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GENESIS OF CALC-ALKALIC ANDESITES FROM OSHIMA-ŌSHIMA AND ICHINOMEGATA VOLCANOES, NORTH JAPAN

by

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(with 11 text-figures and 2 tables)

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Abstract

Ultramafic inclusions in volcanic rocks occur commonly in alkalic rocks. Recently we have examined some of their host rocks in Japan, and found that most of the inclusions from Oshima-Ōshima and Ichinomegata volcanoes, north Japan, occur in calc-alkalic andesite. Occurrence of such inclusions may be significant for the origin of calc-alkalic andesite which is a characteristic volcanic product in island arcs. On the basis of field petrology of Oshima-Ōshima and Ichinomegata volcanoes, two different possible processes are suggested for the genesis of the calc-alkalic andesite magmas, i.e. 1) fractional crystallization of basaltic magma, and 2) partial melting of the upper mantle, respectively.

Introduction

Along the inner zone of the North Honshu Arc, northern Japan, volcanism has been taking place since Miocene period, and many Quaternary volcanoes are distributed (Fig. 1). This situation, together with the existence of a deep-sea trench and active seismicity, the focal plane of which dips under the marginal sea, indicates that the North Honshu Arc has similar tectonic features to the double island arcs of the circum-Pacific belt.

The Quaternary volcanic rocks in this area are grouped in a basalt-andesite-dacite-rhyolite suite, of which andesite and dacite of the calc-alkalic series are generally abundant rocks as in other island arcs. These rocks vary markedly in nature from the Pacific side (calcic and low-potassic) to the Japan Sea side (more alkalic and high-potassic), and considerable amounts of tholeiite, high-alumina basalt or alkali olivine basalt are associated with the calc-alkalic rocks in many volcanoes (Kawano et al., 1961; Katsui et al., 1978). As shown in Fig. 2, the rocks from the Japan Sea side are enriched in Mg and alkalies compared with those from the Pacific side. Daly's average of basalt-andesite-rhyolite divides them into two rock groups as mentioned above.

The rocks from Oshima-Ōshima and Ichinomegata of the Japan Sea side are composed mainly of olivine basalt, slightly undersaturated in silica, and hornblende-pyroxene andesite of the calc-alkalic series which is characterized by the presence of groundmass orthopyroxene and a trend of non-iron enrichment (Table 1). Occurrence of a number of mafic and ultramafic inclusions has been reported from these two volcanoes (Hayashi, 1955; Kuno and Aoki, 1970; Aoki, 1971, 1973; Katsui and Satoh, 1970). The relation between these inclusions and their host rocks, however, has been scarcely discussed. It is well known that ultramafic inclusions in volcanic rocks occur commonly in alkalic rocks (Ross et al., 1954; White, 1966; Forbes and Kuno, 1967). However, recently the writers found that most of

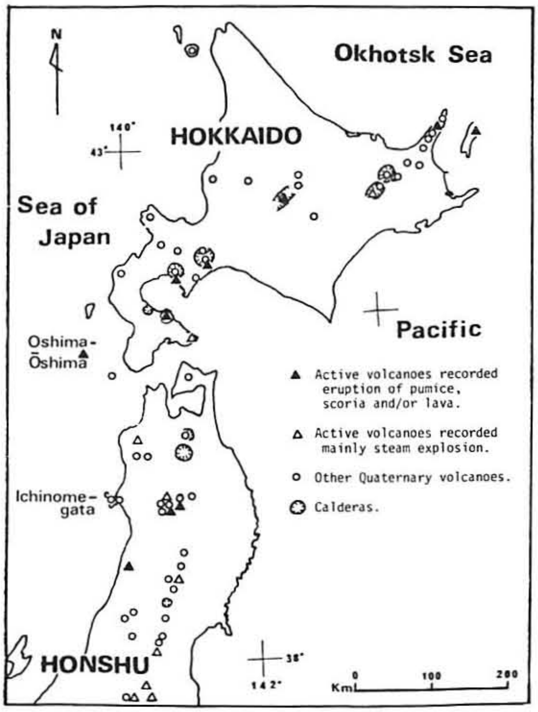


Fig. 1 Distribution of the Quaternary volcanoes in northern Japan, and location of Oshima-Ōshima and Ichinomegata.

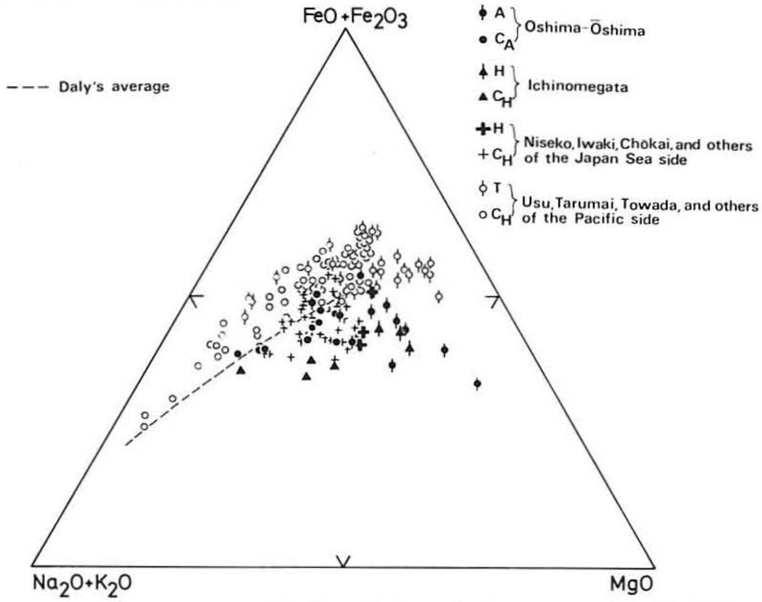


Fig. 2 AFM diagram for the Quaternary volcanic rocks from the inner zone of the North Honshu Arc, northern Japan.
A: alkali rock series, H: high-Al basalt series, T: tholeiite series; C_A, C_H and C_T are calc-alkali rock series associated with A, H and T series, respectively (Katsui et al., 1978). Data from Kawano et al. (1961), Onuma (1963), Yamamoto et al. (1977), Togashi (1977), Katsui et al. (1977, 1978) and unpublished analyses.

Table 1 Selected bulk chemical compositions and CIPW norms of the rocks from Oshima-Ōshima and Ichinomegata volcanoes

	Oshima-Ōshima				Ichinomegata				CIPW norm							
	1	2	3	4	5	6	7			1	2	3	4	5	6	7
SiO_2	48.89	49.90	55.56	61.72	48.98	54.87	63.40		Q	–	0.66	8.29	14.11	–	5.48	21.60
TiO_2	1.02	1.09	0.61	0.37	.93	.64	.35		Or	6.68	11.13	10.57	19.48	7.50	12.00	16.25
Al_2O_3	15.00	16.05	18.28	17.71	17.28	17.78	16.22		Ab	16.78	18.35	22.54	27.26	20.90	28.43	34.78
Fe_2O_3	2.92	5.03	2.46	1.12	2.34	1.84	1.69		An	28.65	28.37	32.54	24.20	34.17	28.87	16.12
FeO	6.41	5.55	5.11	4.33	5.97	4.28	2.01		C	–	–	–	–	–	–	1.28
MnO	0.25	0.14	0.19	0.10	.18	.17	.13	Di	Wo	10.57	9.18	3.48	0.35	3.62	2.34	–
MgO	10.60	7.03	4.05	1.83	8.23	4.84	1.45	Di	En	7.43	6.63	2.01	0.10	2.42	1.49	–
CaO	10.91	10.51	8.57	5.19	8.57	7.14	3.60	Di	Fs	2.24	1.71	1.32	0.26	.92	.70	–
Na_2O	1.95	2.15	2.62	3.21	2.38	3.28	3.94	Hy	En	7.33	10.84	8.03	4.42	15.14	10.91	3.76
K_2O	1.13	1.92	1.80	3.28	1.22	1.97	2.63	Hy	Fs	2.24	2.64	5.41	6.20	5.82	5.08	2.08
P_2O_5	0.05	0.23	0.22	0.20	.19	.29	.37	Ol	Fo	8.16	–	–	–	2.62	–	–
H_2O+	0.64	0.26	0.62	0.83	2.34	2.14	3.29	Ol	Fa	2.85	–	–	–	1.09	–	–
H_2O-	0.12	0.06	0.13	0.16	1.20	.70	.89		Mt	4.17	7.41	3.47	1.62	3.52	2.75	2.55
									Il	1.97	2.12	0.21	0.76	1.82	1.25	.68
Total	99.89	99.92	100.27	100.05	99.81	99.92	99.97		Ap	0.13	0.67	0.67	0.34	.46	.70	.90

1: Augite olivine basalt, a lava of the younger somma (Nishi-yama).
Loc., Yamasedomari.
2: Olivine augite basalt, a central cone lava.
Loc., Yakekuzure.
3: Olivine- and hornblende-bearing augite hypersthene andesite, a lava of the younger somma (Nishi-yama).
Loc., Aidomari.
4: Hornblende augite hypersthene andesite, a lava of the older somma (Higashi-yama).
Loc., Aidomari.
5: Augite olivine basalt, scoriaeous lapilli from Sannomegata maar.
Loc., 250 m east of Sannomegata.
6: Biotite- and hornblende-bearing augite andesite, a gray pumice lump from Ichinomegata maar.
Loc., 500 m east of Ichinomegata.
7: Augite-bearing hornblende biotite dacite, white band in the above gray pumice.
Loc., 500 m east of Ichinomegata.
All analyses by Y. Katsui.
1-4: Katsui (1961), 5-7: new analyses

such inclusions from Oshima-Ōshima and Ichinomegata volcanoes occur in calc-alkalic andesites (Yamamoto et. al., 1977; Katsui and Nemoto, 1977; Katsui et al., 1978). The significance of these findings is discussed here in relation to the genesis of calc-alkalic andesites.

Oshima-Ōshima

This volcanic island is situated off the Japan Sea coast, southwest Hokkaido, and composed of a triple stratovolcano, i.e. Higashi-yama somma, Nishi-yama somma, and central cone (Fig. 3). The history of development of the island is shown in Table 2. The volcanic edifice is made up of lavas and pyroclastics, of which about 70 vol. % is alkalic olivine basalt and the rest is calc-alkalic andesite. The andesite and basalt are intimately associated with each other, even within a single cycle of eruption as in the recorded eruption in 1741–1742 (Table 2). In major element chemistry of the rocks from Oshima-Ōshima, almost continuous variation curves can be traced from basalt to andesite without notable break (Fig. 7). This variation together with the volume relation may suggest derivation of andesite from basaltic magma. (Katsui et al., 1977; Yamamoto et al., 1977)

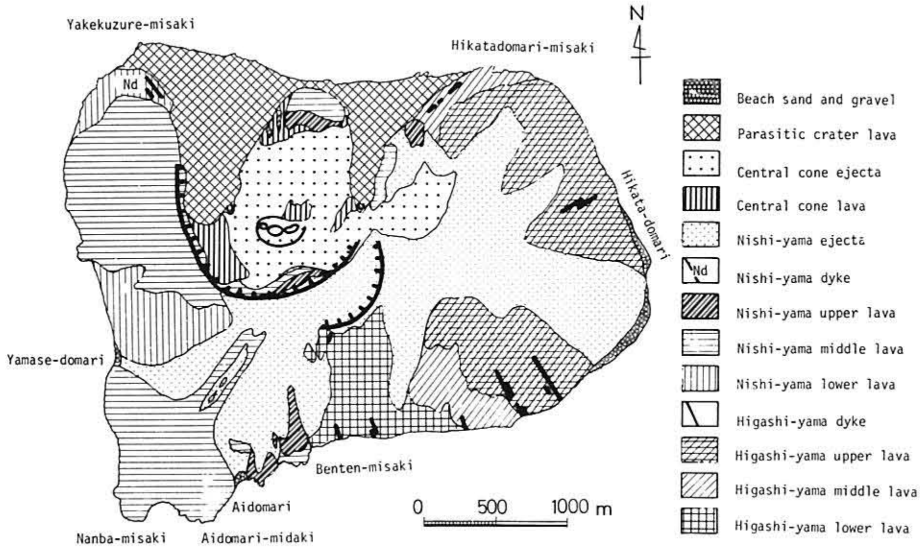


Fig. 3 Geologic map of Oshima-Ōshima Island.

Table 2 Sequence of the evolution of Oshima-Ōshima

Parasitic crater lava	Ol-Au basalt	*Historic eruptions in:*
Central cone ejecta	Ol-Au basalt	*1759, 1768 / 1790*
Central cone lave	Ol-Au basalt	
		Formation of caldera
Nishi-yama ejecta		
scoria	Ol-Au basalt	*1741–1742*
pumice	(Au, Hy) Bi-Ho andesite	
		^{14}C age: 760 ± Y.B.P.
Nishi-yama upper lava	Au-Ol basalt	Intrusion of dykes of Ol-Au basalt
Nishi-yama middle lava	(Ol) Au-Hy andesite (Hy) Ol-Au andesite Au-Hy andesite (Ol, Ho) Au-Hy andesite Ho-Au-Hy andesite Au-Hy-Ho andesite	
Nishi-yama lower lava	Au-Ol basalt Ol-Au basaltic andesite	
		Marine erosion Formation of caldera Intrusion of dykes of Ol-Au basalt Ol andesite
Higashi-yama upper lava	Au-Ol basalt (Hy) Ol-Au andesite	
Higashi-yama middle lava	Hy-Au-Ho andesite Ol-Au basalt	
Higashi-yama lower lava	Au-Ol basalt (Hy) Au-Ol andesite (Hy) Ol-Au-Ho andesite	

Most of the andesite contain abundant ultramafic and mafic inclusions such as dunite, wehrlite, clinopyroxenite, and gabbro which show a typical cumulus texture. Dunite and wehrlite inclusions have intercumulates equivalent to clinopyroxenite or olivine gabbro in composition. Clinopyroxenite inclusions consist of olivine – clinopyroxene cumulates, clinopyroxene – amphibole – phlogopite – calcic plagioclase intercumulates, and interstitial glass with quenched plagioclase and ortho- & clinopyroxene needles. Hornblende gabbro inclusions are made up mainly of calcic plagioclase – hornblende cumulates. Modal compositions of the representative inclusions are shown in Fig. 4. Orthopyroxene is scarcely found in these inclusions, being only a minor constituent mineral, if any.

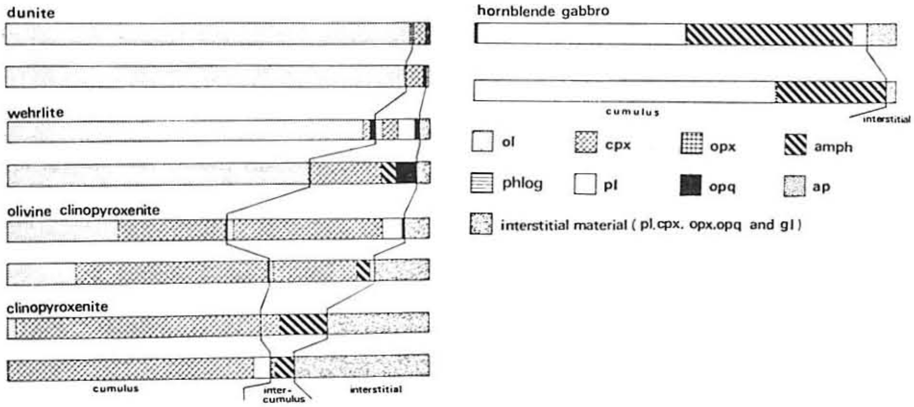


Fig. 4 Modal composition of the ultramafic and mafic inclusions from Oshima-Ōshima.

Amphiboles of the inclusions from Oshima-Ōshima are pargasitic in composition which are similar to those of other mafic volcanic rocks from Lesser Antilles (Cawthorn et al., 1973; Lewis, 1973; Sigurdsson and Shepherd, 1974) and Fossa Magna region of central Japan (Yamazaki et al. 1966) (Fig. 5). Such amphiboles are considered to have crystallized from basaltic magmas at a relatively higher temperature (Heltz, 1973). One more significant evidence is that the amphiboles from Oshima-Ōshima are notably high in K content, being consistent with the potassic nature of their host rocks (Fig. 6). Considering such composition dependence of amphibole on the host rocks, together with the texture and mineral composition mentioned above, the mafic and ultramafic inclusions may have precipitated from the basaltic magma through fractional crystallization at a relatively shallow depth.

In the Harker's variation diagram for the rocks of Oshima-Ōshima (Fig. 7), an abrupt change in the variation trend is noticed at about 51% silica. This change can be interpreted in terms of a two-step process of fractional crystallization of the olivine basalt magma, i.e. olivine and clinopyroxene crystallized at first until the composition of the magma reached about 51% silica, then crystallization of amphibole and calcic plagioclase started, as shown in a subtraction diagram (Fig. 7). Crystallization of pargasitic amphibole and calcic plagioclase from the differentiated basaltic magma, may have yielded a silica over-saturated, calc-alkalic andesite magma. The early separated crystals from the basaltic magma are considered to have

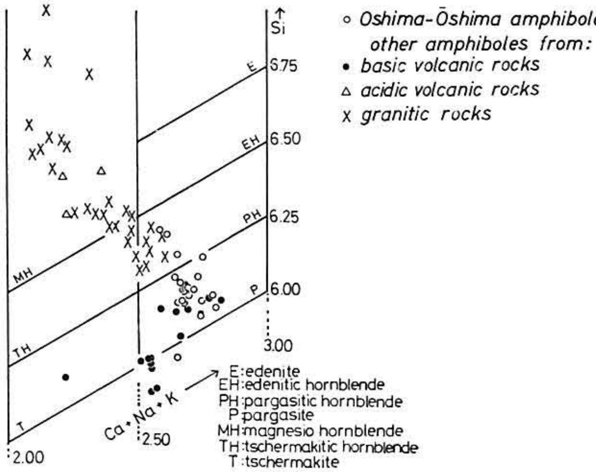


Fig. 5 Plot of Si and Ca+Na+K for amphiboles from Oshima-Ōshima and others. [Source of data] *Oshima-Oshima:* Yamamoto (1977), *other basic volcanic rocks:* Yamazaki et al. (1966), Cawthorn et al. (1973), Lewis (1973), Sigurdsson and Shepherd (1974), Sato et al. (1975), *acidic volcanic rocks:* Nicholls (1971), *granitic rocks:* Kanisawa (1972, 1975, 1976).

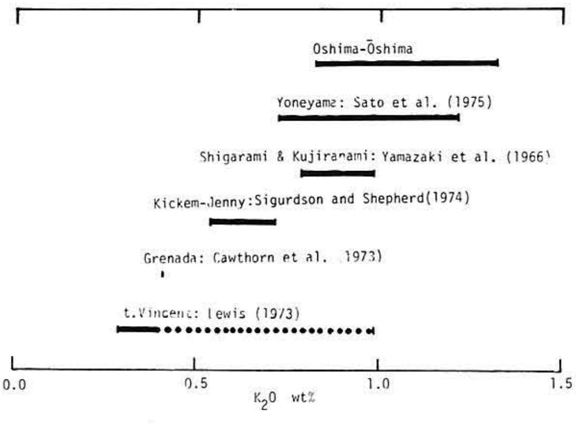
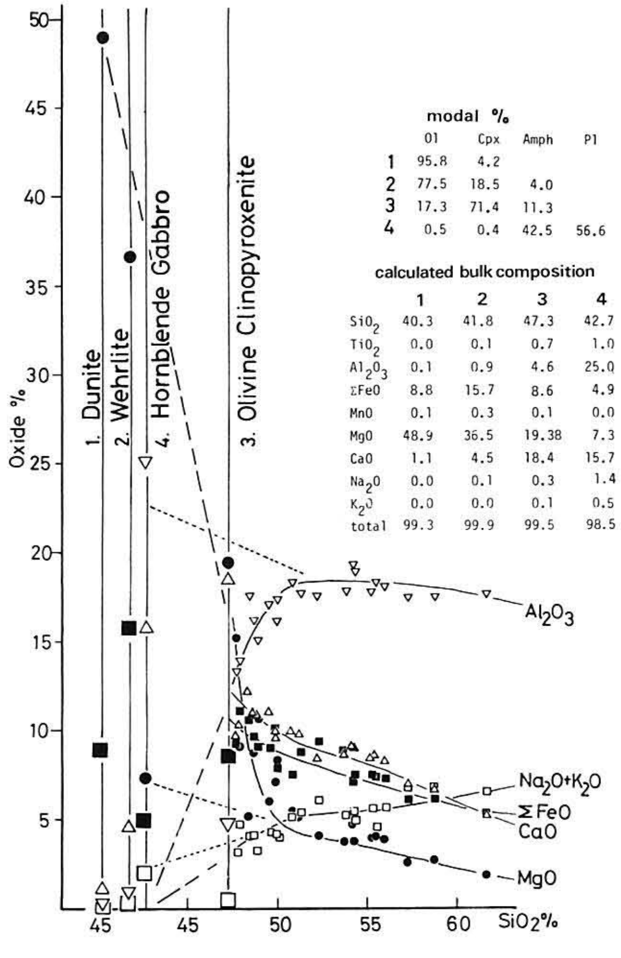


Fig. 6 K_2O content of amphiboles from Oshima-Ōshima and other basic volcanic rocks.

sunk, a part of which were transported to the surface as mafic and ultramafic inclusions by subsequent eruptions.

The above process of the generation of andesite magma should be justified by isotopic geochemistry. Isotopic ratios of Sr and O were determined by Kurasawa and Fujimaki (in Katsui et al., 1978) and Matsuhisa (1975), respectively, on the specimens collected by us. The $^{87}Sr/^{86}Sr$ ratio is almost constant or within an experimental error at 0.703 for both basalt and andesite, whereas the $^{18}O/^{16}O$ ratio increases notably from basalt to andesite (Fig. 8). Such evidence supports that the andesite was generated from the basaltic magma through fractional crystallization, as discussed above.

Recently, on the basis of chemical data (Katsui, 1961; Andō, 1971; Masuda et al., 1975), Mori (1977) applied the Rayleigh distillation law to the Oshima-Ōshima basalt and andesite, and showed a possibility of derivation of the andesite from the basaltic magma



	Ol	Cpx	Amph	Pl
1	95.8	4.2		
2	77.5	18.5	4.0	
3	17.3	71.4	11.3	
4	0.5	0.4	42.5	56.6

	1	2	3	4
SiO_2	40.3	41.8	47.3	42.7
TiO_2	0.0	0.1	0.7	1.0
Al_2O_3	0.1	0.9	4.6	25.0
ΣFeO	8.8	15.7	8.6	4.9
MnO	0.1	0.3	0.1	0.0
MgO	48.9	36.5	19.38	7.3
CaO	1.1	4.5	18.4	15.7
Na_2O	0.0	0.1	0.3	1.4
K_2O	0.0	0.0	0.1	0.5
total	99.3	99.9	99.5	98.5

Fig. 7 Subtraction diagram showing a relation between the ultramafic and mafic inclusions and the volcanic rocks from Oshima-Ōshima.

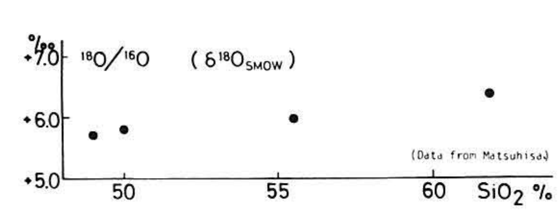


Fig. 8 Oxygen isotopic ratios for the rocks from Oshima-Ōshima. Data from Matsuhisa (1975).

through a process involving amphibole fractionation. However, his pattern of bulk partition coefficients of elements between magma and unidentified mineral precipitate in the fractional crystallization sequence from the primary basalt to andesite, resembles to that of clinopyroxene rather than amphibole, because the two-step process of fractional crystallization was not separated. In the later fractional crystallization sequence from the differentiated basalt (> 51% SiO_2) to andesite, the effect of amphibole and plagioclase fractionation is clearly shown, as recently demonstrated by Yamamoto (in preparation).

Ichinomegata

Ichinomegata volcano in Oga Peninsula on the Japan Sea coast, north Honshu, comprises three maars; Ichinomegata, Ninomegata and Sannomegata. Around these maars pyroclastic deposits are widely distributed (Fig. 9). As shown in the representative columnar section (Fig. 10), these deposits can be divided into three stages by the presence of buried soil. Formation of Ichinomegata maar started with phreatic explosions accompanied by mudflow. Then, in the second stage, phreatic explosions, hydromagmatic explosions with mudflows and base-surges, and pumice eruptions occurred. The essential ejecta of this stage are calc-alkalic andesite pumice with dacite bands. A number of mafic and ultramafic inclusions are found in the deposits of the second stage. Their host rocks are not basalt but

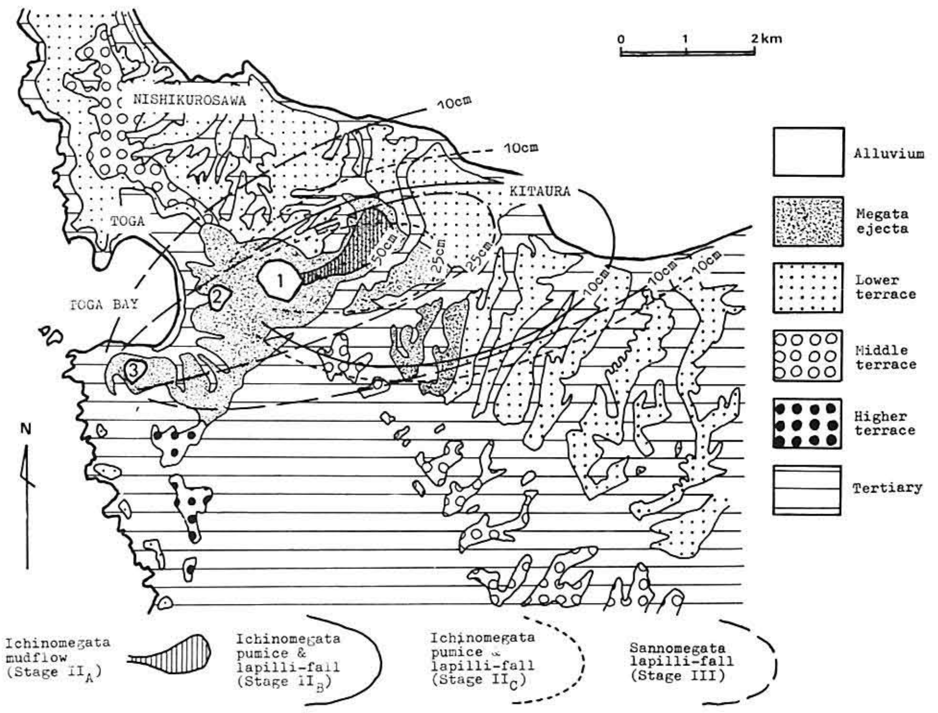


Fig. 9 Map showing the distribution of volcanic ejecta from three maars in Oga Peninsula, 1: Ichinomegata, 2: Ninomegata, and 3: Sannomegata. Tephra falls represented by thickness contour lines.

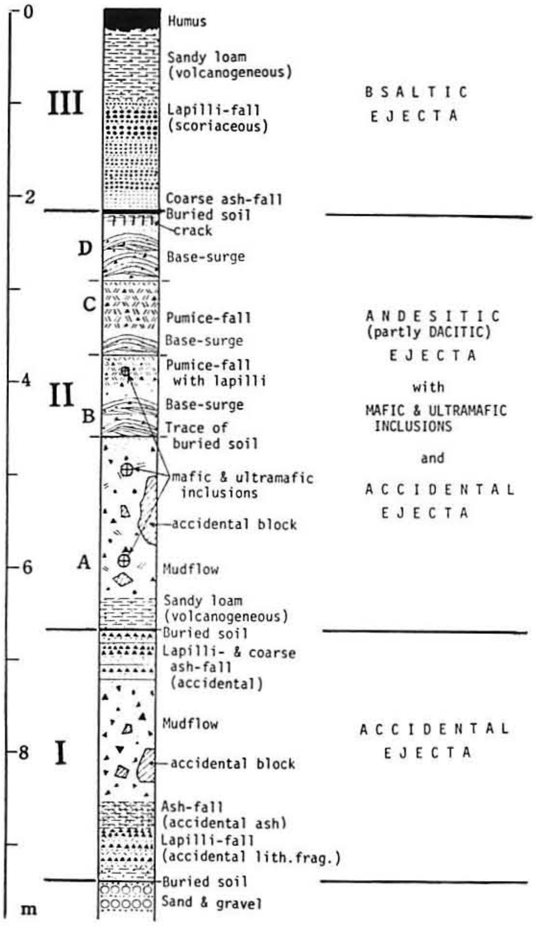


Fig. 10 Columnar section of the volcanic ejecta at 500 m east of Ichinomegata.

andesite pumice. Toward the end of the second stage, Ninomegata maar was opened with ejection of similar products. After a quiescence of activity, volcanic explosion of the third stage started from Sannomegata maar, ejecting scoria and lapilli of high-alumina basalt. This activity is considered to have taken place in a short period, because no traces of buried soil can be found within the lapilli-fall deposit. Mafic and ultramafic inclusions are also found in this deposit, though their occurrence is very rare compared with those of the second stage.

Although Hayashi (1955) mentioned that the activity of Ichinomegata volcano occurred around the Middle Jomon age (ca. 4,000 years ago), our stratigraphic correlation between the Ichinomegata pyroclastics and terrace deposits showed that the activity has taken place in the latest Pleistocene. This estimation is supported by a ^{14}C age (9,070±400 y.B.P.) of wood fragment which was collected from the lacustrine terrace deposit of Ichinomegata (Horie, 1964).

Most of the mafic and ultramafic inclusions are found in the pyroclastic deposits from the first two maars as either isolated blocks or inclusions in andesite pumice lumps (Fig. 11),

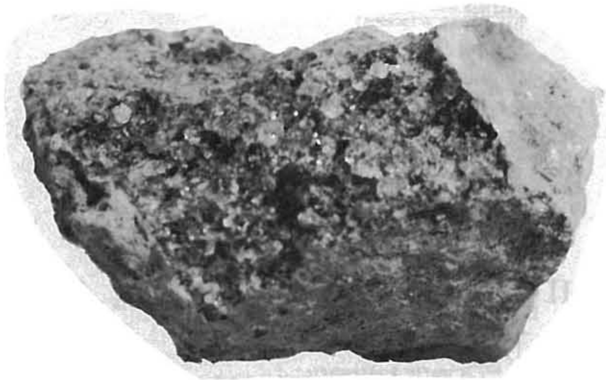


Fig. 11 Spinel lherzolite included in a pumice lump of calc-alkalic andesite from the ejecta of the second stage. Loc., 500 m east of Ichinomegata. (Natural size)

though a few of them occur in the basaltic lapill-fall deposits from the third maar. These inclusions are composed mainly of spinel lherzolite, websterite, gabbro and amphibolite (Kuno and Aoki, 1970; Aoki, 1971, 1973). The ultramafic inclusions of Ichinomegata are very different in mineralogy and texture from those of Oshima-Ōshima. No wehrlite and few dunites have been described from Ichinomegata. Some of the Ichinomegata inclusions bear strong deformation and recrystallization. Another characteristic feature of the Ichinomegata inclusions is that transitional rock types between mafic and ultramafic inclusions are scarcely found. Kuno and Aoki (1970) and Aoki (1971, 1973) reached a conclusion that these ultramafic inclusions have been directly derived from the upper mantle, whereas the mafic ones come from the lower crust, though their host rocks were not received much attention by them.

As shown in Table 1, the host pumice is calc-alkalic andesite with dacite bands. If the ultramafic inclusions have been directly derived from the upper mantle, the andesite magma is considered to have been formed at the same level. This suggests that the calc-alkalic andesite magma may have been produced primarily by partial melting of the upper mantle material, probably under hydrous condition as postulated by Kushiro (1969) and Yoder (1969). On the other hand, the olivine basalt magma erupted at the final stage might have been generated under less hydrous condition, due to depletion of water in the mantle.

Concluding Remarks

A number of models has been proposed for the generation of calc-alkalic andesite on the basis of field petrology, geochemistry, and experimental petrology. The occurrence of mafic and ultramafic inclusions in the calc-alkalic andesites from Oshima-Ōshima and Ichinomegata volcanoes, was studied in detail, the result of which suggested two possible different processes for the genesis of the calc-alkalic andesite magmas; 1) fractional crystallization of basaltic magma for Oshima-Ōshima, and 2) partial melting of the upper mantle for Ichinomegata. A more detailed study is under way and will be reported elswhere.

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