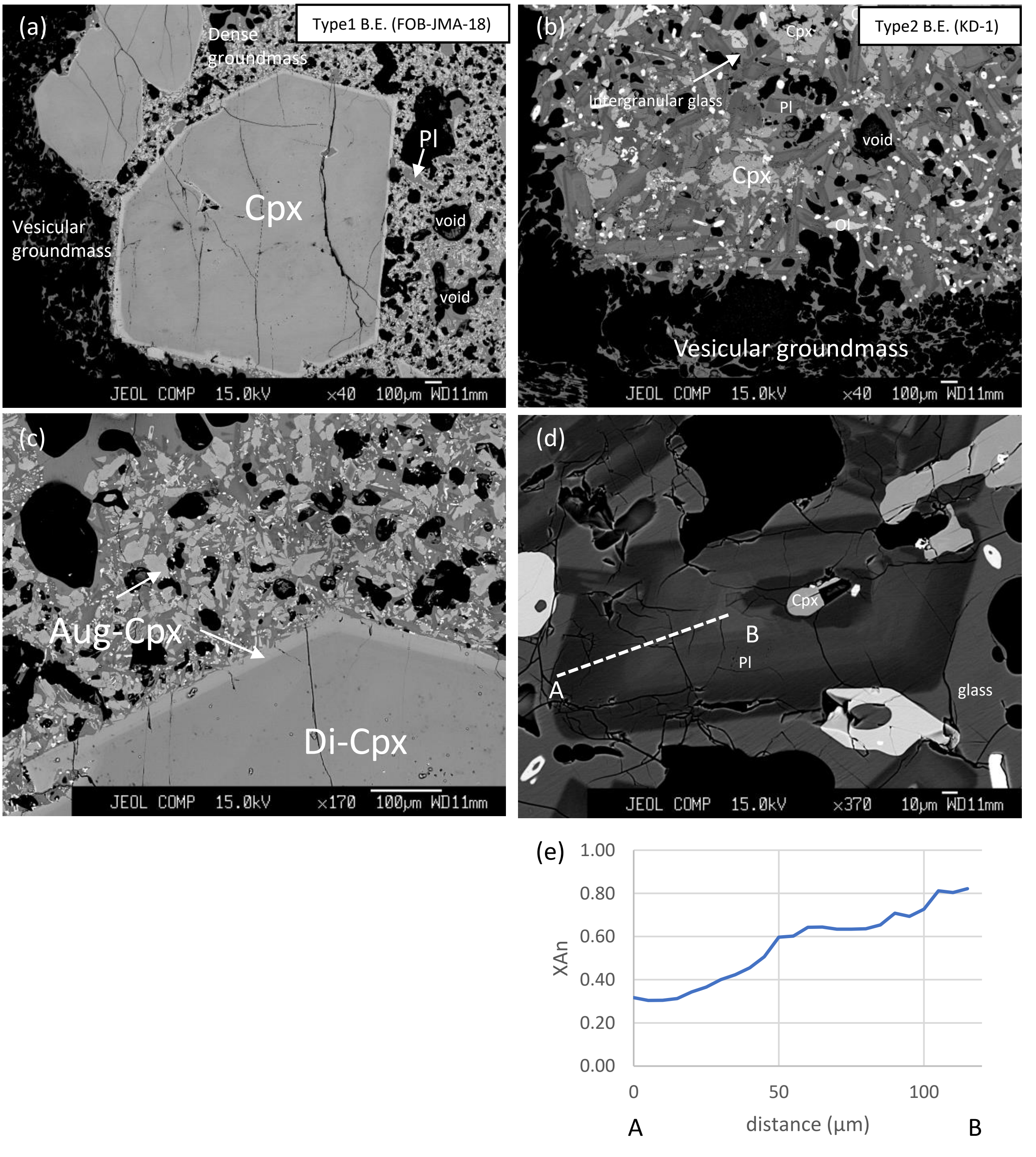

(a)
18
10cm
(b)
Highly-vesicular inside
18
10cm
(c)
Gray type
Black type
Brown type
10cm
10cm
10cm
10cm
Pale gray type
Amber type
Streaky type
10cm
10cm
10cm

# Figure 4

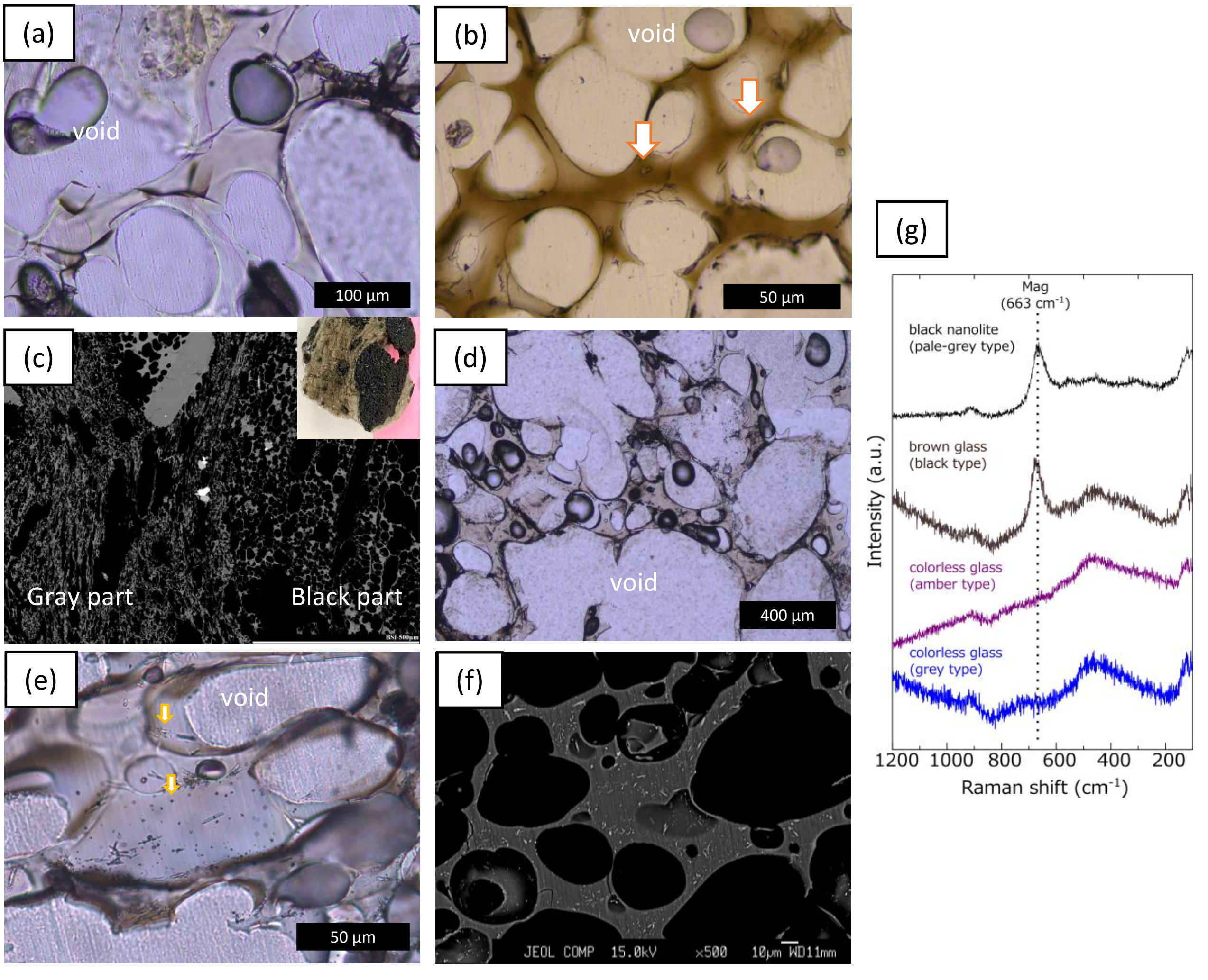


(a)
Brown type (FSD-1)
Pl
Cpx
Groundmass brown glass
Trachytic melt inclusion
200μm
(b)
Pale gray type (AYA-3)
Groundmass glass (trachytic)
High-Mg Ol
Mafic melt inclusion
20μm
(c)
Black type (KGB-1)
Cr-Spl
A
High-Mg Ol
Ap
B
JEOL COMP 15.0kV ×110 100μm WD11mm
(d)
Gray type (FOB-JMA-18)
Fe-sulfide
Mag
Pl rim
glass
Pl core
Ap
Aug-Cpx
JEOL COMP 15.0kV ×40 100μm WD11mm
(e)
Brown type (FSD-1)
Mag
Aug-Cpx
Di-Cpx
JEOL COMP 15.0kV ×90 100μm WD11mm
(f)
White inclusion (FOB-JMA-18)
An95
Amp
Di-Cpx
Mafic MI
JEOL COMP 15.0kV ×85 100μm WD11mm
(g)
Fo (%)
90
85
80
0
100
200
300
400
500
600
700
800
A
B
distance (μm)
Measured composition
Best fit model
(h)
Ca
Mg
Fe
Ca50
Brown type (FSD-1)
core
rim
Black inc. (FOB-JMA-18)
Black type (AYA-2)
type-2 BI (KD-1)
microlite (KGB-1)
Diopside
Augite
Pigeonite
Mg
Fe50

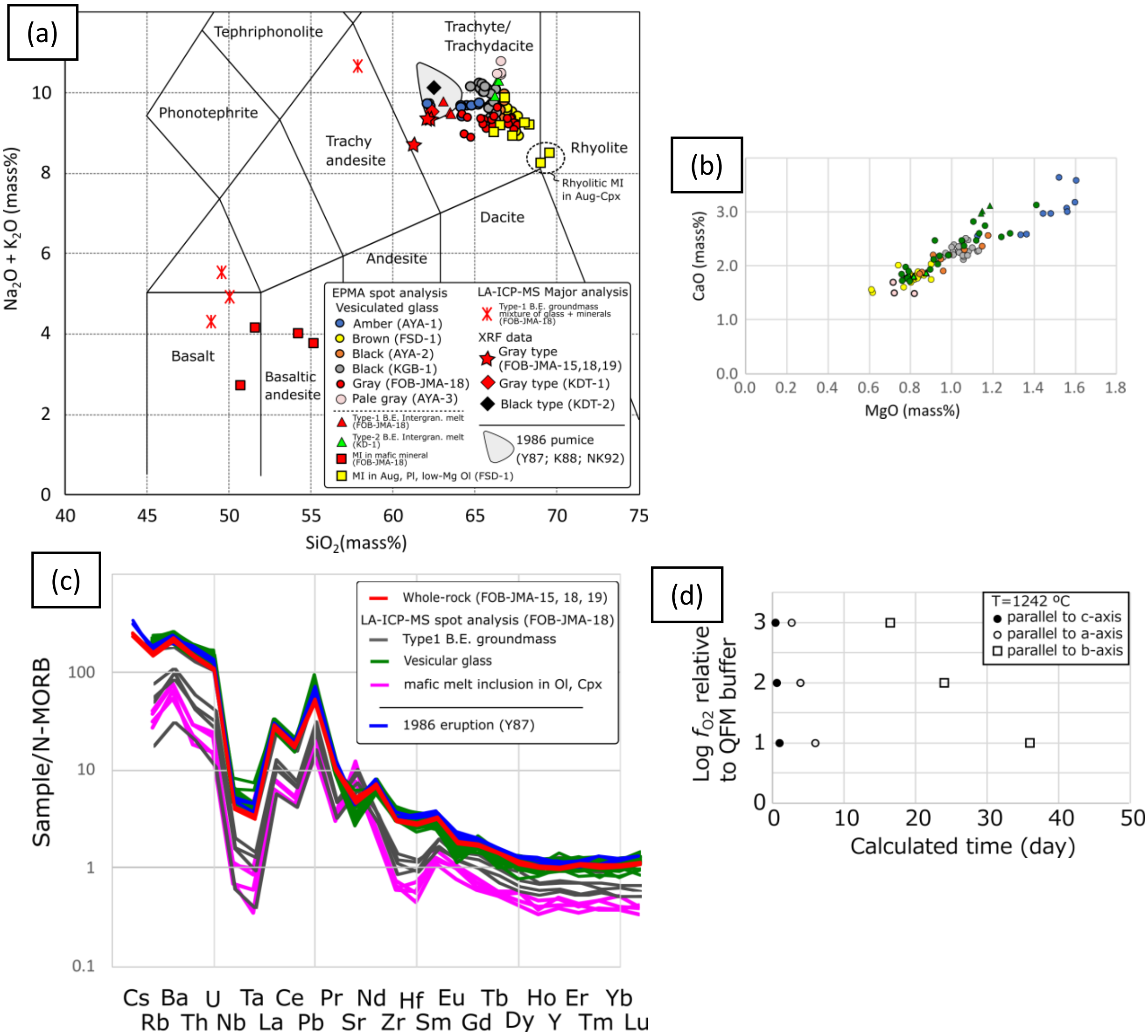
# Figure 5


(a)
Type1 B.E. (FOB-JMA-18)
Dense groundmass
Pl
Cpx
Vesicular groundmass
void
void
JEOL COMP 15.0kV ×40 100μm WD11mm
(b)
Type2 B.E. (KD-1)
Cpx
Intergranular glass
Pl
void
Cpx
Ol
Vesicular groundmass
JEOL COMP 15.0kV ×40 100μm WD11mm
(c)
Aug-Cpx
Di-Cpx
JEOL COMP 15.0kV ×170 100μm WD11mm
(d)
Cpx
B
Pl
A
glass
JEOL COMP 15.0kV ×370 10μm WD11mm
(e)
1.00
0.80
0.60
0.40
0.20
0.00
XAn
0
50
100
A
distance (μm)
B

# Figure 6


(a)
void
100 µm
(b)
void
50 µm
(c)
Gray part
Black part
(d)
void
400 µm
(e)
void
50 µm
(f)
JEOL COMP 15.0kV ×500 10µm WD11mm
(g)
Mag
(663 cm-1)
black nanolite
(pale-grey type)
brown glass
(black type)
colorless glass
(amber type)
colorless glass
(grey type)
Intensity (a.u.)
1200 1000 800 600 400 200
Raman shift (cm-1)

# Figure 7


(a)
Tephriphonolite
Phonotephrite
Trachyte/
Trachydacite
Trachy
andesite
Rhyolite
Rhyolitic MI
in Aug-Cpx
Dacite
Andesite
Basalt
Basaltic
andesite
$Na_2O + K_2O$ (mass%)
$SiO_2$(mass%)
EPMA spot analysis
Vesiculated glass
Amber (AYA-1)
Brown (FSD-1)
Black (AYA-2)
Black (KGB-1)
Gray (FOB-JMA-18)
Pale gray (AYA-3)
Type-1 B.E. Intergran. melt (FOB-JMA-18)
Type-2 B.E. Intergran. melt (KD-1)
MI in mafic mineral (FOB-JMA-18)
MI in Aug, Pl, low-Mg Ol (FSD-1)
LA-ICP-MS Major analysis
Type-1 B.E. groundmass mixture of glass + minerals (FOB-JMA-18)
XRF data
Gray type
(FOB-JMA-15,18,19)
Gray type (KDT-1)
Black type (KDT-2)
1986 pumice
(Y87; K88; NK92)
(b)
CaO (mass%)
MgO (mass%)
(c)
Sample/N-MORB
Whole-rock (FOB-JMA-15, 18, 19)
LA-ICP-MS spot analysis (FOB-JMA-18)
Type1 B.E. groundmass
Vesicular glass
mafic melt inclusion in Ol, Cpx
1986 eruption (Y87)
Cs Ba U Ta Ce Pr Nd Hf Eu Tb Ho Er Yb
Rb Th Nb La Pb Sr Zr Sm Gd Dy Y Tm Lu
(d)
Log $f_{O2}$ relative
to QFM buffer
Calculated time (day)
T=1242 ºC
parallel to c-axis
parallel to a-axis
parallel to b-axis

# Figure 8

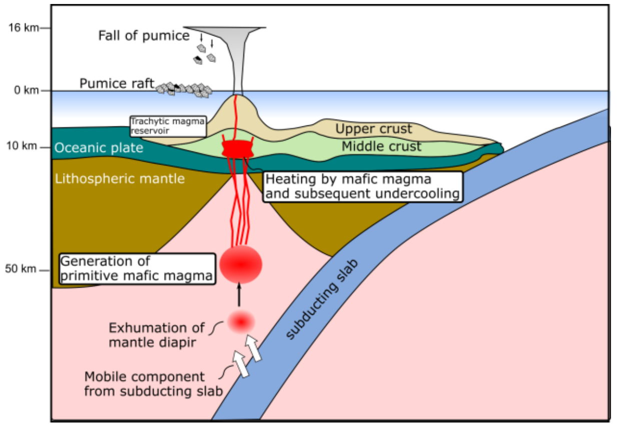

16 km
0 km
10 km
50 km
Fall of pumice
Pumice raft
Trachytic magma reservoir
Upper crust
Middle crust
Oceanic plate
Lithospheric mantle
Heating by mafic magma and subsequent undercooling
Generation of primitive mafic magma
Exhumation of mantle diapir
Mobile component from subducting slab
subducting slab

Table 1

| Mineral | Ol | | | | | |
|---|---|---|---|---|---|---|
| pumice type | Gray | Black | | | Brown | Type-1 B.E. |
| site | Pacific ocean | Minami-daito | | | Amami | Pacific ocean |
| sample No. | FOB-JMA-18 | KGB-1 | | | FSD-1 | FOB-JMA-18 |
| note | | core | rim | microlite | | |
| SiO2 | 35.79 | 40.22 | 40.25 | 34.96 | 36.37 | 38.964 |
| TiO2 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0 |
| Al2O3 | 0.01 | 0.019 | 0.040 | 0.07 | 0.00 | 0.029 |
| Cr2O3 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.016 |
| FeO* | 30.31 | 8.18 | 17.47 | 29.23 | 29.66 | 14.226 |
| MnO | 1.56 | 0.15 | 0.47 | 1.26 | 1.52 | 0.254 |
| MgO | 32.39 | 50.42 | 41.79 | 33.79 | 32.61 | 46.032 |
| CaO | 0.14 | 0.34 | 0.18 | 0.20 | 0.15 | 0.336 |
| Na2O | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0 |
| K2O | 0.00 | 0.00 | 0.01 | 0.05 | 0.00 | 0 |
| NiO | 0.00 | 0.17 | 0.11 | 0.02 | 0.00 | 0.097 |
| Total | 100.21 | 99.53 | 100.32 | 99.58 | 100.32 | 99.95 |
| O= | 4 | 4 | 4 | 4 | 4 | 4 |
| Si | 0.98 | 0.99 | 1.02 | 0.96 | 0.99 | 0.98 |
| Ti | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Al | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cr | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fe3+ | | | | | | |
| Fe2+ | 0.69 | 0.17 | 0.37 | 0.67 | 0.67 | 0.30 |
| Mn | 0.04 | 0.00 | 0.01 | 0.03 | 0.03 | 0.01 |
| Mg | 1.32 | 1.84 | 1.58 | 1.38 | 1.32 | 1.72 |
| Ca | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 |
| Na | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| K | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ni | 0.00 | 0.002 | 0.002 | 0.00 | 0.00 | 0.00 |
| total cation | 3.02 | 3.01 | 2.98 | 3.04 | 3.01 | 3.02 |
| Mg# | 0.66 | 0.92 | 0.81 | 0.67 | 0.67 | 0.67 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Cpx | | | | | | |
| Type-2 B.E. | Grey | | Black | | Brown | | |
| Kita-daito | Amami | | Minami-daito | | Amami | | |
| KD-1 | AYA-2 | | KGB-1 | | FSD-1 | | |
| | core | rim | core | microlite | core | rim | host of rhyolitic MI |
| 36.737 | 50.49 | 49.30 | 52.12 | 50.52 | 51.45 | 52.61 | 53.43 |
| 0.035 | 0.30 | 0.72 | 0.27 | 0.75 | 0.27 | 0.39 | 0.32 |
| 0.012 | 5.10 | 5.67 | 3.38 | 4.26 | 3.89 | 1.48 | 1.13 |
| 0 | 0.00 | 0.00 | 0.39 | 0.02 | 0.12 | 0.01 | 0.00 |
| 30.282 | 6.32 | 8.92 | 4.57 | 8.76 | 4.28 | 9.35 | 9.91 |
| 1.498 | 0.10 | 0.19 | 0.00 | 0.45 | 0.11 | 0.83 | 0.86 |
| 32.21 | 14.62 | 13.30 | 15.56 | 14.52 | 16.06 | 15.35 | 15.26 |
| 0.17 | 23.21 | 21.34 | 23.15 | 19.63 | 23.76 | 19.71 | 19.50 |
| 0.011 | 0.22 | 0.33 | 0.10 | 0.41 | 0.07 | 0.45 | 0.40 |
| 0.012 | 0.02 | 0.01 | 0.02 | 0.03 | 0.02 | 0.05 | 0.00 |
| 0.005 | | | | | | | |
| 100.97 | 100.38 | 99.79 | 99.57 | 99.36 | 100.03 | 100.21 | 100.82 |
| 4 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 0.99 | 1.85 | 1.83 | 1.92 | 1.88 | 1.88 | 1.95 | 1.97 |
| 0.00 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 |
| 0.00 | 0.22 | 0.25 | 0.15 | 0.19 | 0.17 | 0.06 | 0.05 |
| 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 0.08 | 0.06 | 0.00 | 0.04 | 0.07 | 0.06 | 0.02 |
| 0.68 | 0.11 | 0.21 | 0.14 | 0.24 | 0.07 | 0.23 | 0.29 |
| 0.03 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.03 | 0.03 |
| 1.29 | 0.80 | 0.74 | 0.85 | 0.81 | 0.87 | 0.85 | 0.84 |
| 0.00 | 0.91 | 0.85 | 0.91 | 0.78 | 0.93 | 0.78 | 0.77 |
| 0.00 | 0.02 | 0.02 | 0.01 | 0.03 | 0.01 | 0.03 | 0.03 |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00 | | | | | | | |
| 3.01 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| 0.67 | 0.88 | 0.78 | 0.86 | 0.77 | 0.93 | 0.79 | 0.75 |

| | | |
|---|---|---|
| Type-1 B.E. | | Type-2 B.E. |
| Pacific ocean | | Kita-daito |
| FOB-JMA-18 | | KD-1 |
| core | rim | |
| 53.60 | 49.23 | 49.53 |
| 0.20 | 0.43 | 0.76 |
| 1.63 | 4.94 | 5.49 |
| 0.24 | 0.07 | 0.08 |
| 3.21 | 8.46 | 9.45 |
| 0.06 | 0.07 | 0.42 |
| 17.54 | 14.63 | 13.04 |
| 24.24 | 22.06 | 21.55 |
| 0.12 | 0.16 | 0.39 |
| 0.02 | 0.01 | 0.00 |
| 100.87 | 100.05 | 100.71 |
| 6 | 6 | 6 |
| 1.93 | 1.82 | 1.83 |
| 0.01 | 0.01 | 0.02 |
| 0.07 | 0.22 | 0.24 |
| 0.01 | 0.00 | 0.00 |
| 0.05 | 0.13 | 0.09 |
| 0.05 | 0.13 | 0.20 |
| 0.00 | 0.00 | 0.01 |
| 0.94 | 0.81 | 0.72 |
| 0.94 | 0.87 | 0.85 |
| 0.01 | 0.01 | 0.03 |
| 0.00 | 0.00 | 0.00 |
| 4.00 | 4.00 | 4.00 |
| 0.95 | 0.86 | 0.78 |

Table 2

| | Pl | | | | | | |
|---|---|---|---|---|---|---|---|
| pumice type | Gray | | Black | Brown | Type-1 B.E. | Type-2 B.E. | |
| site | Pacific ocean | | Minami-da | Amami | Pacific ocean | Kita-daito | |
| sample No. | FOB-JMA-18 | | KGB-1 | FSD-1 | FOB-JMA-18 | KD-1 | |
| note | core | rim | | | | core | rim |
| SiO2 | 57.33 | 59.86 | 57.91 | 60.18 | 46.27 | 48.30 | 61.17 |
| TiO2 | 0.05 | 0.00 | 0.05 | 0.00 | 0.05 | 0.03 | 0.03 |
| Al2O3 | 26.60 | 24.72 | 26.54 | 24.95 | 33.78 | 32.77 | 24.29 |
| Cr2O3 | 0.12 | 0.00 | 0.00 | 0.01 | 0.00 | 0.03 | 0.03 |
| FeO* | 0.56 | 0.46 | 0.55 | 0.58 | 1.05 | 0.81 | 0.56 |
| MnO | 0.06 | 0.00 | 0.12 | 0.00 | 0.01 | 0.05 | 0.00 |
| MgO | 0.02 | 0.05 | 0.04 | 0.04 | 0.14 | 0.03 | 0.03 |
| CaO | 9.00 | 7.30 | 9.06 | 7.09 | 17.35 | 16.24 | 6.17 |
| Na2O | 5.81 | 6.54 | 5.78 | 6.57 | 1.39 | 1.89 | 6.50 |
| K2O | 0.65 | 1.06 | 0.68 | 1.11 | 0.03 | 0.10 | 1.29 |
| Total | 100.18 | 99.98 | 100.73 | 100.52 | 100.07 | 100.24 | 100.06 |
| O= | 8 | 8 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Si | 2.57 | 2.68 | 2.59 | 2.68 | 2.13 | 2.21 | 2.72 |
| Ti | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Al | 1.41 | 1.30 | 1.40 | 1.31 | 1.84 | 1.77 | 1.28 |
| Cr | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fe3+ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fe2+ | 0.02 | 0.02 | 0.02 | 0.02 | 0.04 | 0.03 | 0.02 |
| Mn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Ca | 0.43 | 0.35 | 0.43 | 0.34 | 0.86 | 0.80 | 0.29 |
| Na | 0.51 | 0.57 | 0.50 | 0.57 | 0.12 | 0.17 | 0.56 |
| K | 0.04 | 0.06 | 0.04 | 0.06 | 0.00 | 0.01 | 0.07 |
| total cation | 4.99 | 4.98 | 4.98 | 4.98 | 5.01 | 4.99 | 4.95 |
| An | 44 | 36 | 45 | 35 | 87 | 82 | 32 |
| Ab | 52 | 58 | 51 | 59 | 13 | 17 | 60 |
| Or | 4 | 6 | 4 | 7 | 0 | 1 | 8 |

| Opaque | Cr-Spl | Mag |
|---|---|---|
| | Black | Brown |
| | Minami-daito | Amami |
| | KGB-1 | FSD-1 |
| | in high-Mg Ol | in Cpx |
| | | |
| | 0.09 | 0.14 |
| | 0.25 | 10.46 |
| | 8.34 | 2.91 |
| | 58.20 | 0.11 |
| | 21.82 | 77.73 |
| | 0.31 | 0.87 |
| | 12.54 | 2.92 |
| | 0.02 | 0.00 |
| | 0.00 | 0.00 |
| | 0.00 | 0.00 |
| | 101.57 | 95.14 |
| | | |
| | 4 | 4 |
| | 0.00 | 0.00 |
| | 0.01 | 0.28 |
| | 0.32 | 0.12 |
| | 1.48 | 0.00 |
| | 0.19 | 1.49 |
| | 0.39 | 0.82 |
| | 0.01 | 0.03 |
| | 0.60 | 0.15 |
| | 0.00 | 0.00 |
| | 0 | 0.00 |
| | 0 | 0.00 |
| | | |
| Cr# | 0.74 | |
| Mg# | 0.60 | 0.15 |

Table 3

| pumice type | Gray | Black | Amber | Pale gray | Brown | | |
|---|---|---|---|---|---|---|---|
| site | Amami | Minami-daito | Amami | Amami | Amami | | |
| sample No. | AYA2 | KGB1 | AYA1 | AYA3 | FSD-1 | | |
| note | | | | | MI in Cpx | MI in low-Mg Ol | MI in Pl |
| SiO2 | 65.63 | 65.22 | 64.69 | 65.56 | 67.67 | 65.89 | 66.75 |
| TiO2 | 0.52 | 0.49 | 0.46 | 0.53 | 0.55 | 0.50 | 0.37 |
| Al2O3 | 16.10 | 16.12 | 16.05 | 15.89 | 16.05 | 16.15 | 15.78 |
| Cr2O3 | 0.00 | 0.04 | 0.01 | 0.00 | 0.03 | 0.00 | 0.02 |
| FeO* | 3.77 | 3.83 | 4.37 | 3.72 | 3.47 | 3.71 | 3.34 |
| MnO | 0.05 | 0.09 | 0.33 | 0.18 | 0.02 | 0.14 | 0.17 |
| MgO | 0.90 | 1.11 | 1.56 | 0.81 | 0.34 | 0.56 | 0.72 |
| CaO | 2.15 | 2.24 | 3.07 | 1.46 | 0.95 | 1.94 | 1.57 |
| Na2O | 4.70 | 4.85 | 4.82 | 4.91 | 4.30 | 4.67 | 4.57 |
| K2O | 4.74 | 4.75 | 4.90 | 5.37 | 3.98 | 5.09 | 4.43 |
| P2O5 | 0.11 | 0.14 | 0.17 | 0.19 | 0.07 | 0.18 | 0.07 |
| F | 0.09 | 0.09 | 0.14 | 0.12 | 0.14 | 0.13 | 0.16 |
| Cl | 0.31 | 0.30 | 0.29 | 0.36 | 0.35 | 0.39 | 0.33 |
| Total | 98.65 | 98.86 | 100.43 | 98.61 | 97.42 | 99.33 | 97.77 |

| Type-1 B.E. | | | Type-2 B.E. |
|---|---|---|---|
| Pacific ocean | | | Kita-daito |
| FOB-JMA-18 | | | KD-1 |
| MI in Cpx | MI in high-Mg Ol | intergranular | intergranular |
| 51.92 | 48.93 | 62.63 | 65.53 |
| 0.53 | 0.57 | 0.33 | 0.41 |
| 20.91 | 16.39 | 16.12 | 16.29 |
| 0.08 | 0.00 | 0.00 | 0.00 |
| 5.59 | 9.04 | 5.83 | 3.95 |
| 0.25 | 0.18 | 0.22 | 0.21 |
| 3.43 | 3.96 | 1.13 | 0.87 |
| 9.17 | 14.87 | 2.97 | 1.85 |
| 2.91 | 1.78 | 4.54 | 4.74 |
| 0.91 | 0.82 | 4.84 | 5.05 |
| n.a. | n.a. | 0.51 | 0.20 |
| 0.04 | 0.02 | 0.21 | 0.11 |
| 0.14 | 0.09 | 0.44 | 0.32 |
| 95.68 | 96.54 | 99.11 | 99.11 |

Table 4

| Pumice type | Gray | Gray | Gray | Gray | Black | Amber |
|---|---|---|---|---|---|---|
| site | Pacific ocean | Pacific ocean | Pacific ocean | Kita-daito | Kita-daito | Amami |
| Sample No. | FOB-JMA-15 | FOB-JMA-18 | FOB-JMA-19 | KD-FOB1 | KD-FOB2 | AYA-01 |
| $SiO_2$ | 60.24 | 60.50 | 59.60 | 60.81 | 60.85 | 60.61 |
| $TiO_2$ | 0.58 | 0.58 | 0.56 | 0.57 | 0.61 | 0.57 |
| $Al_2O_3$ | 16.28 | 15.94 | 15.35 | 16.31 | 16.28 | 15.52 |
| $Fe_2O_3$ | 5.33 | 5.37 | 5.55 | 5.20 | 5.48 | 5.66 |
| MnO | 0.17 | 0.17 | 0.17 | 0.17 | 0.18 | 0.17 |
| MgO | 1.93 | 2.09 | 3.03 | 1.82 | 1.42 | 3.04 |
| CaO | 3.92 | 3.79 | 5.03 | 3.59 | 3.03 | 4.49 |
| $Na_2O$ | 4.70 | 4.70 | 4.33 | 4.82 | 5.14 | 4.55 |
| $K_2O$ | 4.34 | 4.42 | 4.10 | 4.43 | 4.65 | 4.27 |
| $P_2O_5$ | 0.23 | 0.23 | 0.21 | 0.23 | 0.28 | 0.22 |
| Total | 97.70 | 97.78 | 97.93 | 97.94 | 97.91 | 99.10 |
| LOI | 1.38 | 1.47 | 1.58 | 0.55 | 0.78 | 0.04 |

Table 5

| | weight (g) | bulk mag. Sus. (cm3) | MS (cm3/g) |
|---|---|---|---|
| Gray type | 2.996 | 0.022 | 7.44E-03 |
| Black type | 4.857 | 0.045 | 9.23E-03 |

Table 6

| | Mafic member | Trachytic member |
|---|---|---|
| Occurrence | Type-1 black inclusion<br>xenocryst in black-/ pale gray-type | major member of pumice clasts |
| melt SiO2 | 48-55 mass% | 62-70 mass% |
| Ol Mg# | 85-92 | ~65 |
| Cpx composition | diopside | augite |
| Pl composition | An80-95 | An33-44 |
| Other minerals | amphibole | magnetite |