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Volcanic Geology and Rocks of Nakanoshima, Tokara Islands, Kagoshima Prefecture, Japan

Masahiro DAISHI*

(with 2 Tables 8 Figs.)

Abstract

One of the Tokara Islands, Nakanoshima, is situated about 207 km south-southwest of Kagoshima City, and has a beautiful cone-shaped stratovolcano, Otake. This island is composed mainly of the Nakanoshima volcanic rocks, which originated are in this island. The Nakanoshima volcanic rocks consist of the Serizaki andesites in the southeast, the Nanatsuyama andesites in the east, the Sakiwaridake andesites in the south, the Shiizaki andesites in the southwest, the Older Otake volcano in the north, the Nigoriura andesites in the west, the Negamidake andesites in the east and the Younger Otake volcano in ascending order.

The Serizaki andesites are formed by many altered andesitic lava flows and a little pyroclastic rocks of two-pyroxene andesite. The fission track age of lava from Serizaki is 1.75 $\pm$ 0.22 Ma. The Nanatsuyama andesites are composed of dense altered andesitic lava flows and pyroclastic rocks of two-pyroxene andesite. The Sakiwaridake andesites consist of partially altered lava flows and pyroclastic rocks of olivine-bearing and olivine-free two-pyroxene andesite. The Shiizaki andesites are composed of partially altered lava flows and pyroclastic rocks of two-pyroxene andesite. The Older Otake volcano consists of lava flows and pyroclastic rocks of olivine-bearing and olivine-free two-pyroxene andesite. The Nigoriura andesites are composed of lava flows and pyroclastic rocks of two-pyroxene hornblende andesite. The fission track age of lava from Nigoriura is 0.14$\pm$0.06 Ma. The Negamidake andesites are composed of lava flows and pyroclastic rocks of two-pyroxene andesite. The Younger Otake volcano is a stratovolcano with lava flows and pyroclastic rocks of olivine-bearing and olivine-free two-pyroxene andesite.

Almost the Nakanoshima volcanic rocks contain hypersthene in the groundmass (KUNO's hypersthenic rock series) and thus are classified as calcalkaline rock series. The pigeonite in the groundmass is minor found in a few volcanic rocks from the Serizaki andesites. The pyroxene phenocrysts in the Nakanoshima volcanic rocks usually show reverse zoning, and occasionally show normal one. But a few volcanic rocks from the Serizaki, the Sakiwaridake and the Nigoriura andesites only are normally zoned.

The Nakanoshima volcanic rocks are intermediate and the SiO_2 composition range from 64.91 to 53.83%. The $K_{57.5}$ value indicates 1.18, the $FeO^*/MgO_{57.5}$ value is 2.33. They do not carry fo and fa in the norm. Almost the Nakanoshima volcanic rocks are belong to the calcalkaline rock series by MIYASHIRO (1974) and IRVINE and BARAGER (1971).

1· Introduction

Nakanoshima is the largest island in the Tokara Islands. This island is situated 207 km south-southwest of Kagoshima City (lat. 29°50′N, long. 129°52′E). The perimeter is 25 km; the area is 27.54 km^2.

* Geochronology Japan Inc.

A brief sketch of the volcanoes of Nakanoshima was first given by SHIRANO (1884, 1885a, 1885b). After half century, SUZUKI (1936) outlined the geography and geology of this island. KASAMA (1959) reported some chemical and petrographical feature of the volcanic rocks, and gave the simple geological map of Nakanoshima. The author reported the ages of some volcanic rocks from the Tokara Islands (DAISHI *et al.*, 1987). However, most of volcanoes in this island have not been studied in terms of volcanology including volcanic history, petrology, and magma evolution. The present paper presents results of recent studies on the geology, petrography, petrochemistry, mineralogy and geochronology.

2. Geographical setting

Nakanoshima is a polygenetic volcano, similar to other volcanoes in the Tokara Islands. This island is divided into a northern area and a southern area by its geographic features.

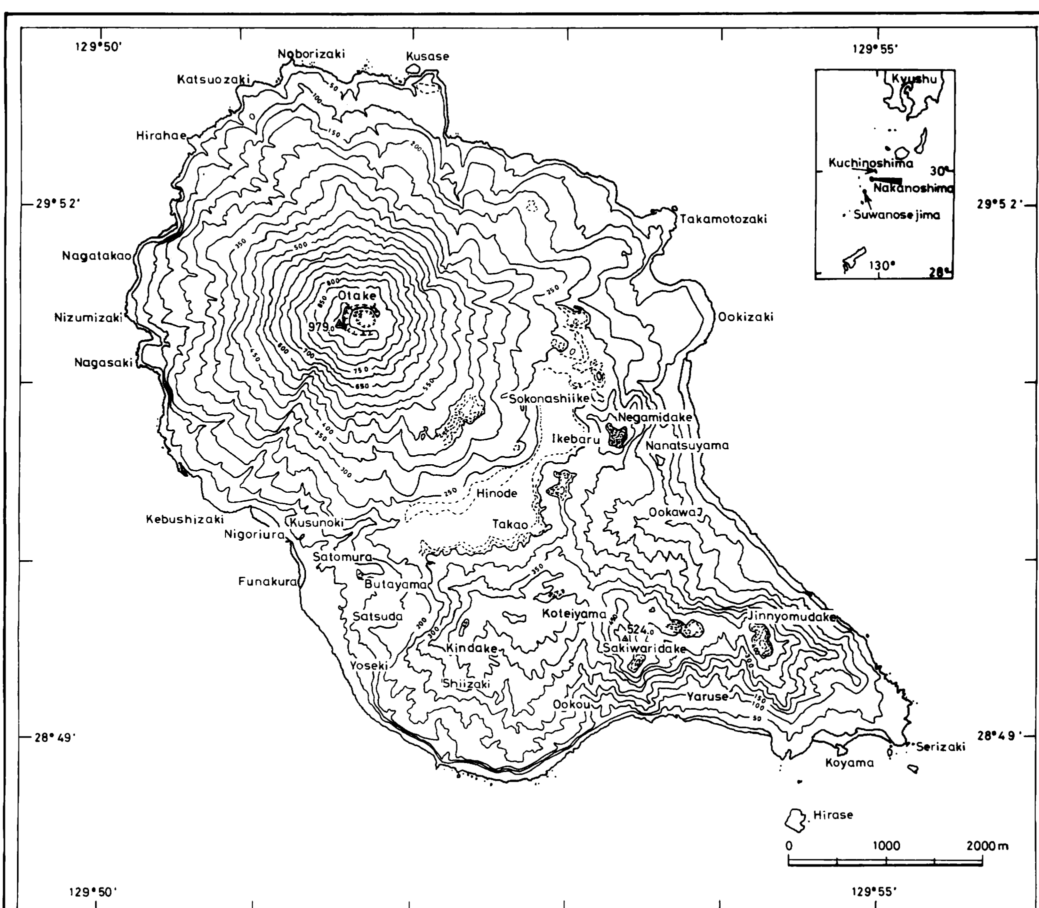

Fig. 1 Geographic Map of Nakanoshima

The geographic map of Nakanoshima is shown in Fig. 1.

The main part of the northern area is occupied by the beautifully cone-shaped Otake stratovolcano (979.0 m average sea level), which has some solfataras in its summit crater and in the explosion crater on the east-northeast slope. The summit crater, about 500 m across, is a bowl-shaped depression, and the highest point in this island is on the western rim of the crater wall. There is another small stratovolcano, Negamidake andesites, (395.2 m a.s.l.) in the southeast edge of the northern area, which is moderately dissected, showing the inner structure of the volcanic body. Nigoriura andesites are exposed in the southwest edge of northern area.

The southern area is composed of at least four volcanoes (Shiizaki, Sakiwaridake, Nanatsuyama and Serizaki andesites), and consists of nearly level mountains ranging in altitude from 400 m to 500 m. A narrow plain, about 200 m height, connects the northern and the southern area.

Vesicular ejecta (scoria, volcanic ash, *etc.*) are scattered over the surface of this island. Rivers are restricted to the areas around Funakura, Ookou, Yaruse and Ookawa. Hot springs gush out at three places in Funakura.

Littoral sediments are found on a small scale at Yoseki, Nanatsuyama, Ookawa and Koyama. Barrier to fringing reefs are formed near Funakura, Yoseki, Koyama and between Ookizaki and northeast seashore of Jinnyomudake.

3. Volcanic geology

The Geologic Map of Nakanoshima is shown in Fig. 2; the volcanic stratigraphy in Fig. 3. This island is composed mainly of the Nakanoshima volcanic rocks, which originated are in this island. The Nakanoshima volcanic rocks consist of the Serizaki andesites in the southeast, the Nanatsuyama andesites in the east, the Sakiwaridake andesites, the Shiizaki andesites in the southwest, the Older Otake volcano, the Nigoriura and the Negamidake andesites, and the Younger Otake volcano in ascending order.

a. Serizaki andesites

The Serizaki andesites are formed by many altered andesitic lava flows, and a little tuff breccia and volcanic breccia, distributed over Serizaki and Yaruse in the southeast. At least five lava flows are found averaging more than 20 m in thickness. The lava in the north of Serizaki shows a ramp structure and flowed from west-northwest. The tuff breccia and volcanic breccia are restricted to the north-northwest seashore of Serizaki. These rocks are greenish, owing to chloritization. The lava flows of these andesites are overlain by one lava flow of the Sakiwaridake andesites at Ookou in the south corner. The boundary between these andesites and the Nanatsuyama andesites is indefinite, owing to alteration. The fission track age of zircon in the lava from Serizaki is 1.75 ± 0.22 Ma (DAISHI *et al.*, 1987), that is lowermost Pleistocene.

The rocks contain phenocrysts of plagioclase, augite and hypersthene. The groundmass consists of plagioclase, augite, hypersthene, with small amounts of opaque minerals,

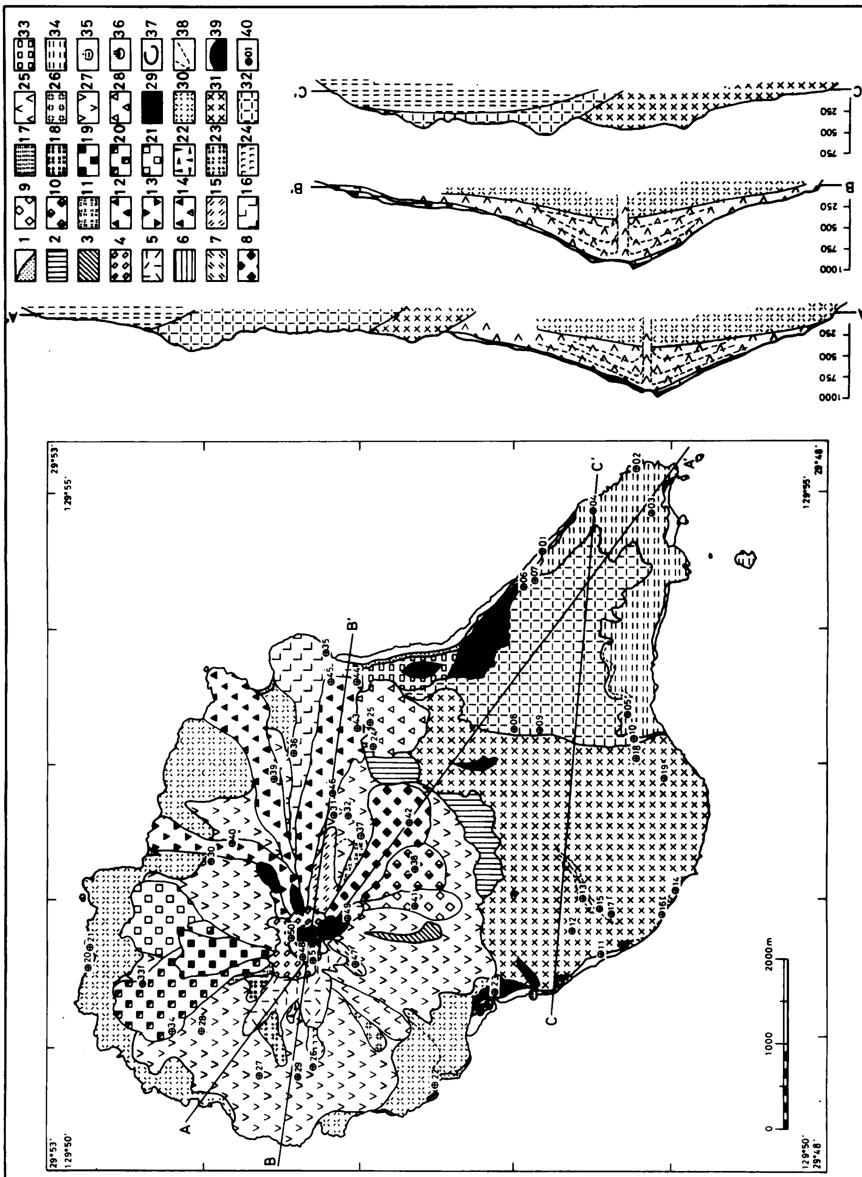

Fig. 2 Geologic Map of Nakanoshima

legend; 1: Coastal gravel with sand and coral reef, 2: Alluvium, 3: Volcanic fan deposit, 4: T_2 pyroclastic rocks, 5: T_1 pyroclastic rocks, 6: Rised coral reef, 7: S_5 lava, 8: S_4 lava, 9: S_3 lava, 10: S_2 lava, 11: S_1 lava, 12: E_5 lava, 13: E_4 lava, 14: E_3 lava, 15: E_2 lava, 16: E_1 lava, 17: N_5 lava, 18: N_4 lava, 19: N_3 lava, 20: N_2 lava, 21: N_1 lava, 22: W_5 lava, 23: W_4 lava, 24: W_3 lava, 25: W_2 lava, 26: W_1 lava, 27: Younger Otake volcano, 28: Negamidake andesites, 29: Nigoriura andesites, 30: Older Otake volcano, 31: Shiizaki andesites, 32: Sakiwaridake andesites, 33: Nanatsuyama andesites, 34: Serizaki andesites, 35: Fumarole, 36: Hot spring, 37: Crater, 38: Flow-unit boundary, 39: Alteration zone, 40: Locality number for analysis

time	stratigraphy		rock type*	age
Recent	Coastal gravel with sand and coral reef	Alluvium		
	Volcanic fan deposit			
↑	T_2 pyroclastic rocks T_1 pyroclastic rocks S_5 lava E_5 lava, E_4 lava, E_3 lava S_4 lava, S_3 lava, S_2 lava E_2 lava, E_1 lava S_1 lava N_5 lava, N_4 lava, N_3 lava, N_2 lava, N_1 lava W_5 lava, W_4 lava, W_3 lava, W_2 lava, W_1 lava Younger Otake volcano	Raised coral reef	A oah { Va→d, Vd	3370±135 y.b.p. 5235±160 y.b.p. ↑ 6300 y.b.p.
		Negamidake andesites	A ah Vd	
		Nigoriura andesites	A hahr VId	0.14±0.06 Ma
↓	Older Otake volcano		A oah Vd	
Lower Pleistocene	Shiizaki andesites		A ah Vd	
	Sakiwaridake andesites		A oah { Va→d, Vd	
	Nanatsuyama andesites		A ah Vd	
	Serizaki andesites		A ah Vd	1.75±0.22 Ma

Fig. 3 Volcanic Stratigraphy of Nakanoshima
rock type; A: andesite, a: augite, h: hypersthene, hr: hornblende, o: olivine
Va→d, Vd and VId are KUNO's classification

apatite and scarce pigeonite. Chlorite and calcite were observed as secondary minerals.

b. Nanatsuyama andesites

The Nanatsuyama andesites are composed of dense altered andesitic lava flows, tuff breccia and volcanic breccia. They are distributed over Nanatsuyama and Ookawa in the east. At least two lava flows are found, but the boundaries between the lava flows and the tuff breccia or volcanic breccia are not clear, due to conspicuous hydrothermal alteration. The altered rocks of these andesites are overlain by the lava flows of the Sakiwaridake andesites near Ookawa and of the Negamidake andesites near Nanatsuyama. The altered pyroclastic rocks of this andesites underlie the E_1 lava flow of the Younger Otake volcano south of Ookizaki.

All the rocks are strongly kaolinized, and there are remnants of a little plagioclase, augite and hypersthene phenocrysts. Kaolin and low quartz were detected as altered minerals by the X-ray diffraction method.

c. Sakiwaridake andesites

The Sakiwaridake andesites consist of partially altered lava flows, tuff breccia and volcanic breccia, distributed over Ookou, Sakiwaridake (524.0 m a.s.l.) and Jinnyomudake (437 m a.s.l.) in the southeast of this island. More than five lava flows are observed, averaging more than 20 m in thickness. They are generally compact. The tuff breccia and volcanic breccia are ordinarily ranging in thickness from 20 m to 30 m, but exceeding 70 m at the north cliff of Jinnyomudake. One lava flow of these andesites is overlain by more than two lava flows of the Shiizaki andesites at Ookou. From the dip of the lava flows, the center of this volcanic activity is inferred to have been between Sakiwaridake and Jinnyomudake.

The rocks contain phenocrysts of plagioclase, augite, hypersthene and scarce olivine (the 4th lava flow). The groundmass consists of plagioclase, augite, hypersthene and glass, with small amounts of opaque minerals, apatite and quartz.

d. Shiizaki andesites

The Shiizaki andesites are composed of partially altered lava flows, volcanic breccia and tuff breccia, distributed over Funakura, Yoseki, Tachigami, Shiizaki and Kindake (446.9 m a.s.l.) in the southwest. More than seven lava flows are exposed, averaging more than 10 m in thickness. The 6th lava flow which crops out at the west slope of Kindake is mineralized. The tuff breccia and volcanic breccia are about 10 m thick. The rocks distributed over Funakura and Butayama were subjected to hydrothermal alteration. The outcrops of these altered rocks are well aligned along a line connecting Funakura to Nanatsuyama. The lava flows of these andesites underlie the pyroclastic rocks of the Negamidake andesites near Ikebaru. From the dip of lava flows, the center of this volcanic activity is inferred to have been near Kindake.

The rocks contain phenocrysts of plagioclase, augite and hypersthene. The groundmass consists of plagioclase, augite, hypersthene and glass, with small amounts of opaque minerals, apatite, phlogopite, quartz, and also scarce spinel. Pyrite was detected in the 6th lava flow by the X-ray diffraction method.

e. Older Otake volcano

The Older Otake volcano consists of lava flows, volcanic breccia, tuff breccia and agglomerate, distributed along the coast around the northern area of this island. At least four lava flows can be observed, each ordinarily ranging in thickness from 20 m to 40 m, and exceeding 60 m at the tip of the lava flow along the seashore from Noborizaki to

Nizumizaki. The agglomerate, ranging up to 100 m in thickness, is present near Kebushizaki. The lava flows are overlain by the lava flows of the Younger Otake volcano at Ookizaki, Takamotozaki, Kusase, *etc.* From the dip and the distribution of the lava flows, the activity center of this volcano is inferred to be near the center of the Younger Otake volcano.

The rocks contain phenocrysts of plagioclase, augite, hypersthene and scarce olivine (the 3rd lava). The groundmass consists of plagioclase, augite, hypersthene and glass, with small amounts of opaque minerals and apatite.

f. Nigoriura andesites

The Nigoriura andesites are composed of agglomerate and a little lava and volcanic breccia, narrowly distributed over Nigoriura in the west. The agglomerate, ranging up to 70 m in thickness, is present near Nigoriura. More than two pumice tuff beds related to this volcanic activity have an extensive distribution. From the products of the volcanic activity, this volcanism was a vigorous as hydromagmatic explosion. The fission track age of zircon in the lava from Nigoriura is 0.14 ± 0.06 Ma (Daishi *et al.*, 1987), that is upper Pleistocene.

The rocks contain phenocrysts of plagioclase, hornblende, hypersthene and scarce augite. The groundmass consists of plagioclase, hornblende, hypersthene and glass, with small amounts of augite, opaque minerals, quartz and apatite.

g. Negamidake andesites

The Negamidake andesites are composed of lava flows, agglomerate, volcanic breccia and tuff breccia, distributed over Negamidake in the east. At least three lava flows, each averaging about 20 m in thickness, are exposed. The lava flow which crops out at the north slope of Negamidake is characterized by the prevalence of platy joints. The agglomerate crops out at the southeast cliff of Negamidake and attains a maximum thickness of 80 m. The lava flows are overlain by the E_5 lava of the Younger Otake volcano at the east edge of Sokonashiike.

The rocks contain phenocrysts of abundant plagioclase, subordinate augite and hypersthene. The groundmass consists of plagioclase, augite, hypersthene and glass, with small amounts of opaque minerals and apatite.

h. Younger Otake volcano

The Younger Otake volcano is a stratovolcano with lava flows, tuff, lapilli tuff, volcanic breccia, tuff breccia and agglomerate. This volcano occupies the main part of the northern area of this island. More than 27 lava flows are found, and are named the 1st to 7th oldest; E_1 to E_5, flowing down to the east slope; S_1 to S_5, flowing down to the south slope; N_1 to N_5, flowing down to the north slope; W_1 to W_5, flowing down to the west slope lava flows. Each of these lava flows is ordinarily ranging in thickness from 10 m to 20 m, and exceeding 50 m at the tip of the lava flows at some outcrops. The E_5 lava flowed out from the Otake summit down to the east coast, and formed the dammed lake Sokonashiike a few thousand years ago. The lava flows older than the N_5 lava flow are covered by the "Akahoya" volcanic ash. More than two piles of these pyroclastic rocks are observed near the Otake summit, each ordinarily ranging in thickness 20 m to 30 m around the summit crater rim. Each pile is composed of well-stratified lapilli tuff, tuff breccia, volcanic breccia and agglomerate, ranging from a few cm to more than 5 m in thickness for each stratum. In 1914, there was a mud eruption in the summit crater.

The rocks contain phenocrysts of plagioclase, augite, hypersthene and scarce olivine. The groundmass consists of plagioclase, augite, hypersthene and glass, with small amounts of opaque minerals and apatite.

i. Raised coral reef

A narrow raised coral reef is found at Funakura. The maximum height of this reef is 13.5 m, and it dips 17° landward. Carbon-14 datings of coral in the uppermost and the lower portions are 3370 ± 135 and 5235 ± 160 years ago, respectively (NAKATA *et al.*, 1978).

j. Volcanic fan deposit

This deposit is found over the south slope of Otake. It shows a reverse graded bedding, and has a maximum thickness of 15 m. This is composed mainly of pebbles to boulders and the roundish from subrounded to subangular with an unconsolidated matrix of tuff. The gravel consists of andesite lava, tuff, scoria and pumice.

As mentioned above, Nakanoshima has been formed through many volcanic activities. The ash layers related to these activities are widely found. Especially, the two pumice tuff beds including hornblende which are related to the volcanism of the Nigoriura andesites, would be most useful for the correlation of the volcanic activities in the other islands of the Ryukyu Arc.

4. Petrography

The Nakanoshima volcanic rocks are mainly two-pyroxene andesite with or without small amounts of olivine phenocrysts. Hornblende is comparatively minor found in the Nigoriura andesites. They contain hypersthene in the groundmass (KUNO's hypersthenic rock series) and thus are classified as calcalkaline rock series. The pigeonite in the groundmass is minor found in a few volcanic rocks from the Serizaki andesites.

Petrographical descriptions are summarized in Fig. 4. These volcanic rocks always contain plagioclase, orthopyroxene, clinopyroxene and magnetite phenocrysts and microphenocrysts. Olivine phenocrysts are found in some volcanic rocks from the Sakiwaridake andesites and the Younger Otake and the Older Otake volcanoes. Hornblende phenocrysts are visible only in the Nigoriura andesites.

Plagioclase phenocrysts are commonly 0.5 mm to 2.0 mm long with maximum 5.0 mm in the Negamidake andesites (NAK-24, 25). They frequently appear moth-eaten, frittered, or sieve-like in texture. They are sometimes glomeroporphyritic aggregates with

Sample No.	Geology			Phenocryst & Microphenocryst						Groundmass										Xenolith Xenocryst
				Plag.^{a}	Opx ^{b}	Cpx ^{c}	Ol ^{d}	Hr ^{e}	Mt ^{f}	Pl	Opx^b	Cpx^c	Ol	Hr	Ph	Mt ^{f}	Ap	Qz	Gl	
NAK-51	Younger Otake volcano	T_2 p.r.	a	64-57,0.6-0.7	75-65 R	43-39,39-36	+°	−	30-29	+	+	+	−	−	−	(36)	+	−	+	
NAK-50			b	+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-49		T_1 p.r.		+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-48		N_5 lava		51-50,1.0-1.3	69-64 R	46-36,48-36	−	−	41-31	+	66	33,46	−	−	−	(66)	+	−	+	
NAK-47		S_5 lava		69-61,0.4-0.7	69-57 R	39-31,53-43	−	−	38-27	+	+	+	−	−	−	+	+	−	+	
NAK-46		E_5 lava	a	+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	biotite
NAK-45			b	70-67,0.4-0.7	74-60 R	44-38,44-38	−	−	+	+	56	+	−	−	−	38-26	+	−	+	
NAK-44			c	66-63,0.5-0.6	67-60' R	43-37,43-32	−	−	25-24	+	59	41,42	−	−	−	34	+	−	+	
NAK-43			d	+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-42		S_4 lava		65-63,0.4-0.6	67-65 R	43-41,42-40	−	−	27-26	+	+	+	−	−	−	49-26	+	−	+	
NAK-41		S_3 lava		+	70-66 R	44-41,43-41	+°	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-40		E_4 lava		76-61,0.2-0.7	73-63 R	44-39,44-38	−	−	+	+	69	+	−	−	−	42	+	−	+	
NAK-39		E_3 lava		68-47,0.4-0.9	76-64 R	44-33,50-39	−	−	35-10	+	+	+	−	−	−	49-46	+	−	+	
NAK-38		S_2 lava		75-60,0.2-0.4	69-65 R	42-33,49-41	+°	−	30	+	68	34,38	−	−	−	32	+	−	+	
NAK-37		S_1 lava		63-61,0.4-0.9	77-65 R	47-40,44-36	−	−	37	+	+	+	−	−	−	20	+	−	+	
NAK-36		E_1 lava	a	59-57,0.4-0.5	71-64 R	43-42,42-40	−	−	27-22	+	71	+	−	−	−	39-27	+	−	+	
NAK-35			b	+	74-66 R	43-41,44-40	−	−	+	+	70	+	−	−	−	+	+	−	+	
NAK-34		N_2 lava	a	63-59,0.3-0.7	70-59 R	43-37,48-40	83-73 N	−	+	+	+	38,50	74	−	−	21	+	−	+	
NAK-33			b	+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-32		7		64-55,0.5-0.7	71-62 R	47-39,45-36	+°	−	+	+	73-72	39,43	−	−	−	35	+	−	+	
NAK-31		6		64-51,0.7-2.9	73-62 R	45-35,47-37	65-62°N	−	+	+	73	39,43	−	−	−	27	+	−	+	
NAK-30		5		+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-29		4		+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-28		3		75-57,0.4-0.6	81-63 R	43-41,44-40	−	−	+	+	+	+	−	−	−	45-21	+	−	+	
NAK-27		2		+	+	+	+	−	+	+	+	+	+	−	−	+	+	−	+	
NAK-26		1		58-38,1.1-1.7	67-57 R	45-42,42-38	+°	−	+	+	75	33,48	−	−	−	31	+	−	+	
NAK-25	Negamidake andesites	2		+	72-65 R	42-38,47-41	−	−	26	+	+	+	−	−	−	+	+	−	+	
NAK-24		1		+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-23	Nigoriura andesite			50-46,1.3-2.8	68-66 N	+	−	74-68	15	+	+	+	−	+	−	+	+	+	+	
NAK-22	Older Otake volcano	3		69-66,0.5-0.6	71-64 R	45-35,45-36	+	−	+	+	67	37,46	−	−	−	35	+	−	+	
NAK-21		2		+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-20		1		63-61,0.5-1.7	67-58 R	43-41,43-40	−	−	+	+	68	+	−	−	−	43-25	+	−	+	
NAK-19	Shiizaki andesites	7		+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	spinel
NAK-18		6		75-64,0.8-0.9	66-56 R	45-39,44-36	−	−	1.6	63	55-51	+	−	−	+	59	+	+	+	
NAK-17		5		+	+	+	−	−	+	+	+	+	−	−	−	+	+	+	+	
NAK-16		4	a	+	66-63 R	45-38,41-37	−	−	+	+	+	+	−	−	+	+	+	−	+	
NAK-15			b	+	69-64 R	43-41,43-40	−	−	+	+	+	+	−	−	+	+	+	+	+	
NAK-14		3	a	+	70-58 R	+	−	−	35	+	+	+	−	−	+	+	+	+	+	spinel
NAK-13			b	+	66-59 R	44-42,44-38	−	−	+	+	+	+	−	−	−	+	+	+	+	
NAK-12		2		+	+	+	−	−	+	+	+	+	−	−	−	+	+	+	+	
NAK-11		1		59-53,0.9-0.7	67-63 R	44-41,41-37	−	−	+	+	66-64	41,42	−	−	−	53	+	+	+	
NAK-10	Sakiwari-dake andesites	5		+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-09		4		72-57,0.4-1.0	72-56 N	44-40,41-34	59-57 N	−	+	+	52	+	53	−	−	36	+	+	+	
NAK-08		3		+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-07		2		+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-06		1		+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	+	
NAK-05	Serisaki andesites	5		+	69-62 R	43-42,43-41	−	−	+	+	+	+	−	−	−	+	+	−	−	*
NAK-04		4		+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	−	*
NAK-03		3		+	+	+	−	−	+	+	+	+	−	−	−	+	+	−	−	*
NAK-02		2		+	70-63 N	43-42,41-38	−	−	+	+	65-63	+	−	−	−	44	+	−	−	*
NAK-01		1		82-58,0.2-1.1	73-66 R	43-40,42-39	−	−	+	+	69-57	15,50	−	−	−	(25)	+	−	−	*

Fig. 4 Constituent minerals and their properties of the Nakanoshima volcanic rocks
Samples are numbered in ascending order of Stratigraphy. abbreviation: a=An and Or more %, EPMA analysed, b=100×Mg/(Mg+Fe+Mn), EPMA analysed, c=En and Wo mole %, EPMA analysed, d=100×Mg/(Mg+Fe+Mn), EPMA analysed, e=100×Mg/(Mg+Fe+Mn), f=USP mole % or (R_2O_3) mole %, EPMA data recalculated, r=with cpx reaction rim, o=with opx reaction rim, R=reversely zoned type, N=normally zoned type, *=altered and devitrification, including chlorite as secondary mineral.

orthopyroxene and clinopyroxene. They are twined on the albite, albite-carlsbad, carlsbad and rarely pericline in laws. Plagioclase phenocrysts include granular crystals of clinopyroxene, orthopyroxene, magnetite, idiomorphic laths of apatite, dusty material and brown glass in order of abundance.

Olivine phenocrysts and microphenocrysts are found in some volcanic rocks from the Sakiwaridake andesites and the Older Otake and the Younger Otake volcanoes. Their maximum diameter is 0.8 mm. Most olivine has a reaction rim of orthopyroxene in volcanic rocks from the Younger Otake volcano.

Orthopyroxene phenocrysts are usually 0.5 mm to 1.0 mm in length, sometimes 3.0 mm or more. Rarely they occur as glomeroporphyritic aggregates with clinopyroxene. Orthopyroxene crystals enclose granular crystals of plagioclase, clinopyroxene, magnetite, brown glass, dusty materials and idiomorphic laths apatite in order of abundance. Orthopyroxene phenocrysts are often in parallel intergrowth with clinopyroxene phenocrysts or are sometimes surrounded by clinopyroxene phenocrysts with regular or irregular boundaries. Sometimes orthopyroxene has a reaction rim of granular crystals of clinopyroxene. The zonal structure is mostly of reverse type having a broad hypersthene core with a narrow rim of more En rich hypersthene or bronzite.

Clinopyroxene phenocrysts are usually 0.5 mm to 1.0 mm in length, maximum 3.0 mm or more. Inclusions are granular crystals of plagioclase, orthopyroxene, magnetite, brown glass, dusty material and idiomorphic needle apatite in order of abundance.

Hornblende phenocrysts are found only in the Nigoriura andesites (NAK-23). They are usually 0.5 mm to 3.0 mm in length, maximum 5.0 mm or more. They included granular crystals of plagioclase, magnetite, dusty material and idiomorphic laths apatite in order of abundance.

Magnetite phenocrysts and microphenocrysts are rarely found. Their maximum size is about 0.8 mm in length.

The groundmass is commonly hyalopilitic; hyaline in some pyroclastic rocks. The groundmass consists of idiomorphic lath plagioclase, orthopyroxene, clinopyroxene, magnetite, apatite and glass, and sometimes small amounts of hornblende (NAK-24), olivine (NAK-34, 27, 09), quartz (NAK-23, 18, 17, 15 ~ 11, 09) and phlogopite (NAK-18, 16, 15, 14).

Biotite (NAK-46) and spinel (NAK-19, 14) crystals present as xenocrysts are observed in some volcanic rocks.

5. Chemistry of the Rocks

Whole rock analysis using fluorescent X-rays was made on 25 volcanic rocks from Nakanoshima. The rock samples were powdered, and then fused using a flux of $Li_2B_4O_7$.

A. Chemical composition

Chemical and norm compositions of 25 volcanic rocks from Nakanoshima are given in Table 1 and plotted on Harker's diagram in Fig. 5. These volcanic rocks have a higher

Table 1 Chemical and norm compositions of 25 volcanic rocks from Nakanoshima

No.		NAK-49	NAK-48	NAK-47	NAK-46	NAK-42	NAK-41	NAK-40	NAK-39	NAK-38	NAK-37	NAK-35	NAK-34	NAK-31	NAK-25	NAK-23	NAK-20	NAK-19	NAK-17	NAK-15	NAK-12	NAK-09	NAK-08	NAK-07	NAK-06	NAK-05
SiO_2		57.21	56.76	58.31	58.62	57.73	56.30	57.90	55.99	57.32	58.98	57.75	55.66	56.22	58.29	63.91	57.68	53.83	56.89	57.81	57.00	56.02	56.44	55.24	55.56	64.91
TiO_2		0.66	0.63	0.67	0.69	0.65	0.70	0.66	0.67	0.68	0.60	0.65	0.61	0.66	0.59	0.48	0.63	0.68	0.62	0.58	0.72	0.67	0.63	0.67	0.69	0.68
Al_2O_3		17.13	17.92	18.18	16.59	17.48	17.78	17.34	18.02	17.40	17.82	17.62	18.22	17.57	20.17	16.20	17.40	19.04	17.87	17.66	16.68	17.90	17.90	19.09	18.62	16.29
Fe_2O_3		5.27	5.61	6.70	5.20	4.38	4.16	4.29	6.57	4.43	5.58	4.14	4.30	4.72	2.85	3.49	4.52	5.16	4.80	4.52	5.53	4.95	4.36	5.93	4.90	4.05
FeO		2.59	1.83	1.41	3.05	3.35	4.18	3.54	1.94	3.61	1.84	3.58	3.65	3.71	2.91	1.37	3.31	3.85	3.28	3.15	3.01	3.78	4.03	2.25	3.42	1.31
MnO		0.14	0.13	0.14	0.15	0.14	0.15	0.15	0.15	0.14	0.13	0.15	0.14	0.16	0.10	0.12	0.14	0.15	0.14	0.13	0.16	0.15	0.14	0.13	0.17	0.12
MgO		3.52	3.54	3.42	3.74	3.61	3.92	3.49	3.74	3.69	3.22	3.37	4.13	3.80	1.84	2.07	3.71	3.92	3.67	3.46	3.23	3.77	3.88	2.69	3.41	0.79
CaO		7.39	6.35	5.87	7.44	7.54	8.18	7.35	7.41	7.63	7.11	7.35	8.47	7.93	7.53	4.85	7.90	5.47	7.53	7.34	6.80	6.92	7.79	7.08	7.72	3.61
Na_2O		2.76	2.44	2.55	2.75	2.72	2.69	2.85	2.68	2.72	2.86	2.92	2.53	2.72	3.07	3.19	2.73	2.25	2.60	2.78	2.70	2.57	2.63	2.68	2.89	3.32
K_2O		1.26	1.09	1.16	1.41	1.22	1.07	1.13	1.05	1.20	1.29	1.20	1.03	1.01	1.23	1.74	1.16	1.02	1.10	1.22	1.20	1.02	0.99	0.91	0.96	1.95
P_2O_5		0.10	0.11	0.09	0.10	0.10	0.10	0.11	0.10	0.10	0.09	0.12	0.08	0.11	0.10	0.06	0.09	0.07	0.07	0.07	0.09	0.08	0.08	0.09	0.10	0.13
H_2O+		0.92	2.61	0.68	0.42	0.81	0.73	0.72	0.69	0.73	0.93	0.78	0.89	0.97	0.67	1.59	0.51	2.35	0.75	0.50	1.16	1.37	0.78	1.83	0.85	1.41
H_2O-		0.39	1.27	0.87	0.10	0.19	0.08	0.13	0.51	0.15	0.17	0.08	0.12	0.17	0.30	0.26	0.00	1.49	0.24	0.19	1.02	0.81	0.19	1.05	0.56	0.56
Total		99.34	100.29	99.85	100.26	99.92	100.04	99.66	99.52	99.80	100.62	99.71	99.83	99.75	99.65	99.33	99.78	99.28	99.56	99.41	99.30	100.01	99.84	99.64	99.85	99.13
Q		16.69	19.82	22.04	17.41	16.25	13.37	16.36	15.66	15.56	18.21	15.58	13.16	14.49	16.13	25.39	15.91	18.58	16.22	16.51	18.25	16.02	14.59	17.24	13.66	29.59
C		----	1.44	2.64	----	----	----	----	----	----	----	----	----	----	0.34	0.39	----	4.46	----	----	----	0.18	----	1.04	----	2.46
or		7.45	6.44	6.86	8.33	7.21	6.32	6.68	6.21	7.09	7.62	7.09	6.09	5.97	7.27	10.28	6.86	6.03	6.50	7.21	7.09	6.03	5.85	5.38	5.67	11.52
ab		23.35	20.85	21.58	23.27	23.02	22.76	24.12	22.68	23.02	24.20	24.71	21.41	23.02	25.98	26.99	23.10	19.04	22.00	23.52	22.85	21.75	22.25	22.68	24.45	28.09
an		30.63	30.79	27.54	28.76	31.88	33.28	31.18	34.04	31.72	31.98	31.43	35.32	32.75	36.70	23.67	31.80	26.68	33.84	32.10	29.85	33.81	34.11	34.54	35.00	17.06
di	wo	2.25	----	----	3.13	2.03	2.78	1.91	0.87	2.29	1.13	1.78	2.58	2.45	----	----	2.84	----	1.28	1.61	1.38	----	1.68	----	1.11	----
	en	1.94	----	----	2.61	1.53	1.90	1.39	0.75	1.68	0.98	1.26	1.89	1.81	----	----	2.18	----	1.00	1.24	1.18	----	1.17	----	0.85	----
	fs	----	----	----	0.12	0.29	0.65	0.34	----	0.39	----	0.36	0.44	0.41	----	----	0.37	----	0.14	0.19	0.01	----	0.37	----	0.14	----
hy	en	6.83	8.82	8.52	6.70	7.46	7.86	7.31	8.57	7.51	7.04	7.13	8.39	7.65	4.58	5.16	7.06	9.76	8.14	7.37	6.86	9.39	8.49	6.70	7.64	1.97
	fs	----	----	----	0.32	1.43	2.71	1.80	----	1.72	----	2.00	1.96	1.71	2.20	----	1.20	1.96	1.15	1.14	0.06	2.02	2.65	----	1.27	----
mt		6.89	4.50	3.06	7.54	6.35	6.03	6.22	4.80	6.42	4.61	6.00	6.23	6.84	4.13	3.42	6.55	7.48	6.96	6.55	8.02	7.18	6.32	5.73	7.10	2.64
hm		0.52	2.51	4.59	----	----	----	----	3.26	----	2.40	----	----	----	----	1.13	----	----	----	----	----	----	----	1.98	----	2.23
il		1.25	1.20	1.27	1.31	1.23	1.33	1.25	1.27	1.29	1.14	1.23	1.16	1.25	1.12	0.91	1.20	1.29	1.18	1.10	1.37	1.27	1.20	1.27	1.31	1.29
ap		0.24	0.26	0.21	0.24	0.24	0.24	0.26	0.24	0.24	0.21	0.28	0.19	0.26	0.24	0.14	0.21	0.17	0.17	0.17	0.21	0.19	0.19	0.21	0.24	0.31

NAK+Sample Nos. are the same as in Fig. 4.

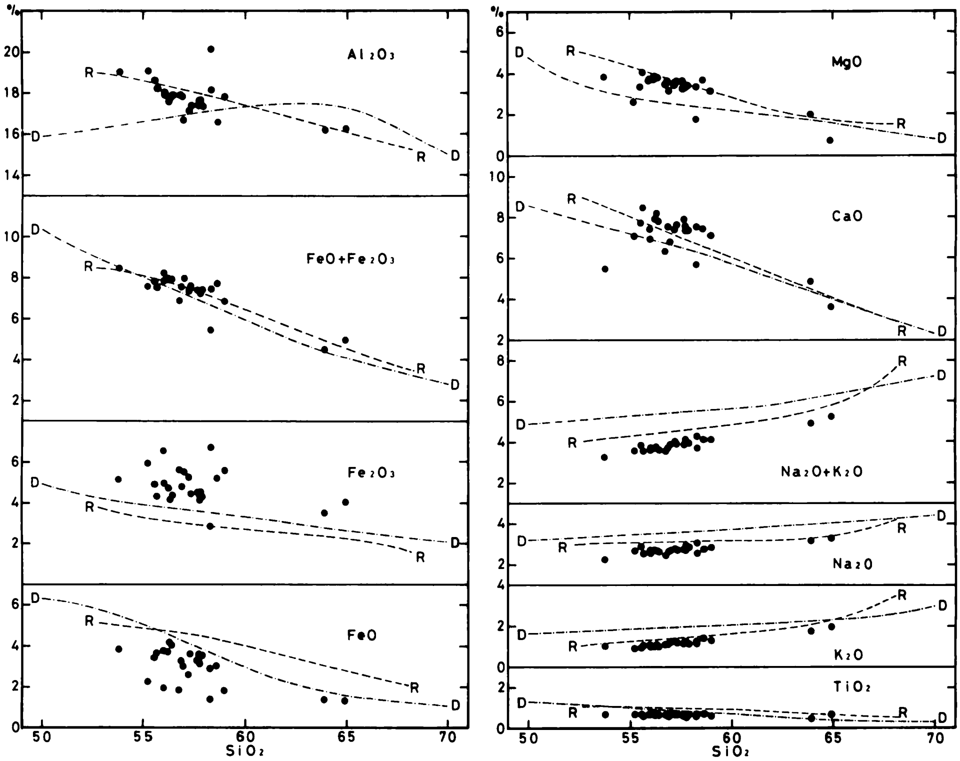

Fig. 5 Harker's oxide variation diagram of the volcanic rocks from Nakanoshima
Dashed (*R-R*) line connects MATSUMOTO's (1963) average volcanic rocks of Ryukyu volcanic zone. The *dot-dashed* (*D-D*) line connects DALY's (1914) world average of calcalkaline volcanic rocks.

Fe_2O_3 and CaO contents and a lower FeO, Na_2O, K_2O, Na_2O+K_2O and TiO_2 contents than the average volcanic rocks of the Ryukyu volcanic zone[1] (MATSUMOTO, H., 1963). They are slightly richer in Al_2O_3, $FeO+Fe_2O_3$, Fe_2O_3 and MgO and poorer in FeO, Na_2O+K_2O, Na_2O, K_2O and TiO_2 than the world average calcalkaline volcanic rocks (DALY, 1914). The $FeO^{*2}/MgO_{57.5}$ (*i.e.*, FeO^*/MgO ratio at 57.5% SiO_2) value is 2.33, and the $K_{57.5}$ value indicates 1.18.

NAK-25 volcanic rock is more 20% in Al_2O_3 and have very a higher Al_2O_3 content and lower $FeO+Fe_2O_3$, FeO and MgO contents than the other volcanic rocks. This rock characteristically contain abundant plagioclase phenocrysts.

The Nakanoshima volcanic rocks do not carry fo and fa in the norm. This is also true of rocks from other volcanic Ryukyu islands: the Satsuma-Iwojima (ONO *et al.*, 1982),

1. Data to calculated the average are mainly from the Aso volcanic rocks, and partly from the other volcanic rocks. Namely, these average compositions do not show the mean of all Quaternary volcanic rocks from the Ryukyu Islands.
2. FeO^* is total Fe as FeO

Kuchinoshima (DAISHI, 1988), Suwanosejima (MATSUMOTO, H., 1956; 1964; MURAUCHI, 1954; DAISHI, 1988), Akusekijima (DAISHI, 1988), Gajyajima (MATSUMOTO, H., 1960), Tairajima (DAISHI, 1988), Yokoatejima (MATSUMOTO, Y. and MATSUMOTO, H., 1966), and Okinawa-Torishima (MATSUMOTO, Y., 1978).

B. Chemical investigation of the Nakanoshima volcanic rocks

Fig. 6 and Fig. 7 are presented to investigate the chemical feature of the Nakanoshima volcanic rocks.

Fig. 6 shows that these volcanic rocks are mainly scattered in the calcalkaline andesites field by MIYASHIRO (1974) in accordance with petrographical characters *i.e.*, these volcanic rocks with groundmass hypersthene[3]. Some volcanic rocks from the Serizaki (NAK-05), the Sakiwaridake (NAK-06, 07), the Shiizaki (NAK-12, 19), the Negamidake (NAK-25) andesites are plotted in the tholeiitic andesites field. All volcanic rocks are plotted on the richer area of the FeO*/MgO ratio than the MATSUMOTO's (1963) average volcanic rocks of the Ryukyu volcanic zone, and shows a trend similar to DALY's (1914) world average calcalkaline volcanic rocks.

Fig. 7 shows that the Nakanoshima volcanic rocks are plotted almost in the calcalkaline suites field by IRVINE and BARAGER (1971). Only two volcanic rocks from the Serizaki (NAK-05) and the Shiizaki (NAK-12) andesites are scattered in the tholeiitic suites field. Almost all these volcanic rocks are scattered on the $FeO + Fe_2O_3$ richer side than the

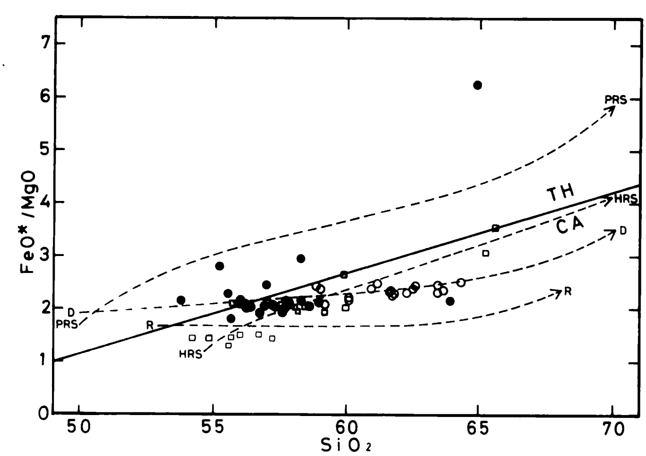

Fig. 6 FeO*/MgO vs. SiO_2 diagram
R-R and *D-D* lines are the same as in Fig. 5. *PRS-PRS* and *HRS-HRS* lines connect KUNO's (1968) average composition of the pigeonitic and the hypersthenic rock series in Japan respectively. A *heavy solid line* separates from tholeiitic (*TH*) to calcalkaline (*CA*) andesites (MIYASHIRO, 1974). *closed circle*: the Nakanoshima volcanic rocks, *open circle*: the Kuchinoshima volcanic rocks, *open square*: the Suwanosejima volcanic rocks.

3. KUNO (1950, 1959, 1968) argued that the calcalkaline series was characterized by groundmass hypersthene and low FeO*/MgO ratios.

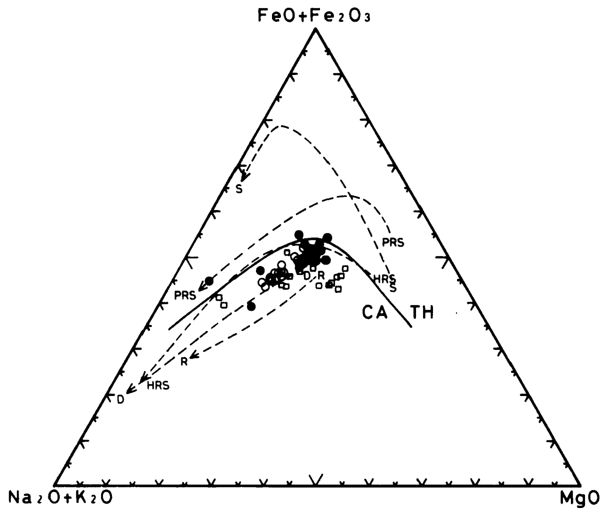

Fig. 7 AFM diagram
R-R, D-D, HRS-HRS and *PRS-PRS* lines and *symbols* are the same as in Figs. 5 and 6. *S-S* line connects average composition of Skaergaard intrusion (WAGER and DEER, 1939; WAGER and BROWN, 1967). *Heavy solid line* separates tholeiitic (*TH*) from calcalkaline (*CA*) suites using criteria of IRVINE and BARAGER (1971).

MATSUMOTO's (1963) average volcanic rocks of the Ryukyu volcanic zone. One evolution curve is recognizable and shows a trend similar to DALY's (1914) world average calcalkaline volcanic rocks.

6. Chemistry of Minerals

The volcanic rocks from the island, made up by far the greatest bulk of the island, are made up minerals. These volcanic rocks are usually porphyritic in texture, thereby providing a rock mineralogic record of their history. This chapter deals mainly with two pyroxenes, carrying their chemical composition to understand the essential features of the rocks.

A. Mineral description and their properties

Plagioclase, orthopyroxene, clinopyroxene and magnetite phenocrysts and/or microphenocrysts are always found in the Nakanoshima volcanic rocks. Hornblende and olivine phenocrysts and/or microphenocrysts are sometimes included in the volcanic rocks.

a. plagioclase

Plagioclase crystals are the most ubiquitous and usually the most abundant phenocrysts in the rocks, typically constituting 40% of the phenocrysts by volume (NAK-24, 25).

Usually plagioclase is the only feldspar present as a phenocryst or in the groundmass. Plagioclase phenocrysts are highly variable in composition due to pronounced and complex zoning. They range in composition from An 38 to An 82 (Fig. 4) with modes of about An 60. Compositions within thin sections often are as variable as within suites, commonly covering a range of 10 to 25 mol% An. Compositions within individual crystals frequently vary by 10 to 20 mol% An, but are almost homogeneous. Or contents (Fig. 4) are lower in phenocrysts or groundmass plagioclase than in normative feldspars (Table 1), indicating concentration of K in glass. Oscillatory zoning is characteristic of plagioclase phenocrysts in the rocks. Oscillations are 3 to 15 μ thick and typically fluctuate by 1 to 10 mol% An, returning repeatedly to a constant maximum An content or gradually decreasing in maximum An content outward. Normal zoning seems to predominate throughout most of the volume of most plagioclase phenocrysts. Rims are usually abruptly more sodic than mantle regions. However, nonoscillatory reversed zoning also is common, either as one or more narrow interruptions (spikes) in an otherwise normally or oscillatorally zoned crystal, or as an overlay of a broad calcic sheath, usually including rim, on a sodic core.

b. orthopyroxene

Orthopyroxene is second to plagioclase in its abundance and ubiquity as a phenocryst in the rocks, averaging about 3 modal %. Orthopyroxene phenocrysts have more variable and higher Fe/Mg ratios than coexisting augite, ranging from En 75 to En 56 (Fig. 4). Phenocrysts in the rocks are mostly reversed zoned.

The chemical composition of pyroxenes are treated after.

c. clinopyroxene

Clinopyroxene is second with orthopyroxene to plagioclase in its abundance and ubiquity as a phenocryst in the rocks, averaging about 3 modal %. The most striking feature of augite phenocrysts in the restricted range in composition, which mostly lie between Wo 38–45, En 36–44, Fs 15–20 (Fig. 4). Augite in the most common groundmass pyroxene in the rocks. Groundmass augites either are similar to phenocrysts in composition, or are more ferrous or less calcic or both. Subcalcic augite is restricted to the rims of the other pyroxene phenocrysts and to the groundmass, and is rarely observed.

d. olivine

Olivine phenocrysts occur in some volcanic rocks, usually in amounts <0.5 vol.%. They have a ordinarily compositional range from Fo 80 to Fo 60.

e. amphibole

Only one amphibole, a hornblende, occurs in the rocks from the Nigoriura andesites. These hornblende andesites contain an average of 4 to 5 vol.% amphibole as a phenocryst coexisting with most combinations of augite, orthopyroxene and plagioclase. FeO*/MgO ratios of amphibole phenocrysts lie between 0.58 and 0.78 (Fig. 4). Host rock ratios exceed those of their amphibole. Similarly, Fe/Mg ratios of amphibole and pyroxene phenocrysts correlate positively, usually being slightly higher in amphiboles than coexisting clinopyroxene. Reversed Fe/Mg zoning occurs in mostly hornblendes of the rocks.

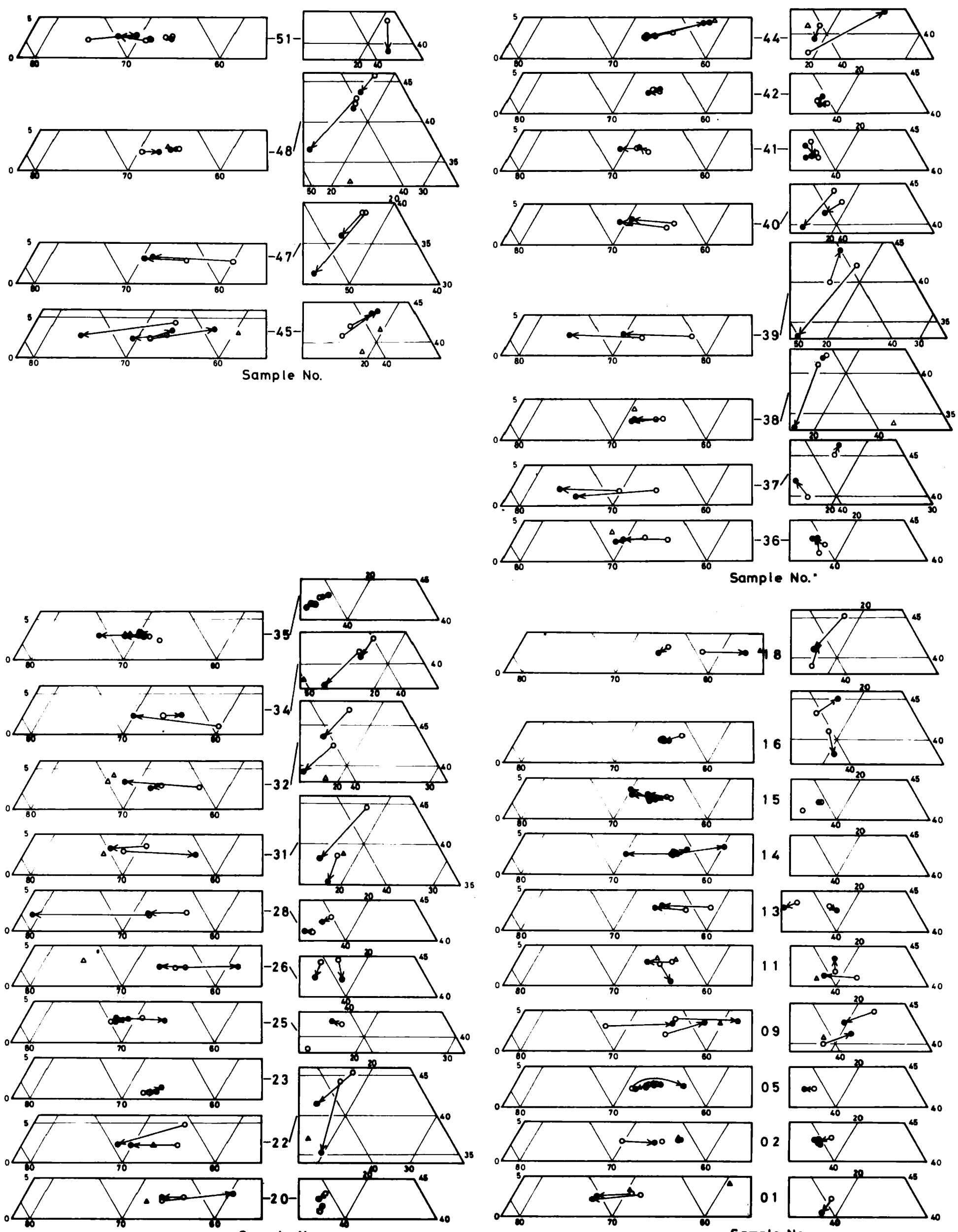

Fig. 8 $CaMgSi_2O_6$-$CaFeSi_2O_6$-$Mg_2Si_2O_6$-$Fe_2Si_2O_6$ diagram of pyroxene for 32 volcanic rocks from Nakanoshima
Arrows point from core to rim; *open circle*: core, *filled circle*: rim, *open triangle*: groundmass. NAK+Sample Nos. are the same as in Fig. 4.

f. oxide

Only one oxide, a titanomagnetite (hereafter called magnetite), occurs in the Nakanoshima volcanic rocks except xenocryst. Usually 0.2 to 0.6 vol.% magnetite is present as a phenocryst (0.25 mm to 0.80 mm diameter) or microphenocryst often in close proximity to pyroxenes. Ulvospinel ($TiFe_2^{2+}O_4$) contents of magnetite phenocrysts lie between 10 and 41 mol% (Fig. 4). Magnetite phenocryst cores are usually poorer in Ti but richer in Fe, Mg and Al than phenocryst rims or groundmass grains.

B. Chemistry of Pyroxenes

The orthopyroxene, clinopyroxene and the other constituent minerals in 32 samples from Nakanoshima have been analyzed with Energy Dispersion type (Hitachi-Kevex, JEOL-Link) and Wave Dispersion type (JEOL JXA-5A) Electron probe micro analyzers. Here I can takes space for only treatment of pyroxenes.

The $CaMgSi_2O_6$—$CaFeSi_2O_6$—$Mg_2Si_2O_6$—$Fe_2Si_2O_6$ diagrams of pyroxenes in the volcanic rocks from Nakanoshima are shown in Fig. 8.

The orthopyroxene in the Nakanoshima volcanic rocks have both reverse and normal zoning. Majority of phenocrysts are reversely zoned, but NAK-02, NAK-09 and NAK-23 rocks only are normally zoned. The Mg content becomes slightly smaller toward the upper lava flows in the Serizaki andesites (NAK-01 ∼ 05). Orthopyroxene phenocrysts range in composition from En 81 to En 56.

The clinopyroxene phenocrysts show both reverse and normal zoning. Most crystals are reversely zoned. The rim and groundmass clinopyroxene are more magnesian and less calcic. The Mg content becomes slightly larger negatively with orthopyroxene toward the upper lava flows in the Serizaki andesites (NAK-01 ∼ 05).

7. Age of the rocks

Until recently there was no direct means of measuring the absolute age of younger volcanic rocks such as from the Ryukyu Islands. Geological ages had been estimated from geological evidence, until I started dating rocks. In the last few decades have I had anything approaching a real clock to measure geologic time, radiometric age determination. It uses the breakdown of radioactive materials in the rocks or in substances buried by the lava flows or ash beds at the time of their formation. In this study, fission track methods have been used as one of the radiometric age determination method without an expensive apparatus.

A. Fission track age determination

Fission track dating was carried out by the *External-surface Internal-detector method* (hereafter *ESID* method; Daishi *et al.*, 1987). ESID method generally using a sample which has a small spontaneous track density (*e.g.*, Quaternary volcanic rocks) whose spontaneous and induced tracks can be counted on the same plain of zircon.

The experimental method and environment of the fission track age determination are sometimes different for each experimenter. I will report the experimental method and environment of this method.

a. Separation and selection of zircon

A proper volume (*e.g.*, acidic rocks: 1～5 kg; medium andesitic rocks: 5～20 kg) of each rock sample was shattered by a jaw-crasher and/or a disk-crasher and 48～200 meshes portion are sifted out from powder grains. The heavy minerals were concentrated by panning, magnetic separation using Hallimond's magnetic separator, and heavy liquid separation (bromoform: specific gravity $d^{15}=2.89$) minerals. The weakly magnetic minerals were eliminated by isodynamic-separator. They were heated in hydrofluoric acid (added few drops of H_2O and H_2SO_4) to solved silica minerals. If they included pyrite resulted from mineralization, they were heated in nitric acid solution (HNO_3: $H_2O=1:1$) to solved the minerals. After that, the zircon was boiled with dilute hydrochloric acid because there is a possibility that the surface is contaminated with iron oxide *etc*.

. The zircon were selected the similar form and diameter of crystal because there is a possibility that the uranium content differs among zircon grains. The zircon which shows deeper color than the other crystals was removed by hand-picking to avoid the mixing of accidental crystal of zircon.

b. Etching

About 50 grains of zircon was mounted on a polyhexafluoroethylene (teflon hexafluoride) sheet. A crystal plain of the zircon was cleaned using a DP-cloth without diamond-paste. The zircon was etched for 40～70 hours in eutectic mixture of 50.6 mol% KOH and 49.4 mol% NaOH (GLEADOW *et al.*, 1976) at 215±1°C. The etching time is quite different from the sample age (*i.e.* track density). Younger samples are generally in need longer in time than older samples.

Muscovite, external detector, was etched about 45 minutes in 46% HF maintained to 25±1°C.

c. Neutron irradiation

The muscovite external detector was attached to the zircon mounting on a teflon hexafluoride sheet for check the induced track density. Similarly the muscovite detector was attached to the standard glass (NBS962a) for the monitor of neutron dose. They are put in a capsule together, and thermal neutrons were irradiated for 5 minutes in the rotation specimen rack of the Rikkyo University nuclear reactor (TRIGA *Mark* II).

Thermal neutron dose was determined by the muscovite as a external detector attached to the standard glass. Thermal neutron dose ϕ is shown as following numerical formula.

$$\phi = \phi_k \times \rho_u / \rho_k$$

ϕ_k: thermal neutron dose of standard glass irradiated at NBS nuclear reactor

ρ_u: track density of muscovite attached to standard glass irradiated with sample

ρ_k: track density of muscovite attached to standard glass which irradiated at NBS nuclear reactor

d. Counting of tracks

An optical microscope (dry 1,000×) was used for the counting of tracks. The tracks were counted in the 2π geometry field excepting area with inclusion and the part of damaged by etching.

f. Numerical formula of the fission track dating

Next numerical formula was obtained when the constants are substituted to PRICE and WALKER's (1963) fission track dating numerical formula (fission track decay constant of $^{238}U=7.03\times10^{-17}$/yr.: ROBERTS, *et al.*, 1968; $^{235}U/^{238}U$ ratio of isotopic abundance= 7.2525×10^{-3}: STEIGER and JÄGER, 1977).

$$A=6.45\times10^{9}\ \ln(1+9.28\times10^{-18}\times\phi\times\rho_s/\rho_i)$$

ρ_s: spontaneous track density of ^{238}U

ρ_i: induced track density of ^{235}U.

The error of age is calculated by the next equation.

$$E=\sqrt{Er(s)^2+Er(i)^2+Er(d)^2}$$

Er(s): relative standard error of spontaneous track density

Er(i): relative standard error of induced track density

Er(d): relative standard error of thermal neutron dose

The results calculated from the aforementioned methods were then statistically tested by Precision index (P.I.) statistics (HAYASHI and FUJII, 1985).

B. Fission track ages of the rocks

I have been collected more than 10 rock specimens to age determination from Nakanoshima. However, the fission track ages could be determined only 2 rocks. Because, many basic to medium (olivine bearing andesite ~ two-pyroxene andesite) volcanic rocks do not contain enough zircon for fission track age determination, and many accidental zircons are included in the rock specimen[4].

Table 2 Fission track ages of zircon in two volcanic rocks from Nakanoshima (DAISHI *et al.*, 1987)

sample No.	spontaneous track number	spontaneous track density $\times10^6 cm^{-2}$	induced track number	induced track density $\times10^6 cm^{-2}$	thermal neutron dose $\times10^{14} cm^{-2}$	PI*	age and std. error (Ma)
KAG-008	81	0.2656 ± 0.0295	371	1.216 ± 0.063	1.34 ± 0.04	90	**1.75 ± 0.22**
KAG-009	6	0.0018 ± 0.0007	336	0.1017 ± 0.0055	1.34 ± 0.04	98	**0.14 ± 0.06**

* PI, precision index (HAYASHI and FUJII, 1985)

4. If the P.I. statistics data is smaller than 50, the age of the sample is rejected.

The fission track ages are shown in Table 2. Sample KAG-008 from the Serizaki andesites is 1.75±0.22 Ma, that is lower Pleistocene. Sample KAG-009 from the Nigoriura andesites indicates 0.14±0.06 Ma, that is upper Pleistocene.

8. Conclusion

The present paper treats the results of detailed studies on geology of Nakanoshima together with petrology and mineralogy of volcanic rocks. Fission track ages have also been measured. These data leads to the discussion of the volcanic history of Nakanoshima.

The volcanic history began when a submarine volcano which was situated on a planation surface about 700 m below sea level emerged above the sea in the lowermost Pleistocene. The volcanic activity at that time might be explosive, because the hot magma coming in contact with sea water from large volumes of steam resulting in violent and spectacular steam explosion. This explosive volcanism accumulated the deposits consisting of voluminous essential material. Most of these deposits might have been rapidly eroded by a rough sea as soon as its accumulation. However, a few of these deposits might have been vigorous durability for the erosion of sea. They are tuff breccia and volcanic breccia which are restricted to the north-northwest seashore of Serizaki, and had been formed the islet.

The volcanism became quieter *e.g.*, the eruption with voluminous lava flows with or without accidental pyroclastic rocks. The reason will be that the vent (*i.e.*, magma) was far from sea water because of the formation of the islet. The lava flows of the Serizaki andesites probably formed under these environments. As a result of the voluminous lava flows, the islet had vigorous durability for the erosion of sea, and became extending in its area.

The Nanatsuyama, the Sakiwaridake and the Shiizaki andesites were formed during the mountain-building stage. The volcanism might be explosive, characterized by the island arc eruption. During this stage, one stratovolcano edifice was formed. Following this, another stratovolcano body was also formed destroying the first one in or the right side of the first stratovolcano edifice. These volcanic activities took place repeatedly.

The Older Otake volcanism took place at north side of the islet after short time of the mountain-building volcanic activities. The large volume lava flows might have formed through this volcanism like the activities of the Serizaki andesites, and became more extending in its area.

The volcanic activities forming the Nigoriura andesites might be explosive *e.g.*, the eruption type as phreatomagmatic eruption. This is the magma was uplifted with tectonic movements (fault forming) coming in contact with subsurface water and/or sea water inundated along the fault. The eruption type presumable from the products were differed from that of the other volcanoes *i.e.*, hornblende andesite.

The Younger Otake volcanism formed the large stratovolcano like the activities of the mountain-building stage, and that continued to the present.

From field evidences, obtained fission track ages together with rejected unreliable ones, and estimated ages by zircon color, the oldest of these volcanic rocks is considered to be the Serizaki andesites. The fission track age of the Serizaki andesites shows 1.75 Ma, the lowermost Pleistocene. Namely the volcanic activity of Nakanoshima started in the lowermost Pleistocene and is still active today.

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