Voyage to the west: pumice raft from the Fukutoku-Oka-no-Ba in the northwest Pacific drifted over the South China Sea to Thailand

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Abstract

The 2021 eruption of Fukutoku-Oka-no-Ba (FOB) in the northwest Pacific on 13 August 2021 produced a large volume of pumice that drifted westward for ~1300 km to the Nansei Islands, Japan. Some pumice clasts were transported farther southwest to Taiwan and the Philippines or northeast to the Kanto district of Japan by the Kuroshio current. In February 2022, pumice with similar characteristics to the FOB pumice was deposited along the east coast of the Malay Peninsula, along the Gulf of Thailand. The pumice clasts deposited in Songkhla Province, Thailand, were <4 cm in length and more rounded than to those collected in the Nansei Islands. Most of the clasts consisted of clinopyroxene, plagioclase (andesine) and olivine phenocrysts in a vesiculated grey groundmass, with black-coloured spots, some of which exhibited signatures of a basaltic magma, including anorthite-rich plagioclase with basaltic melt inclusions. The whole-rock compositions of the pumice are trachytic, with SiO_2 contents of 61 mass% and total alkali contents ($Na_2O + K_2O$) of 9 mass%, similar to those collected in Japan. The minerals in the pumice from Thailand have similar compositions to those in FOB pumice. These pumice in Thailand were from the 2021 FOB eruption, and drifted >2800 km south-westward across the South China Sea, partly affected by the monsoon and corresponding seasonal ocean circulation. Pumice from large oceanic eruptions can spread across borders; therefore, an international pumice monitoring network might be required for future eruptions.

Keywords: pumice rafts, Fukutoku-Oka-no-Ba, Izu-Ogasawara arc

Introduction

Pumice rafting involves the dynamic interplay between volcanism, ocean currents, marine biology, and the human economy. The movement of geological rafts is thought to be a beneficial dispersal mechanism for shallow marine organisms (Bryan *et al*., 2012). In contrast, a large amount of floating material is hazardous to humans and can reduce economic activity by damaging ships, for example, or discouraging tourism. Recent progress in satellite technology enables daily observation of large pumice rafts, and numerical models can provide precise forecasts of their drift that can help produce hazard maps (Jutzeler *et al*., 2020). However, it is difficult to track small rafts, and complex processes can move floating materials to unexpected places.

Fukutoku-Oka-no-Ba (FOB) is a submarine volcano in the NW Pacific located at 24°17.1′N/141°28.9′E, ~5 km northeast of Minami-Iōtō Island and ~1300 km south of mainland Japan (Fig. 1a). Several eruptions of the volcano and discoloration of the sea surface have been recorded in the literature, indicating that the volcano is highly active (Tsuya, 1937; Maeno *et al*., 2022). The 2021 eruption occurred on the early morning of 13 August (Japan Standard Time) (Metz, 2022) and produced a large amount of pumice that formed rafts of ~0.1–0.3 km^3 in size (Maeno *et al*., 2022). The pumice rafts were transported to the west by the Kuroshio Counter-current, and after 2-months of drifting, the clasts arrived at the Nansei Islands, Japan (Usami & Shinjo, 2022; Yoshida *et al*., 2022). Although a large amount of pumice was deposited on the Nansei Islands, some of the floating pumice continued to drift eastward and arrived in eastern Japan in the middle of November. Some also drifted westward and arrived in Taiwan and the Philippines in late November (Fig. 1a; Yoshida *et al*., 2022). On 9 February, a considerable amount of pumice arrived on the beaches of Songkhla province in southern Thailand and subsequently at Chumphon and Rayong provinces in the north of the Gulf of Thailand (Fig. 1a, b). This pumice is similar to the 2021 FOB pumice collected in Japan, although there was initially confusion about its origin. Because there were no apparent submarine volcanic eruptions nearby, the pumice clasts found in Thailand were first thought to have originated from the Hunga Tonga–Hunga Ha'apai eruption in Tonga on 15 January 2022; however, it was too early for the arrival of pumice from a source located >9500 km away. This paper describes the petrographic characteristics of the pumice collected in Thailand and discusses the >4000 km-long voyage of the pumice rafts from FOB.

Methods

Whole-rock compositions of representative pumice clasts were determined by X-ray fluorescence (XRF) spectrometry (Rigaku ZSX Primus II) at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka, Japan. Mineral and glass compositions were determined using a field emission gun electron microprobe (EMP) analyser with five wavelength-dispersive X-ray detectors (JEOL, JXA-8500F) at JAMSTEC. Details of the analytical procedure were presented by Sato *et al*. (2020) and Yoshida *et al*. (2022).

Petrography and Mineralogy

The pumice clasts investigated in this study were collected from Thung Yai and Samila beaches in Songkhla Province, Thailand, on 10 February 2022. The clasts are more rounded than those collected in the Nansei Islands and are <4 cm in length. According to Yoshida *et al*. (2022), most clasts are gray-type pumice, although one clast is a mixture of black and grey pumice (Fig. 1c). Goose barnacles of <2 cm are often found on the clasts (Fig. 1c). The whole-rock compositions of the representative grey pumice clasts from the two localities are listed in Table 1. The pumice clasts consist of plagioclase (Pl), clinopyroxene (Cpx), and olivine (Ol) phenocrysts in a vesiculated groundmass of volcanic glass, with a small amount of apatite and opaque minerals (Fig. 2a). In addition, poorly vesiculated black enclaves were identified (Fig. 2b). Representative mineral and glass compositions are listed in Tables

1 and 2, respectively.

The grey pumice clasts from Thung Yai beach and Samila beach yield whole-rock SiO_2 contents of 61.6 and 61.8 mass% and total alkali (K_2O + Na_2O) contents of 9.2 and 9.1 mass%, respectively, on an anhydrous basis. These are almost identical to the FOB trachyte samples from the 2021 and earlier eruptions (Fig. 2c). EMP analyses of the vesiculated glass in the groundmass yield higher SiO_2 (65-66 mass%) and total alkali (10-10.6 mass%), while the interstice of the type-1 black enclaves yield slightly lower SiO_2 (~64 mass%) and higher FeO* (~4.4 mass%).

Plagioclase in the groundmass is andesine, with X_{An} (=Ca/[Ca+Na+K]) values of 0.41 and 0.32 in the core and rim, respectively. Glass associated with or included as melt inclusions in coarse-grained plagioclase is brown and yields a similar composition to the colorless groundmass glass (Table 1). Clinopyroxene in the groundmass is augite, with Mg# (=Mg/[Mg+Fe] × 100) of 76. Olivine in the groundmass yields Mg# of 65. High-Mg (Mg# ~90) olivine crystals occur in the mixed black and grey pumice clast (SM-01) and are associated with brown glass (Table 2).

The black enclaves consist of clinopyroxene and plagioclase phenocrysts in a poorly vesiculated groundmass with abundant clinopyroxene, plagioclase, and magnetite microlites of <100 μm in length (Fig. 2b). Olivine microlites are possibly also present, although individual analyses could not be carried out due to their small size. Plagioclase phenocrysts in the black enclave are mostly anorthite with X_{An} values of 0.95, and contain basaltic melt inclusions with SiO_2 contents of 47 mass%. Clinopyroxene phenocrysts in the black enclave have diopside cores with Mg# of 89 and Al-rich augite rim (Al = 0.38 on the basis of 6 oxygen) with Mg# of 83 (Fig. 2b). Clinopyroxene microlites yield Al-rich augite compositions similar to those of phenocryst rims. In contrast, plagioclase microlites are andesine (X_{An} = 0.46) similar to the core of the plagioclase phenocrysts in the vesicular groundmass. The interstitial glass in the black enclave yields low SiO_2 and high FeO contents (Table 1). These compositions are the same as those of the type-1 black enclave found in the grey FOB pumice (Yoshida *et al.*, 2022)

Discussion and Implications

The petrographic and geochemical characteristics of the pumice clasts in the raft that arrived in Thailand are similar to those of the FOB pumice observed on the coast of Japan (Yoshida *et al.*, 2022). In particular, the poorly vesiculated black enclaves in the pumice from Thailand are similar to the type-1 black enclaves reported in the FOB pumice by Yoshida *et al.* (2022). The diopsidic Cpx and anorthite-rich Pl compositions indicate that the originated in a basaltic magma, were the distinguishing characteristics of the FOB pumice (Yoshida *et al.*, 2022). These observations suggest that the pumice raft from the 2021 FOB eruption drifted ~2800 km from Taiwan and the Philippines to the Gulf of Thailand in ~ 80 days (Fig. 1a). The pumice clasts that arrived in Thailand are smaller than those observed in Japan, possibly due to abrasion during the long voyage. In addition, black pumice was rare in the pumice raft after the long journey to Thailand. Yoshida *et al.* (2022) reported contrasting microtextures in the grey and black pumice, despite the similar porosity: the grey pumice has small, elongated vesicles and the black pumice has large, spherical vesicles. Mitchell *et al.* (2021) suggested that pumice with higher vesicle numbers is more likely to continue floating, which might explain why more of the grey pumice with small vesicles, and thus high vesicle numbers, survived the long voyage to Thailand.

The South China Sea (SCS) lies in the monsoon regime, and strong northeast winds prevail over the region during winter (~9 m/s on average; Hu *et al.*, 2000). The pumice raft that drifted to the Philippines and Taiwan could have been transported into the SCS from the Luzon Strait by an intrusion of the Kuroshio current. These intrusions are unlikely to occur during the late spring to summer, due to the north-eastward current in the northern SCS (Hu *et al.*, 2000).

The average speed of the pumice as it drifted from the Philippines to Thailand was ~40 cm/s, similar to the south-westward current in the northern SCS during winter (30-45 cm/s; Hu *et al.*, 2000). After the 1986 FOB eruption, a possible pumice raft from FOB was observed ~200 km off the coast of Vietnam (16°28.2′N, 110°66.7′E) on 28 August 1986 by the crew of the Dutch ship MV *Nedlloyd Colombo* (Smithsonian Institution, 1986; Bryan *et al.*, 2012). The 1986 FOB pumice raft arrived in the western Okinawa in late May (Kato, 1988). Given the distance between Okinawa and Vietnam (~1800 km) and the difference of ~3 months in arrival time, the pumice raft drifted at ~23 cm/s, which is 2/3 the speed of the 2021 pumice raft. This difference is possibly due to the north-eastward circulation in the SCS during summer.

Pumice was observed not only at the entrance of the Gulf of Thailand (Songkhla Province), but also in the inner part of the gulf (Rayong Province; Fig. 1a). The northeast monsoon occurs during winter, when a surface current along the western coast of the Gulf of Thailand is likely to develop (Sojisuporn *et al.*, 2010). Pumice drifting from south to north in the gulf could have been driven by this seasonal circulation. Estimating the total amount of floating pumice in a particular area is difficult, as small pumice rafts are difficult to observe in satellite images. Although seasonal circulation in the Gulf of Thailand and the SCS would not tend to bring a large amount of pumice, the behaviour of pumice rafts can vary depending on short-term and small-scale heterogeneities in wind and current behaviour.

The 2021 FOB eruption produced a large amount of floating pumice, some of which remained around the Nansei Islands, where the raft first arrived, while some continued drifting eastward and westward. Deposited pumice clasts can start drifting again due to high tides, and thus the amount of deposited pumice should decrease with time. These cycles of pumice deposition and removal are similar to those of other light material, including plastic waste, and the deposited pumice often accompanies such material (Fig. 1b). Storms are important events that control the deposition and removal of light material along coasts (Nakajima *et al.*, 2022). Recent progress in satellite technologies has provided powerful tools for tracking pumice rafts, if weather permits (Jutzeler *et al*., 2020). A combination of observations and simulations of pumice rafts enables the production and updating of hazard maps. Confirmation of the origin of the pumice and the extent of pumice dispersal would provide a better understanding of pumice rafting from FOB and would help prepare for coming eruption. FOB is one of the most active volcanoes in Japan and has produced multiple pumice rafts over the last 100 years (Kato, 1988; Bryan *et al*., 2012; Yoshida *et al*., 2022). Records of the locations and arrival times of pumice rafts are crucial for disaster prevention in the Circum-Pacific belt. An international pumice monitoring network might be required for future large eruptions.

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Figure and Table Captions

Figure 1. (a) Summary of the arrival dates of drifting pumice modified after Yoshida *et al.* (2022). (b) Dark grey pumice deposit along the high tide line at Thung Yai beach in Songkhla Province, Thailand, on 10 February 2022. Plastic waste was also observed. (c) Gray pumice clasts collected on Samila beach in Songkhla Province, Thailand, with black spots and often with attached goose barnacles. One clast contained a black band.

Figure 2. (a) Photomicrograph of a pumice clast collected from Thung Yai beach (sample TY-1) in Songkhla Province. Plagioclase (Pl), clinopyroxene (Cpx), and olivine (Ol) phenocrysts were observed. The glass adhering to, and as melt inclusions in, Pl phenocrysts is brown, whereas the groundmass glass is colourless. "Vac" indicates a vesicle. (b) Backscattered electron image of the black enclave in TY-1. Anorthite-rich Pl and diopsidic Cpx with an augitic rim occur in the poorly vesiculated groundmass of the black enclave that contained ubiquitous magnetite. (c) Total alkali ($Na_2O + K_2O$) versus SiO_2 diagram for the classification of volcanic rocks, showing the whole-rock and glass compositions of pumice clasts from Thailand. Previously reported data for pumice rafts from the 2021 (Yoshida *et al.*, 2022) and 1986 eruptions of FOB are also shown. Y87: Yoshida *et al.* (1987), K88: Kato (1988), NK92: Nakano & Kawanabe (1992).

Table 1. Whole rock and groundmass glass compositions of the pumice.
Footnote: FeO*, total iron as FeO. n.a., not analysed.

Table 2. Representative mineral compositions.
Footnote: FeO*, total iron as FeO. Fe^{3+}/Fe^{2+} was determined as follows: total cation =4 (clinopyroxene), $(Fe^{2+} + Mg + Mn) = 1$ (magnetite).

Figure 1

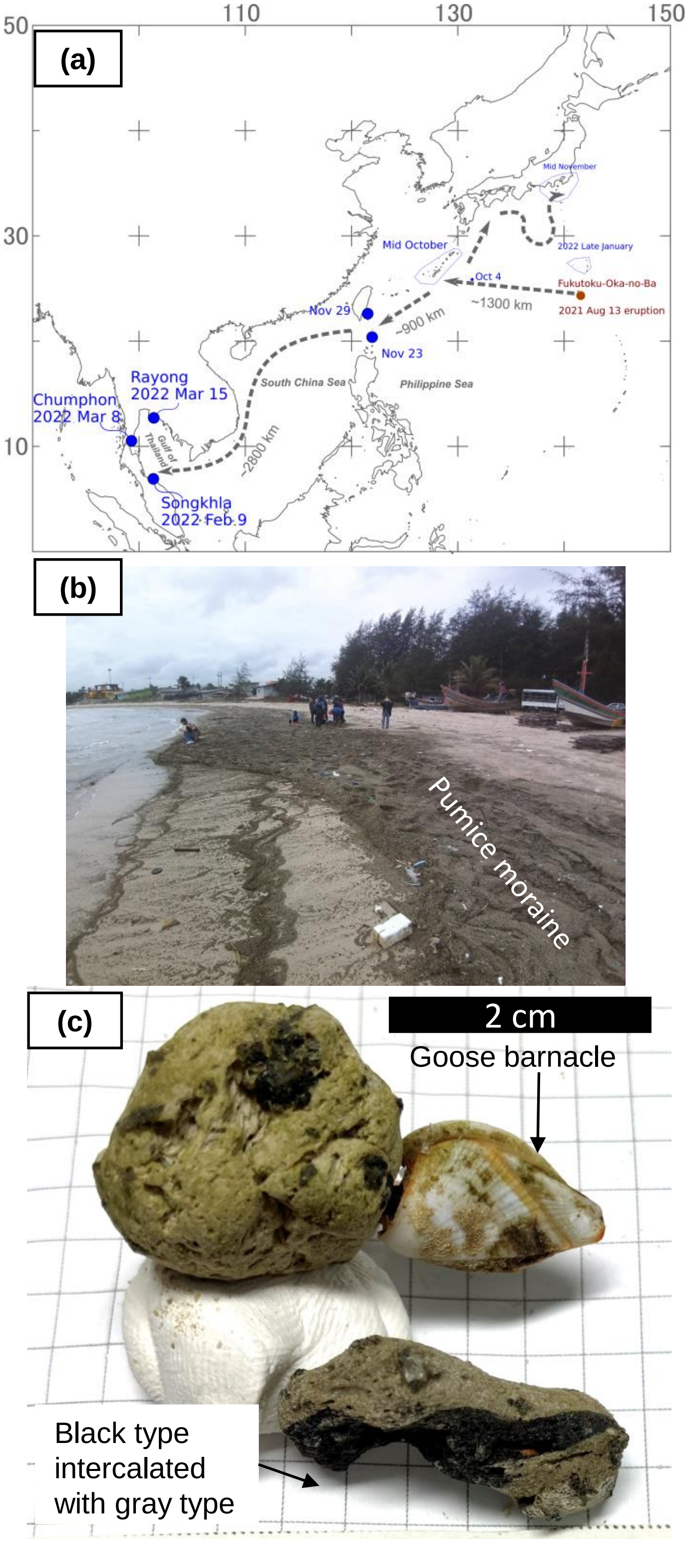
(a)
50
30
10
110
130
150
Mid November
2022 Late January
Mid October
Oct 4
Fukutoku-Oka-no-Ba
2021 Aug 13 eruption
~1300 km
~900 km
Nov 29
Nov 23
South China Sea
Philippine Sea
Rayong
2022 Mar 15
Chumphon
2022 Mar 8
Gulf of Thailand
~2800 km
Songkhla
2022 Feb 9
(b)
Pumice moraine
(c)
2 cm
Goose barnacle
Black type
intercalated
with gray type

Figure 2

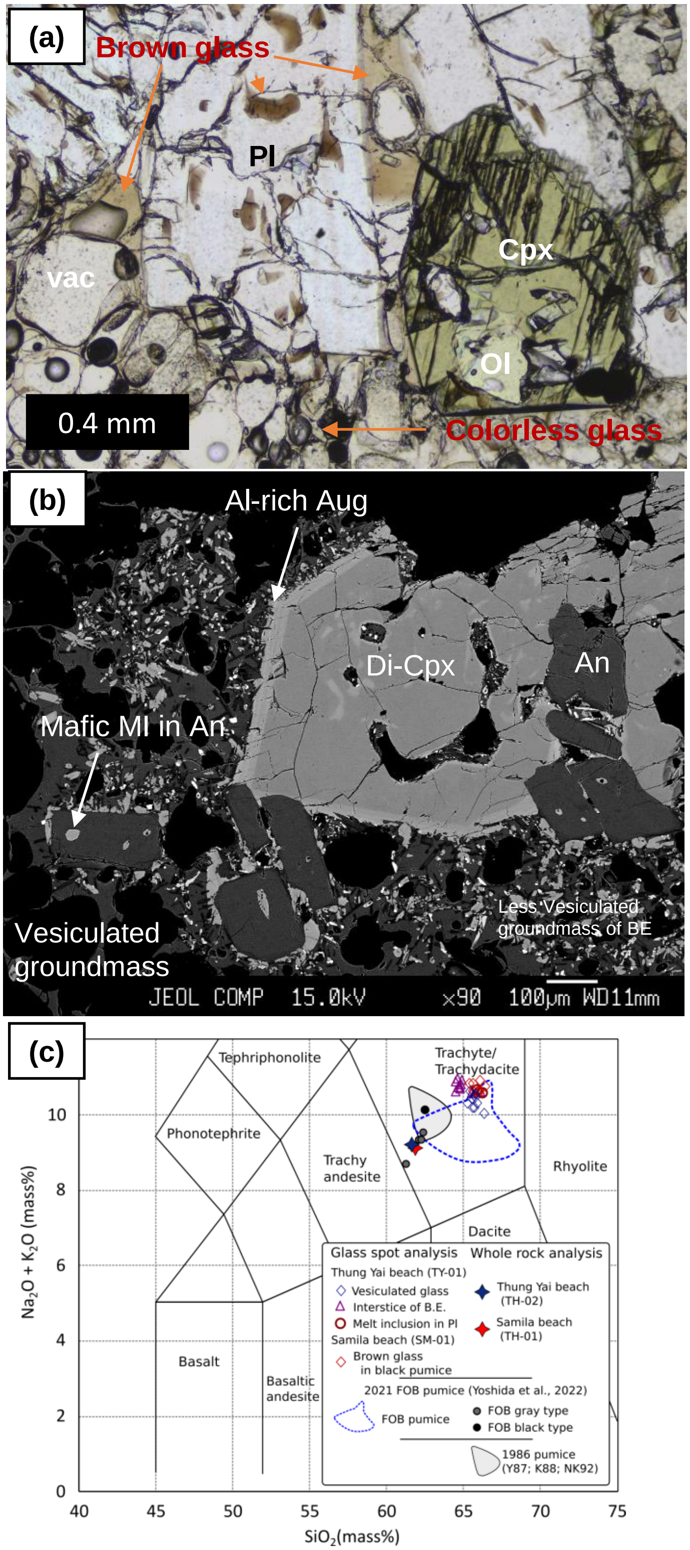
(a)
Brown glass
Pl
Cpx
vac
Ol
0.4 mm
Colorless glass
(b)
Al-rich Aug
Di-Cpx
An
Mafic MI in An
Vesiculated groundmass
Less Vesiculated groundmass of BE
JEOL COMP 15.0kV ×90 100μm WD11mm
(c)
Tephriphonolite
Trachyte/ Trachydacite
Phonotephrite
Trachy andesite
Rhyolite
Dacite
Basalt
Basaltic andesite
Glass spot analysis
Whole rock analysis
Thung Yai beach (TY-01)
◇ Vesiculated glass
△ Interstice of B.E.
○ Melt inclusion in Pl
Samila beach (SM-01)
◇ Brown glass in black pumice
Thung Yai beach (TH-02)
Samila beach (TH-01)
2021 FOB pumice (Yoshida et al., 2022)
FOB pumice
● FOB gray type
● FOB black type
1986 pumice (Y87; K88; NK92)
$Na_2O + K_2O$ (mass%)
0
2
4
6
8
10
40
45
50
55
60
65
70
75
SiO_2(mass%)

Table 1

	XRF whole rock analysis		EMP spot analysis				
Sample No.	TH-01	TH-02	TY-01				SM-01
locality	Samila beach	Thung Yai beach	Thung Yai beach				Samila beach
			Gray pumice		Black enclave in gray pumice		Black pumice
occurrence			groundmass	melt inclusion in andesine	interstice in black enclaves	melt inclusion in anorthite	brown glass
n=			10	10	10	2	8
SiO2	60.748	60.497	65.07	64.94	64.29	46.95	65.35
TiO2	0.567	0.584	0.51	0.48	0.42	0.86	0.48
Al2O3	15.971	16.031	16.22	16.16	16.37	11.33	16.17
Cr2O3	n.a.	n.a.	0.00	0.01	0.03	0.01	0.03
FeO*	5.447	5.589	3.95	3.41	4.41	13.29	3.71
MnO	0.17	0.171	0.17	0.12	0.14	0.22	0.11
MgO	2.51	2.516	1.08	0.75	0.99	8.52	0.82
CaO	4.189	4.094	1.79	1.69	1.70	10.97	1.91
Na2O	4.53	4.602	5.02	5.15	5.23	2.23	5.29
K2O	4.42	4.435	5.22	5.24	5.42	1.35	5.31
P2O5	0.23	0.232	0.16	0.16	0.24	0.16	0.19
F	n.a.	n.a.	0.12	0.12	0.12	0.27	0.09
Cl	n.a.	n.a.	0.29	0.32	0.36	0.12	0.32
total	98.782	98.751	99.60	98.56	99.72	96.27	99.79
LOI	0.64	0.64					

Table 2

Sample	TY-01											SM-01
occurrenc	Gray pumice, phenocryst					Black enclave, phenocryst			Black enclave, microlite			with brown glass
	Pl, core	Pl, rim	Cpx	Ol	Mag	Pl	Cpx, core	Cpx, rim	Pl	Cpx	Mag	Ol
SiO2	57.88	59.88	53.13	37.56	0.12	44.40	50.35	46.268	56.851	44.774	0.268	41.05
TiO2	0.02	0.03	0.29	0.00	10.47	0.00	0.38	0.888	0.139	0.977	7.527	0.01
Al2O3	25.86	24.16	1.55	0.02	2.98	34.40	4.46	8.605	26.035	10.234	3.673	0.02
Cr2O3	0.00	0.04	0.05	0.00	0.01	0.02	0.00	0	0.01	0.02	0.069	0.04
FeO*	0.57	0.47	9.32	30.84	77.97	0.92	6.38	9.272	0.948	10.653	77.843	9.87
MnO	0.03	0.08	0.75	1.87	1.07	0.03	0.20	0.095	0.012	0.146	0.539	0.19
MgO	0.00	0.05	15.26	31.91	2.94	0.10	15.22	12.578	0.121	12.017	2.805	49.10
CaO	8.67	6.72	19.85	0.41	0.06	19.13	22.92	22.064	9.437	20.917	0.115	0.26
Na2O	6.36	7.13	0.40	0.03	0.00	0.57	0.14	0.207	5.602	0.263	0	0.00
K2O	0.79	1.10	0.02	0.00	0.02	0.04	0.01	0.017	0.88	0.042	0.08	0.01
total	100.19	99.66	100.63	102.64	95.62	99.62	100.06	99.99	100.04	100.04	92.92	100.53
O=	8	8	6	4	3	8	6	6	8	6	3	4
Si	2.60	2.69	1.96	1.00	0.00	2.07	1.85	1.72	2.57	1.66	0.01	1.00
Ti	0.00	0.00	0.01	0.00	0.22	0.00	0.01	0.02	0.00	0.03	0.16	0.00
Al	1.37	1.28	0.07	0.00	0.10	1.89	0.19	0.38	1.39	0.45	0.12	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe3+			0.03		0.94		0.10	0.14		0.20	0.98	
Fe2+	0.02	0.02	0.26	0.69	0.85	0.04	0.10	0.14	0.04	0.13	0.87	0.20
Mn	0.00	0.00	0.02	0.04	0.02	0.00	0.01	0.00	0.00	0.00	0.01	0.00
Mg	0.00	0.00	0.84	1.26	0.12	0.01	0.83	0.70	0.01	0.67	0.12	1.78
Ca	0.42	0.32	0.78	0.01	0.00	0.95	0.90	0.88	0.46	0.83	0.00	0.01
Na	0.55	0.62	0.03	0.00	0.00	0.05	0.01	0.01	0.49	0.02	0.00	0.00
K	0.05	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00
XAn	0.41	0.32				0.95			0.46			
XAb	0.54	0.62				0.05			0.49			
Xor	0.04	0.06				0.00			0.05			
Mg#			76	65			89	83		83		