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 2 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 $\text{SiO}_2 = 61$–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 nanocrystals 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 c. 1200 °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
drift pumice, Fukutoku-Oka-no-Ba, Izu-Bonin-Mariana arc, nanolite, Plinian eruption

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 (Figure 1a). Five eruptions have been recorded in 1904–1905, 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...
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 NS direction, respectively, and rises 2000–2200 m above the surrounding ocean floor (Figure 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 (Figure 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 has ~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 lengths of 1.5 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, Japan Standard Time, UTC + 9:00) 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 pumice was estimated to be 100–500 × 10⁶ m³ (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 “0” shape, then the eastern 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 (Figure 1a; Yoshida et al., 1987; Kato, 1988; Mori et al., 1992). An ocean bottom observatory instrument installed near Nishinoshima accidentally drifted from the Izu-Bonin arc towards the Nansei Islands in 2020, 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 traveled 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. Drifting of pumice continued along the Kuroshio current and arrived at the shores of Kanto area and Izu Islands in Mid-November. From the southwest Japan to eastern area, drifting pumice followed a large-meandering of the Kuroshio Current (e.g., Aoki et al., 2020) and might have drifted along the offshore path

(e.g., Furukawa, 1995). Geochemical analyses and petrographical observations have been conducted on pumice erupted in 1904, 1914, and 1986 (Kato, 1988; Nakano & Kawanabe, 1992; Tsuya, 1937; Yoshida et al., 1987). Major element composition the FOB pumices are trachyte similar to the nearby lito volcano, which magma type is rare in the Izu-Ogasawara arc. In contrast, FOB pumices are isotopically distinct from the products of the lito, but similar to the Hiyoshi Volcanic Complex to the south of the FOB (Sun et al., 1998).
(Figure 1a). 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 (EMP) 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. Beam diameter was set to 3 μm for minerals and 5 μm for glass.

Raman spectra were obtained with a Raman spectrophotometer (RAMANtouch VIS-HP-MAST; Nanophoton) equipped with a 532 nm semiconductor 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 AgNO₃ 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 Li₂B₄O₇ 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. We also analyzed a reference basalt (JB-2: Jochum et al., 2016), yielding results in good agreement with the certified values (Table S2).

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 & 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).

2.1 | 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 October 5, 2021. The drift pumice clasts were reported on Kikai Island on 10th October, and they continued to other islands located farther west, subsequently the arrivals were reported from Izu Islands and Boso Peninsula in Mid-November. Pumice clasts traveling to west have arrived at Philippine (23 November) and Taiwan (29 November), while those in the north-eastern side arrived later at Yakushima Island (5 December) and Wakayama Prefecture (13 December) even though these places are not so far away from the Nansei Islands (Figure 1a).

The first identification of the drift pumice clasts on Kita-daito Island was on 5th 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 suggested that the pumice raft was offshore on 30th September, the day of the typhoon attack (Figure 1a). On Minami-daito 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 (Figure 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 (Figure 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 (Figure 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 the 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 in. 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 (Figure 1a).

2.2 | 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 (Figure 3b), 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 (Figure 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 (Figure 3a,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. Plagioclase-dominated clot also occurs as dark-colored materials that resemble to “Uzura-ishi (quail’s egg stone)” commonly observed as pebbles on the shore of Ioto Island (e.g., Homma, 1925).

Black type: This type occurs as independent black pumice clasts or together with the gray pumice (Figure 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-colored part occurs 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.

### 3 | PETROGRAPHY AND GEOCHEMISTRY

#### 3.1 | Petrography and mineral chemistry of pumice

The pumice clasts consist mainly of phenocrysts of plagioclase (Pl), clinopyroxene (Cpx), rare olivine (Ol), and a groundmass of vesiculated glass and minor amounts ofapatite and opaque minerals (Figure 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.

One generation of Ol is phenocrysts or inclusions in Pl phenocrysts in the vesiculated groundmass of the gray and brown pumice, with Mg# values (Mg/[Mg + Fe] × 100) of ~65 and almost free of NiO. A few Ol micro-crystals were observed in the vesiculated glass in groundmass of the black pumice, which are up to ~10 μm in diameter and have a similar composition as the low-Mg Ol (Mg# = ~65). The other type occurs as euhedral phenocrysts in the vesiculated groundmass of black pumice, and has Mg# = 92 (Figure 4c,g), NiO (up to 0.17 mass%), and Al₂O₃ (~0.019 mass%). This high-Mg Ol has a low-Mg rim with Mg# = ~80 showing a clear diffusion profile of ~20 μm thick (Figure 4g). High-Mg Ol also occurs in the pale gray pumice, with lower Mg# values of up to 87.

Clinopyroxene occurs as phenocrysts in all pumice types. The Cpx has a diopside (Di) to augite (Aug) composition (Figure 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 vesiculated glass in 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 vesiculated groundmass of gray pumice, and is andesine with Ca-rich cores (An₄₅) and Na-rich rims (An₃₃) (Figure 4d). Pl in the black pumice is fine-grained (<300 μm) and homogeneous, with An₃₀–₄₅. Some Pl that occurs as phenocryst coexisting with Di and micro-crystals in the black enclaves has an anorthite composition with An₈₉–₉₅. Rare pargasitic amphibole coexists with the anorthitic plagioclase (Figure 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 (Figure 4a). Melt inclusions in low-Mg Ol are brown-colored, while those in high-Mg Ol are colorless (Figure 4b).

#### 3.2 | Petrography and mineral chemistry of black enclaves

Black enclaves, typically occurring in the gray pumice, have two types of occurrences, called type-1 and type-2. Type-1 black enclaves have a weakly vesiculated fine-grained groundmass consisting mainly of Pl, Cpx, Mag, and intergrain glass with phenocrysts of Cpx and Ol (Figure 5a). Type-2 black enclaves have an equigranular texture and consist of Cpx, Ol, and Pl, with minor amounts of magnetite and intergrain glass (Figure 5b). Weak vesicular is also recognized in type-2 black enclaves. Ol phenocrysts in type-1 black enclaves are high-Mg (Mg# = 85) 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 augite rims. Pl occurs as fine-grained crystals in the groundmass of type-1 black enclaves, most of which are up to 200 μm in length, and has high anorthite contents of up to An87. 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 (An82) to rim (An32) (Figure 5d,e). Intergrain glass of both type-1 and 2 black enclaves exhibit colorless and the black color of the enclaves are derived from the high abundance of magnetite in both types (Figure 5f,g).

### 3.3 Glass and whole-rock geochemical compositions

The textures 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 (Figure 6a–c). Glass surrounding Pl phenocrysts and melt inclusions in Pl in the gray pumice also exhibited brown-colored (Figure 4a). Amber pumice has a completely different texture, comprising large bubbles and relatively high glass connectivity (Figure 6d), resulting in its relatively high hardness.
| Mineral | Ol Type-1 | Type-2 | Cpx Type-1 | Type-2 | Pale | Minami-daito | FOB-JMA-18 | Gray | Black | Brown | Amber | B.E. | Gray | Black | Brown | Amber | Amami | Minami-daito | FOB-JMA-18 | Pale | Rim | Core | Host of rhyolitic MI | Core | Rim |
|---------|----------|--------|------------|--------|------|--------------|-----------|------|-------|-------|-------|------|------|-------|-------|-------|-------|--------------|--------|------|-----|-----|----------------|--------|-----|
| Site    | Site     | Site   | Site       | Site   | Site | Site         | Site      | Site | Site | Site | Site | Site | Site | Site | Site | Site | Site | Site | Site | Host of rhyolitic MI | Site | Site |
| Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean | Pacific ocean |
| Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. | Sample no. |
| KGB-1 | FSD-1 | AYA-1 | AYA-3 | KD-1 | AYA-2 | KGB-1 | FSD-1 | AYA-1 | AYA-3 | FOB-JMA-18 | KD-1 | FOB-JMA-18 | Kamami | FOB-JMA-18 | Kamami | FOB-JMA-18 |
| Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note | Note |
| Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si | Si |
| FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* | FeO* |
| TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 | TiO2 |
| Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 | Al2O3 |
| Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 | Cr2O3 |
| MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO | MgO |
| CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO | CaO |
| Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O | Na2O |
| K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O | K2O |
| NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO | NiO |
| Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation | Total cation |
| 3.02 | 3.01 | 2.98 | 3.04 | 3.01 | 3.01 | 3.02 | 3.02 | 3.01 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | (Continues)
Vesicular glass in the groundmass is transparent and brown in the black and brown pumices, whereas that in the gray and amber pumice is colorless (Figure 6a,b). Glass in the pale gray pumice is also colorless, but contains abundant micro-crystals (<5 μm) visible under an optical microscope, which are either rectangular or circular in shape (Figure 6e,f). These black micro-crystals were identified as magnetite by Raman microscopy (Figure 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 (Figure 6g), even though no micro-crystals were visible under the optical microscope. In contrast, the 663 cm\(^{-1}\) peak did not appear in the spectra of the colorless glass in gray and amber pumices.

The glass compositions determined by EMP analyses exhibit trachytic compositions, regardless of the pumice type and glass color (Figure 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 (Figure 7b).

Intragrain melt in type-1 black enclaves has lower SiO\(_2\) contents (~62 mass%) as compared with the vesiculated glass, whereas intragrain 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 (Figure 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, and had a rhyolitic composition with SiO\(_2\) = 68–69 mass% (Figure 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 (Figure 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 black enclaves and vesicular (trachytic) glass of gray pumice are analyzed and shown in spider diagram (Figure 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 black enclaves exhibited intermediate compositions between trachytic glass and mafic inclusions.
Table 2: Representative chemical composition of plagioclase and opaque minerals

| Pumice type | Pl                | Opaque          | Cr-Spl          | Mag          | Type-1 B.E. | Type-2 B.E. | Site                      | Sample No.   | Note      | Cr#    | An     | Ab     | Or     |
|-------------|-------------------|-----------------|-----------------|--------------|-------------|-------------|---------------------------|--------------|----------|--------|--------|--------|--------|
| Site        | Sample No.        |                 |                 |              | Pacific ocean | Pacific ocean |                          |              |          |        |        |        |        |
| Pacific ocean | FOB-JMA-18 | Gray  | Black | Mag  | Gray  | Mag  | Gray  | Pacific ocean | Kita-daito |         |        |        |        |        |
| Minami-daito | KGB-1         | Brown | Minami | Mag  | Pacific Ocean | Mag  | KGB-1 | FOB-JMA-18     | KD-1         |         |        |        |        |        |
| Amami       | FSD-1        | Amber | Amami   | Mag  | Mag  | Mag  | FSD-1 | Mag  | KGB-1 | In high-Mg Ol | FSD-1 | AYA-3 | AYA-3 |
| Amami       | AYA-1        | Pale  | Gray  | type | Pale  | Gray  | AYA-3 | Mag  | KGB-1 | In Cpx       | AYA-1 | AYA-3 | AYA-3 |
| Amami       | AYA-1        | Pale  | Gray  | Pale  | Pale  | Gray  | AYA-3 | Mag  | KGB-1 | In Cpx       | AYA-3 | Amami | Amami |
| Amami       | AYA-1        | Pale  | Gray  | Pale  | Pale  | Gray  | AYA-3 | Mag  | AYA-3 | In high-Mg Ol |

|                | Core | Rim | Core | Rim |
|----------------|------|-----|------|-----|
| SiO2           | 57.33 | 59.86 | 57.91 | 60.18 |
| TiO2           | 0.05  | 0.00  | 0.05  | 0.00  |
| Al2O3          | 26.60 | 24.72 | 26.54 | 24.85  |
| Cr2O3          | 0.12  | 0.00  | 0.00  | 0.00  |
| FeO*           | 0.56  | 0.46  | 0.55  | 0.42  |
| MnO            | 0.06  | 0.00  | 0.12  | 0.01  |
| MgO            | 0.02  | 0.05  | 0.04  | 0.06  |
| CaO            | 9.00  | 7.30  | 9.06  | 7.92  |
| Na2O           | 5.81  | 6.54  | 5.78  | 6.41  |
| K2O            | 0.65  | 1.06  | 0.68  | 1.11  |
| Total          | 100.18 | 99.98 | 100.73 | 100.52 |
| O=             | 8     | 8    | 8     | 8    |
| Si             | 2.57  | 2.68  | 2.59  | 2.68  |
| Ti             | 0.00  | 0.00  | 0.00  | 0.00  |
| Al             | 1.41  | 1.30  | 1.40  | 1.34  |
| Cr             | 0.00  | 0.00  | 0.00  | 0.00  |
| Fe3+           | 0.00  | 0.00  | 0.00  | 0.00  |
| Fe2+           | 0.02  | 0.02  | 0.02  | 0.02  |
| Mn             | 0.00  | 0.00  | 0.00  | 0.00  |
| Mg             | 0.00  | 0.00  | 0.00  | 0.00  |
| Ca             | 0.43  | 0.35  | 0.43  | 0.34  |
| Na             | 0.51  | 0.57  | 0.50  | 0.57  |
| K              | 0.04  | 0.06  | 0.04  | 0.06  |
| Total cation   | 4.99  | 4.98  | 4.98  | 4.98  |

Note: FeO*: total iron as FeO. Fe3+/Fe2+ for opaque minerals were calculated so that sum of Fe2+, 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, Cr# = Cr/(Cr + Al) × 100, Mg# = Mg/(Mg + Fe2+) × 100. B.E.: Black enclave.
### Table 3: Representative chemical composition of volcanic glass determined by EMP analyses

| Pumice type | Site | Sample no. | N. analyzed | Gray Pacific Ocean FOB-JMA-18 KD-1 | Gray Kita-daito KGB1 | Black Minamidaito Amami Amami | Amber Amami | Pale gray Amami | Brown Amami | Type-1 B.E. Pacific Ocean FOB-JMA-18 KD-1 | Type-2 B.E. Kita-daito KD-1 |
|-------------|------|------------|-------------|----------------------------------|---------------------|--------------------------|-------------|---------------|-------------|---------------------------------|--------------------------|
|             |      |            |             |                                  |                     |                          |             |               |             |                                 |                          |
|             |      |            |             |                                  |                     |                          |             |               |             |                                 |                          |
| Note        |      |            |             |                                  |                     |                          |             |               |             |                                 |                          |

|   | SiO₂ | TiO₂ | Al₂O₃ | Cr₂O₃ | FeO* | MnO | MgO | CaO | Na₂O | K₂O | P₂O₅ | F | Cl | Total |
|---|------|------|-------|-------|------|----|-----|-----|------|-----|------|---|----|-------|
| 1 | 65.98| 0.51 | 16.38 | 0.04  | 3.86 | 0.17| 0.97| 2.26| 4.62 | 4.93| 0.11 | 0.14| 0.32| 100.29 |
| 2 | 66.47| 0.52 | 16.17 | 0.04  | 3.54 | 0.16| 0.80| 1.84| 4.69 | 5.07 | 0.14 | 0.14| 0.31| 99.90  |
| 3 | 65.36| 0.52 | 16.31 | 0.02  | 3.88 | 0.14| 0.80| 2.25| 4.80 | 4.96 | 0.14 | 0.10| 0.31| 99.81  |
| 4 | 64.27| 0.56 | 16.36 | 0.01  | 4.47 | 0.17| 1.03| 3.01| 4.82 | 4.83 | 0.14 | 0.12| 0.26| 100.48 |
| 5 | 65.93| 0.52 | 16.08 | 0.01  | 3.57 | 0.17| 1.46| 1.60| 5.03 | 5.42 | 0.14 | 0.16| 0.26| 99.65  |
| 6 | 66.37| 0.56 | 16.29 | 0.01  | 3.91 | 0.15| 0.76| 1.78| 4.63 | 4.70 | 0.14 | 0.16| 0.32| 99.81  |
| 7 | 67.67| 0.55 | 16.05 | 0.03  | 3.47 | 0.15| 0.83| 0.95| 4.30 | 3.98 | 0.07 | 0.16| 0.35| 97.90  |
| 8 | 65.89| 0.50 | 16.15 | 0.00  | 3.71 | 0.14| 0.34| 1.94| 4.67 | 5.09 | 0.18 | 0.17| 0.39| 99.33  |
| 9 | 66.75| 0.37 | 15.78 | 0.02  | 3.34 | 0.17| 0.72| 1.57| 4.57 | 4.43 | 0.07 | 0.25| 0.33| 97.77  |
| 10| 51.92| 0.53 | 20.91 | 0.00  | 5.59 | 0.18| 3.43| 9.17| 1.78 | 0.91 | n.a. | n.a. | 0.14| 96.54  |
| 11| 48.93| 0.57 | 16.39 | 0.00  | 9.04 | 0.18| 3.96| 14.87| 4.54 | 0.82 | n.a. | n.a. | 0.09| 99.11  |
| 12| 62.63| 0.33 | 16.12 | 0.00  | 5.83 | 0.22| 1.13| 2.97| 4.84 | 0.84 | 1.46 | 0.76 | 0.44| 99.11  |
| 13| 65.53| 0.41 | 16.29 | 0.00  | 3.95 | 0.21| 0.87| 1.85| 5.05 | 0.32 | 0.51 | 0.20 | 0.11| 99.11  |

Note: FeO*: total iron as FeO. B.E.: Black enclave.
### TABLE 4  XRF whole-rock analyses of the selected pumice samples

| Pumice type | Site          | Sample no.   | SiO$_2$   | TiO$_2$  | Al$_2$O$_3$ | Fe$_2$O$_3$ | MnO   | MgO  | CaO  | Na$_2$O | K$_2$O | P$_2$O$_5$ | Total | LOI   |
|------------|--------------|--------------|-----------|----------|-------------|-------------|-------|------|------|---------|--------|------------|--------|-------|
| Gray       | Pacific ocean| FOB-JMA-15   | 60.24     | 0.58     | 16.28       | 5.33        | 0.17  | 1.93 | 3.92 | 4.70    | 4.34   | 0.23       | 97.70  | 1.38  |
| Gray       | Pacific ocean| FOB-JMA-18   | 60.50     | 0.58     | 15.94       | 5.37        | 0.17  | 2.09 | 3.79 | 4.70    | 4.70   | 0.23       | 97.78  | 1.47  |
| Gray       | Pacific ocean| FOB-JMA-19   | 59.60     | 0.56     | 15.35       | 5.55        | 0.17  | 3.03 | 5.03 | 4.33    | 4.42   | 0.21       | 97.93  | 1.58  |
| Gray       | Kita-daito   | KD-FOB1      | 60.81     | 0.57     | 16.31       | 5.20        | 0.17  | 1.82 | 3.59 | 4.82    | 4.43   | 0.23       | 97.94  | 0.55  |
| Gray       | Kita-daito   | KD-FOB2      | 60.85     | 0.61     | 16.28       | 5.48        | 0.18  | 1.42 | 3.03 | 5.14    | 4.65   | 0.28       | 97.91  | 0.78  |
| Black      | Kita-daito   | KD-FOB2      | 60.61     | 0.57     | 15.52       | 5.66        | 0.17  | 1.42 | 3.04 | 5.55    | 4.27   | 0.22       | 99.10  | 0.04  |
| Amber      | Amami        | AYA-01       |           |          |             |             |       |      |      |         |        |            |        |       |

**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 intergran melt. (b) Type-2 black enclave exhibiting equigranular texture of Cpx, Pl, and Ol, filled with intergran 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 rimward decrease in An content. A-B line indicates the position of the line profile shown in (e). (f) A-B line profile of An content. (f and g) Photomicrograph of the intergran glass of type-1 and -2 black enclaves, both showing colorless glass.
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 microcrystals in the glass. (g) Typical Raman spectra of the black microcrystals in the pale gray pumice and other glasses. The brown-colored glass of black and brown pumice shows the magnetite peak at 663 cm⁻¹ although no crystal is visible under optical microscope observation.

FIGURE 7 (a) Total alkali versus SiO₂ 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 modeling and applied fO₂ relative to QFM buffer.
3.4 | Magnetic susceptibility of pumice

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.

3.5 | 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-

| TABLE 5 | Mass-normalized susceptibility of gray and black pumice samples |
|----------|---------------------------------|
|          | Weight (g) | Bulk mag. Sus. (cm$^3$) | MS (cm$^3$/g) |
| Gray type | 2.996      | 0.022                  | 7.44E-03     |
| Black type| 4.857      | 0.045                  | 9.23E-03     |

Mg O$_2$ and diopside Cpx; and (2) those associated with trachytic melt, including low-Mg O$_2$, augitic Cpx, Mag, and PI (An$_{34-33}$).

Temperature conditions of (1) were estimated using the Al-in-Ol thermometer (Coogan et al., 2014). Given that the high-Mg O$_2$ in the black pumice contains Cr-Spl as inclusion, the compositional pair of an O$_2$ core (Mg$\# = 92$) and Cr-Spl (Cr$\# = \frac{Cr}{Cr + Al} \times 100 = 82$) of the black pumice (KGB-1) yielded a temperature of 1226 °C. Another pair of high-Mg O$_2$ (Mg$\# = 88$) and corresponding Cr-Spl inclusion (Cr$\# = 63$) found in the pale gray pumice (AYA-3) yielded a temperature of 1129 °C. This range is well comparable with the suggested uncertainty of the calibration (± 20 °C). Accordingly, the temperature of the injected mafic melt should be around 1200 °C.

Pressure–temperature conditions of (2) were determined using the magnetite geothermometer (Canil & Lacourse, 2020) for Mag inclusions in Cpx (Figure 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 compositional variation of the analyzed pumice clasts shall affect the P–T estimation but the estimated variation could be smaller than

| TABLE 6 | Summary of the coexisting mineral and melt assemblages |
|----------|-------------------------------------------------------|
|          | Mafic member | Trachytic member |
| Occurrence | Type-1 black enclave, xenocryst in black-/ | Major member of pumice clasts |
| Melt SiO$_2$ | 48–55 mass% | 62–70 mass% |
| O$_2$ Mg$\#$ | 85–92 | ~65 |
| Cpx composition | Diopside | Augite |
| PI composition | An$_{80-95}$ | An$_{33-44}$ |
| Other minerals | Amphibole (pargasitic), Cr-spinel | Magnetite |

FIGURE 8 | Schematic picture of the FOB 2021 eruption from the preparing stage (a) to the explosive eruption stage (c). Details are in text
the suggested uncertainties of ±60 °C and 170 MPa for thermometer and barometer, respectively.

4 | DISCUSSION

4.1 | 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 Fe₂O₃/FeO ratio (Kato, 1988). Raman spectroscopy revealed that the brown-colored glass contained magnetite, although no micro-crystals were observed under the microscope (Figure 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 >100 nm, Mujin et al. (2017) defined the term “ultrananolite” for grains smaller than <30 nm and redefined the term “nanolite” (in a strict sense) 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 in a broad sense for the grain size, and use 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 Meldob volcanic field, Sudan. They measured the Fe₂O₃/FeO ratios and magnetic susceptibility for the pumice erupted at 5 ka, which revealed a weak positive correlation between whole-rock Fe₂O₃ contents and magnetic susceptibility. In their study, glass in dark gray pumice was also transparent and brown, and they realized that this increased its viscosity, this can explain the less deformed texture of the black pumice as compared with the gray pumice (Figure 6c).

4.2 | 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):

\[
D_{Fe}^{O_1} = 5380 \left( \frac{f_{O2}}{10^{-3}} \right)^{1/6} \times 10^{3.3(Fe/O)} \exp \left( -\frac{226000}{8314 \times T[K]} \right) \tag{1}
\]

where Fo refers Mg# of olivine and the diffusion coefficients for the other axis are assumed to be:

\[
D_{Fe}^{O_2} \sim 6D_{Fe}^{O_1} \sim 6D_{Fe}^{O_3}
\]

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 modeling:

\[
\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial C}{\partial x} \right) \tag{3}
\]

Given that the high-Mg Ol had a plateau core composition of Mg# = 92 (Figure 4g), we used this as the initial value. The rim composition of Mg# = 81 (point A in Figure 4c) 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 mislocation of the analytical site. We fitted between point A and the corresponding side. Analytical points were taken by 4 μm steps and more than 90 points (~400 μm) were involved for the fitting, although only 10 points at the rim side showed a diffusion profile.

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 = 1226 °C (derived from Ol–Cr–Spl thermometry) and f_o2 values varying from QFM + 1 to +3 following the calibration of Myers and Eugster (1983), although 1226 °C is slightly out of the calibration range.
Given that the temperature of 1226 °C obtained from Ol is the maximum estimate where intragrain diffusion has taken place, it should be noted that the following timescales are the minimum estimates. 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 14 to 31 h for the $f_{O_2}$ range from QFM + 1 to +3. Depending on the crystal orientation, the estimated time becomes as long as 50 days.

4.3 Variable pumice types and their role during the explosive eruption

As Mujin and Nakamura (2020) indicated based on the variable degrees of nano- and microlite growth in the lava/pumice of a single eruption, minor components of the drift pumice, such as pale-gray type, may have originated from the rewelded materials that have fallen back in the previous eruptions(s). However, the common occurrence of the black pumice coexisting with the gray type with clear boundary strongly indicates that the black pumice played certain 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 may represent the main magma in 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 the groundmass of type-1 black enclaves shows intermediate composition between trachytic and mafic melts (Figure 7c), type-1 black enclaves represent the mixing nature of the ascending mafic magma and trachytic magma reservoir (Figure 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., Shukuno et al., 2006; Tamura et al., 2003; 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 is 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 be 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 (Figure 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 (Figure 7d). Fe oxide nanolites are considered to form due to cooling and/or diffusive H2O loss (Danyushevsky et al., 2002; Di Genova et al., 2017, 2018). The experimental study of Cáceres et al. (2021) indicated that the nucleation of Fe–Ti oxide nanolites occurs at cooling rates of <0.5 °C/min in the rhyolitic system, i.e. too quick quenching cannot make nanolites to occur. Although the whole-rock composition is different in our case, given the temperature difference of mafic magma (1226 °C) and trachytic magma (930 °C), cooling duration of >12 h produces the cooling rate of <0.5 °C/min and would be suitable for the nanolites precipitation in a silicic magma system, which is in good agreement with the timescales estimated from the diffusion modeling. The presence of magmatic nanolites can enhance heterogeneous bubble nucleation and lead to an explosive eruption of silicic magma (Cáceres et al., 2020). Accordingly, it is suggested that the black pumice had become black due to heating by injected mafic magma and subsequent cooling. Then, nanolites-bearing black pumice had involved in the Plinian eruption due to its increased viscosity.

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 diopside Cpx heated a certain amount of trachytic magma reservoir under FOB, triggering the 2021 explosive eruption (Figure 8). More detailed micro-textual 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.

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CONFLICT OF INTEREST
There are no entities or relationship, etc. presenting a potential conflict of interest requiring disclosure in relation to this manuscript.

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