Geochronology of alkali volcanism in Oki-Dogo Island, Southwest Japan: Geochemical evolution of basalts related to the opening of the Japan Sea

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Geochronological and geochemical studies were performed on alkali volcanic rocks from Oki-Dogo Island, locating about 60 km off the coast of Southwest Japan inside the Japan Sea. There are big differences both in age and in geochemistry between the oldest alkali rocks and the younger rocks; the former having significant Nb- and Ta-depletion and Ba- and K₂O-enrichment erupted at 19–18 Ma when the opening of the Japan Sea was ongoing, while the latter with no Ta-depletion were active between 5.5–0.6 Ma considerably after the cessation of the rifting activity. Syn-extensional rocks should not have erupted in the active subduction zone but are probably originated from or at least contaminated by the lithosphere beneath the early Proterozoic crust. The lithosphere is considered to have suffered mantle metasomatism to form phlogopite selectively enriched in Ba and K₂O by fluids, which had been released from previous subductions at the Asian continental margin. Partial melting of such lithospheric mantle during the active rifting was essential for the generation of Ba- and K₂O-enriched alkali basalt magmas. The younger basaltic rocks are probably originated either from the asthenosphere or the deeper plume mantle. A suite of volcanic rocks from mugearite through trachyte to alkali rhyolite gave concordant ages of 5.5–5.4 Ma. These ages suggest that a previously reported Rb-Sr whole rock age of 6.8 ± 0.3 Ma does not represent the age of eruption and is probably disturbed by magma mixing between basic and acidic end members.

INTRODUCTION

Oki-Dogo Island is a small island in the Japan Sea, about 60 km off coast of Southwest Japan (Fig. 1). This island is well known for its bearing some alkali basalt lava flows with abundant mantle-derived spinel ilmenite nodules (Takahashi, 1978), and also for the existence of the Early Proterozoic metamorphic complex (Tanaka and Hoshino, 1987). The metamorphic complex is considered to be a continental fragment drifted away from the main Asian continent when the opening of the Japan Sea occurred (Tamaki, 1988). Various kinds of Neogene-Quaternary volcanic rocks crop out on this island covering the pre-Tertiary basement rocks and Paleogene calc-

alkalic volcanic rocks (Uchimizu, 1966; Yamazaki *et al.*, 1991). They are mainly alkali volcanic rocks ranging from SiO₂-undersaturated alkali basalts through mugearite and trachyte to SiO₂-oversaturated alkali rhyolites (Uchimizu, 1966; Xu, 1988). Geochemical studies on such alkali volcanic rocks (Xu, 1988; Nakamura *et al.*, 1989) have clarified that older alkali basaltic rocks have geochemical signature similar to subduction-related basalts, while younger ones to within-plate basalts. Biostratigraphic information suggests that older basalts erupted in early Miocene (Yamazaki *et al.*, 1990, 1991), while limited K-Ar and Rb-Sr age data on younger volcanic rocks span between 6.8 and 0.85 Ma (Kaneoka and Ozima, 1970; Kaneoka *et al.*, 1977; Iwata *et al.*, 1988; Fujimaki *et al.*,

Fig. 1. Index map of Oki-Dogo Island. Solid triangles show localities of Quaternary volcanoes in SW Japan. Bathymetric counters of every 1,000 m are shown by dotted lines.

1989). As the active rifting and the opening of the Japan Sea are believed to have occurred during early to middle Miocene time, the geochemical difference between the older and younger volcanic rocks might be related to such a tectonic event.

In this paper, we give new K-Ar age data for some volcanic rocks from Oki-Dogo with major and trace element chemistry data, and discuss the time progressive variations in magma chemistry and speculate their origins related to the back-arc rifting behind the Japanese Islands.

TECTONIC SETTING

The Japan Sea is a back-arc basin behind the Japanese Islands, and many structural highs and basins were recognized by submarine topographic and seismic profile studies (Tamaki, 1988) (Fig. 1). Some large scale topographic highs, like Yamato Rise, are considered to be continental fragments left behind when Japanese Islands drifted away from the mainland Asia (Tamaki,

1988).

Oki-Dogo Island locates about 60 km off the coast of Southwest Japan, resting on a submarine topographic high extending in N-S direction from Shimane Peninsula to Oki Bank, together with Oki-Dozen Island, another island made up with late Miocene alkalic volcanics (Tiba, 1975; Wada *et al.*, 1990). The exposure of the lower Proterozoic gneiss in the northeastern part of the Oki-Dogo Island (Tanaka and Hoshino, 1987) suggest that Oki Bank is one of continental fragments mentioned above (Tamaki, 1988). This submarine high bounds the western end of the southernmost submarine graben in the Japan Sea, Oki Trough.

To the south of Oki Trough, there runs an E-W trending buried graben between Oki-Dogo Island and the mainland SW Japan. This graben runs from the off coast of the western part of Honshu for about 500 km in length. Early to Middle Miocene sediments and volcanics completely fill up the graben where granitic basements subsided more than 1,000 m (Yamauchi and Yoshitani, 1981; Tanaka and Ogusa, 1981; Kano and Yoshida, 1985), and the most subsided southern part was turned into a folded zone, called Shindo folded belt (Otuka, 1939). The volcanic activity in and around this graben started about 24 Ma with progressive rifting (Kano, 1991) and ceased at 15–14 Ma, according to the radiometric age constraints given by Kano and Nakano (1985) and Uto (1989). This graben should be the southernmost constituent of a "Basin and Range" type rift graben system formed during the opening of the Japan Sea.

There have been many arguments when and how the back-arc opening occurred behind the Japanese Islands (Otofuji *et al.*, 1985; Tamaki, 1986, 1988). Recent studies on Cenozoic stratigraphy of the Japanese Islands (Kano *et al.*, 1991), ^{40}Ar - ^{39}Ar dating of submarine volcanic rocks from the Japan Sea (Kaneoka *et al.*, 1990, 1992), and results of Ocean Drilling Project (Jolivet and Tamaki, 1992) suggest that the back-arc opening started in Early Miocene and almost ceased in Middle Miocene.

GEOLOGIC OUTLINE

The outline of geology of Oki-Dogo Island (Fig. 2), combined with previous works and current age determinations, is as follows:

Basement rocks of Oki-Dogo Island are Proterozoic metamorphic rocks whose Nd-Sm whole-rock ages are about 2 Ga (Tanaka and Hoshino, 1987), and granitic rocks of Palaeozoic and Neogene age (Tainosho *et al.*, 1991). These rocks are exposed on the northeastern part of the Island. Paleogene to Early Miocene sedimentary rocks and intercalating calc-alkalic volcanic rocks are distributed surrounding the basement rocks.

The oldest alkali volcanic rocks are subaque-

ous lavas and volcanoclastics in the Kori Formation (KF), which sporadically appear in various parts of the Island beneath the thick coverage of younger volcanic products (Yamazaki, 1991; Yamazaki *et al.*, 1990, 1991). Even though a fission-track zircon age of 13.7 ± 0.7 Ma is obtained for a tuff intercalated in trachybasalts (Yamazaki and Ganzawa, 1989), Yamazaki *et al.* (1990, 1991) and Yamazaki (1991) assigned these alkali basaltic rocks to the lower Miocene according to the diatom biostratigraphy. Chemistry of these volcanic rocks is quite different from the younger alkali volcanics, and Xu (1988) called these rocks as shoshonite or banakite.

After a long erosional interval, three groups of

Fig. 2. Generalized geologic map of Oki-Dogo Island (modified after Yamazaki *et al.*, 1991; Uchimizu, 1966) along with sample localities. 1: Alluvium and Talus, 2: Misaki Basalt Group (MBG), 3: Saigo Basalt Group (SBG), 4: Omine Basalt Group (OBG), 5: Tsuzurao Quartz Rhyolite Group (TRG), 6: Hei Trachyte Group (HTG), 7: Oki Trachyte-rhyolite Group (OTG), 8: Tsuma Formation (Tertiary sediments), 9: Kori Formation (KF), 10: Tokibariyama Formation, 11: Pre-Tertiary basements (mainly Proterozoic metamorphic rocks). Circles, triangles and squares show localities of samples for younger basalts (MBG, SBG and OBG), OTG, and KF, respectively.

intermediate to silicic alkali volcanics, the Oki Trachyte-Rhyolite Group (OTG), the Hei Trachyte Group (HTG) and the Tsuzurao Quartz Rhyolite Group (TRG), erupted in the ascending order (Uchimizu, 1966). OTG is composed of various kinds of rocks ranging from mugearite through trachyte to alkali rhyolite, which are supposed to have erupted successively with no or little time interval from arcuate ring vents (Uchimizu, 1966). The total eruptive volume exceeds 20 km³, and is distributed along the western sector of the island. A K-Ar age of 6.3 Ma* (Kaneoka and Ozima, 1970) and a fission-track age of 3.9 Ma (Suzuki, 1970) are obtained for rhyolitic obsidians belonging to OTG. Iwata *et al.* (1988) gave a Rb-Sr whole rock isochron age of 6.8 ± 0.2 Ma for ten volcanic rocks ranging from mugearite to rhyolite belonging to OTG. Fujimaki *et al.* (1989), on the other hand, reported two K-Ar ages of 5.4 Ma for mugearite lavas. Younger felsic volcanic rocks, HTG and TRG, are much smaller in volume than OTG, and are distributed inside the ring vent system of the OTG, in the south-central (HTG) and the northeastern (TRG) part of the island.

Three alkali basalt groups, Omine Basalt Group (OBG), Saigo Basalt Group (SBG) and Misaki Basalt Group (MBG), make up the youngest volcanic groups in the Island (Uchimizu, 1966; Xu, 1988). Some basalt lavas belonging to OBG have moderate to abundant amounts of xenolithic fragments including mantle-derived spinel peridotites (Takahashi, 1978). On the other hand, lavas of SBG and MBG rarely have such xenoliths. K-Ar ages between 4.6 Ma and 3.30 ± 0.12 Ma are obtained for OBG (Kaneoka *et al.*, 1977; Fujimaki *et al.*, 1989). Hirooka and Kawai (1967) and Kano and Nakano (1985) gave K-Ar ages of 0.85 Ma** and 1.3 ± 0.2 Ma, respectively for basalt lavas belonging to SBG. MBG, preserving relatively young volcanic landform, is considered to form the youngest volcanic strata in the island

(Uchimizu, 1966), but no radiometric information is so far known.

K-Ar DATING

K-Ar dating was done for 15 volcanic rocks in total; 3 lava flows from KF, 3 lava flows and 1 dike rock from OTG, 4 lava flows from OBG, 3 lava flows from SBG, and 1 lava flow from MSG. No attempt has been made on dating volcanic rocks belonging to HTG and TRG. All analyses were done on whole rock samples excluding any visible xenolithic and xenocrystic fragments. Most rocks are fresh with no or little alteration. Three basaltic rocks belonging to the KF are slightly altered, and olivine phenocrysts and groundmass glass (less than a few volume %) were replaced by clay minerals.

Except for one analysis which was made at Univ. Tokyo, all analyses were done at the Geological Survey of Japan using the following procedure. After crushing and sieving, rock fragments of 16–32 mesh fractions were examined under the binocular microscope not to include any large xenolithic fragments. Aliquots of these rock fragments were further pulverized for potassium analysis. Argon was extracted using a high-vacuum off-line extraction system made of pyrex glass. Eight to ten grams of each sample were weighed into a pre-fired disposable molybdenum crucible and loaded into the extraction system. The line was then baked at 200°C under a vacuum for three hours, and samples outside the oven for the glass-line were baked overnight at about 100°C. Crucibles were heated by a radio-frequency induction furnace up to about 1400°C, and extracted gas was mixed by a known amount of ³⁸Ar spike and was purified by a liquid N₂ trap and two Ti getters. Purified noble gas was then collected by a charcoal trap soaked in liquid N₂ and detached from the line under a vacuum. Argon isotope analyses were made using a VG Micromass 603 mass spectrometer. Potassium analyses were done by the flame photometry (Matsumoto, 1989). One analysis on OMS was done at Univ. Tokyo following the same procedure with that in Kaneoka and Ozima (1970)

*Recalculated using the current decay constants (Steiger and Jäger, 1977)

**Average of two analyses; 0.823 ± 0.048 Ma and 0.880 ± 0.035 Ma, again recalculated using the current decay constants (Steiger and Jäger, 1977)

Table 1. K-Ar ages for volcanic rocks from Oki-Dogo Island

KA No.	Sample ID	K ₂ O (wt%)	⁴⁰ Ar _{rad} (10 ⁻⁶ ml STP/g)	Atm. Ar (%)	Age (Ma)
Misaki Basalt Group (MBG)					
1333	MISG-1 (133°20'28"E, 36°11'01"N)	1.60	0.0284	87.1	0.55 ± 0.09
Saigo Basalt Group (SBG)					
1817	SBB (133°18'54"E, 36°12'58"N)	2.13	0.0435	85.7	0.63 ± 0.09
1820	FBA (133°21'38"E, 36°17'25"N)	0.948	0.0243	81.9	0.79 ± 0.13
1812	SBA	2.87	0.127	40.3	1.38 ± 0.08
1826			0.113	53.3	1.22 ± 0.05
	(133°19'03"E, 36°13'14"N)			av.	1.29 ± 0.05
Omine Basalt Group (OBG)					
1818	NBB (133°19'12"E, 36°18'13"N)	1.43	1.08	65.9	2.35 ± 0.13
1819	FBB (133°21'51"E, 36°17'38"N)	2.09	1.78	66.8	2.65 ± 0.15
1332	SHB (133°17'11"E, 36°20'38"N)	0.826	0.0749	80.0	2.81 ± 0.28
1815	DMB (133°20'04"E, 36°15'22"N)	1.38	1.95	63.6	4.38 ± 0.23
Oki Trachyte-rhyolite Group (OTG)					
1324	OMS	6.02	1.07	30.8	5.51 ± 0.18
		6.11	1.08	49.9	5.49 ± 0.09*
	(133°12'31"E, 36°17'08"N)				
1325	UTG (133°16'19"E, 36°12'51"N)	3.60	0.634	52.2	5.46 ± 0.23
1323	SHZ (133°17'14"E, 36°19'49"N)	6.00	1.05	20.4	5.42 ± 0.17
1383	ET78090402 (133°11'27"E, 36°16'18"N)	2.84	0.499	45.9	5.45 ± 0.21
Kori Formation (KF)					
1322	NGU (133°11'17"E, 36°12'33"N)	1.74	1.02	35.3	18.0 ± 0.6
1382	ET78090206 (133°10'48"E, 36°15'00"N)	2.65	1.65	42.2	19.2 ± 0.7
1413	ET78083107 (133°11'22"E, 36°12'33"N)	2.58	1.51	33.2	18.0 ± 0.6

*Dated by I. Kaneoka at Univ. Tokyo.

Others are dated by K. Uto at Geological Survey of Japan (GSJ).

KA No.: laboratory analytical number at GSJ.

$\lambda_{\beta} = 4.962 \times 10^{-10}/y$, $\lambda_e = 0.581 \times 10^{-10}/y$, $^{40}K/K = 0.01167 \text{ atm\%}$ (Steiger and Jäger, 1977).

Quoted errors are 1σ .

and Kaneoka *et al.* (1977).

Analytical results are shown in Table 1. Analytical uncertainties are calculated following the equation of Cox and Dalrymple (1967). Two ages for OMS, one of which was made at GSJ and the

other at Univ. Tokyo, agree well each other within analytical uncertainties. This suggests that three previous ages by Kaneoka and Ozima (1970) and Kaneoka *et al.* (1977) and current ages can be discussed at the same accuracy level.

Three ages for KF are about 18–19 Ma, which are identical each other within analytical uncertainties. These ages are considered to represent the ages of eruption even though these rocks suffer a little to moderate degrees of alterations, because three rocks give identical ages regardless of the considerable variation in K_2O contents (1.74–2.65 wt%). These ages are older than the fission-track age of 13.7 ± 0.7 Ma (Yamazaki and Ganzawa, 1989), but are concordant to the biostratigraphic estimate (Yamazaki *et al.*, 1990, 1991; Yamazaki, 1991).

Four rocks of OTG also gave very concordant ages of 5.42–5.51 Ma. The deviation of ages, 0.09 million years, is much less than analytical uncertainties, 0.18–0.22 million years, for individual ages. These ages are also consistent with the ages of 5.4 Ma for two mugearites by Fujimaki *et al.* (1989). On the other hand, these ages are considerably younger than the Rb-Sr whole rock age, 6.9 ± 0.3 Ma, by Iwata *et al.* (1988). They are also slightly younger than the K-Ar age, 6.3 Ma, by Kaneoka and Ozima (1970) and older than the fission-track age, 3.6 Ma, by Suzuki (1970). Among four rocks dated in this study, two samples, OMS and UTG, were also used to obtain the Rb-Sr isochron age by Iwata *et al.* (1988). In addition, the different sample but from the same outcrop from which SHZ was taken was also used for the Rb-Sr dating. The reason for the discrepancy between K-Ar and Rb-Sr systems will be discussed later.

Four ages for alkali basalt lavas belonging to OBG scatter widely from 4.4 to 2.4 Ma, comparing to the tight age grouping for those of OTG. Even though an age for one lava (DMB), 4.38 ± 0.23 Ma, is considerably older than other three ages from 2.8 Ma to 2.4 Ma, this age agrees well with the age, 4.6 Ma (the average of two analyses; 4.68 ± 0.21 Ma and 4.51 ± 0.2 Ma) for a basalt probably belonging to the same lava unit (Fujimaki *et al.*, 1989). Two ages by Kaneoka *et al.* (1977), 3.30 ± 0.12 Ma and 3.6 Ma fill the gap between two age groups. These data suggest that the basalt volcanism of OBG continued intermittently for about two million years from about 4.4 Ma to

about 2.4 Ma.

Four other alkali basalt lavas belonging to either SBG or MBG gave ages ranging from 1.30 ± 0.05 Ma to 0.55 ± 0.09 Ma, 1.1 to 1.8 million years younger than the youngest age for OBG far beyond the analytical uncertainties. These ages well agree with previous ages for two basalts of SBG, 0.85 Ma (Hirooka and Kawai, 1967) and 1.3 ± 0.2 Ma (Kano and Nakano, 1985). The age for MISG-1 belonging to MSG is slightly younger than ages for basalts belonging to SBG, which is concordant with the previous stratigraphy (Uchimizu, 1966; Xu, 1988). The time discrepancy between two groups is, however, negligible if we consider the analytical uncertainties. There has been no logical reason (e.g., petrographical and/or chemical differences) to divide these basaltic rocks into two groups except for the observation that the MBG lava flow, spreading in the southeastern end of this island, preserves the youthful volcanic topography (Uchimizu, 1966). It might be more reasonable to consider that both basalt groups form a continuous single volcanic activity from the view point of K-Ar ages.

As a summary of the present and existing K-Ar ages, it is concluded that four cycles of alkali volcanic activity occurred in Oki-Dogo Island in the past 19 million years; 19–18 Ma, 5.5–5.4 Ma, 4.4–2.4 Ma, and 1.3–0.55 Ma. This sporadic and discontinuous volcanism in Oki-Dogo Island contrasts with the relatively instantaneous volcanism at about 6 Ma in the nearby Oki-Dozen Island (Morris *et al.*, 1990; Wada *et al.*, 1990), and none of them are contemporaneous with the volcanic activity in Oki-Dozen Island.

GEOCHEMISTRY

Even though many major and trace element data have been published (Nakamura *et al.*, 1989, 1990), we add some chemical compositions for dated rocks. The results are shown in Table 2. Major element data of most rocks were determined by wet chemistry analyzed by H. Haramura in Univ. Tokyo except for a few data obtained by XRF either at Univ. Toronto (Nakamura *et al.*,

Fig. 3. MgO variation diagrams for selected major and trace elements. Open squares: Younger basalts (MBG, SBG, OBG); open triangles: OTG; solid circles: KF.

1989) or at Univ. Tokyo (Aramaki, 1987). Trace elements were obtained mainly by INAA either at GSJ following the procedure of Tanaka *et al.* (1988) or at Univ. Toronto together with those given in Nakamura *et al.* (1989). Some additional elements either by XRF or by isotope dilution are added in Table 2 mainly from the published literature. Details of the credit are given below the table. Some elemental plots and chondrite-normalized REE patterns are shown in Figs. 3 and 4 for selected data from Nakamura *et al.* (1989, 1990) and the current study. It is obvious that the

basaltic rocks of KF are remarkably depleted in HFSE (High-Field Strength Elements) like Ti and Ta compared with younger basaltic rocks. On the other hand, there is no systematic geochemical difference among the three younger basaltic volcanic groups. Mugearites belonging to OTG, having differentiated chemistry (i.e., high FeO*/MgO ratios, low Ni and Cr contents), have relatively similar incompatible element ratios to the three younger basalt groups.

CONTEMPORANEOUS ERUPTIONS OF COMPOSITIONALLY DIVERGED MAGMAS AT 5.5 Ma

Magma mixing: false Rb-Sr age for OTG

Rhyolites of Neogene ages with high Rb but low Sr contents have great potential to give precise Rb-Sr ages even though Rb-Sr system is generally applied for older igneous and metamorphic rocks. Radicati di Brozolo *et al.* (1981) gave Rb-Sr mineral isochron ages of about 3.3–3.7 ka for leucite-biotite-pyroxene-whole rock pairs from the Italian high-K volcanics. On the other hand, the caution should be paid if the method is applied to a suite of whole rocks having wide variation in Rb/Sr ratios, because these rocks might not have a same initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. Wide variations in Sr isotopic ratios have been reported among recent volcanic products from a single volcano (Notsu *et al.*, 1990; Kurasawa *et al.*, 1986). Kurasawa *et al.* (1986) reported a 368 Ma Rb-Sr “isochron” for volcanic rocks from Quaternary Kirishima volcano, Southwest Japan. Halliday *et al.* (1989) also gave Rb-Sr isochron ages of “ 2.09 ± 0.06 , 1.90 ± 0.02 and 1.14 ± 0.08 Ma” for pre-caldera rhyolites of Glass Mountain in the Long Valley Caldera, whose K-Ar ages range from 2.1 to 0.79 Ma. Kurasawa *et al.* (1986) attributed the pseudo-isochron to the AFC (assimilation fractional crystallization) process (their “combined process”), while Halliday *et al.* (1989) interpreted that Rb-Sr ages represent ages when the chemical stratifications were formed in the magma chamber.

Iwata *et al.* (1988) made systematic Rb-Sr isotopic studies on a mugurite-trachyte-rhyolite

Table 2. Major and trace element data for dated volcanic rocks along with other age known basalts from Oki-Dogo Island

Sample No.	MISG-1 ⁽¹⁾	MISG-2 ⁽¹⁾	SBB ⁽¹⁾	FBA ⁽¹⁾	SBA ⁽¹⁾	NBB ⁽¹⁾	FBB ⁽¹⁾	SHB ⁽¹⁾	KRB ⁽¹⁾
UNIT	MBG	MBG	SBG	SBG	SBG	OBG	OBG	OBG	OBG
AGE	0.55±0.09	~0.55	0.63±0.09	0.79±0.13	1.30±0.05	2.35±0.13	2.65±0.15	2.81±0.28	3.61
SiO ₂	47.11	46.58	46.44	47.36	47.29	49.11	47.53	45.08	47.47
TiO ₂	1.75	1.66	2.54	2.63	2.72	2.12	2.31	2.55	2.43
Al ₂ O ₃	15.00	15.01	16.91	16.57	16.36	16.08	15.45	14.17	17.15
Fe ₂ O ₃	3.04	3.54	1.55	2.98	2.10	3.89	1.82	3.02	2.26
FeO	7.09	6.83	7.66	6.72	7.37	6.26	7.81	7.14	7.22
MnO	0.15	0.17	0.15	0.17	0.18	0.14	0.15	0.17	0.15
MgO	10.76	10.67	7.11	7.39	7.67	7.03	9.88	10.54	8.76
CaO	9.41	9.33	8.63	8.60	7.60	8.66	7.66	9.69	8.03
Na ₂ O	3.02	3.50	3.49	4.54	3.44	3.89	3.84	4.47	3.67
K ₂ O	1.57	0.83	2.27	0.99	2.77	1.43	1.91	0.77	1.69
P ₂ O ₅	0.58	0.22	0.92	0.60	0.82	0.63	0.73	0.74	0.66
Total	99.48	98.34	97.67	98.55	98.32	99.24	99.09	98.34	99.49
Fe/Mg	0.91	0.94	1.27	1.27	1.21	1.39	0.96	0.94	1.06
Co		66.0	37.0		40.0		51.0	58.9	46.0
Ni		280	150		170		260	190	270
Sc		26.0	21.0		18.0		19.0	25.3	21.0
Cr		650	180		170		320	210	270
V									
Rb		46	61		79		43		37
Cs									
Sr		600	870		830		720		720
Ba		520	1030		970		620		810
Zr		160	230		280		230		210
Y		19	24		28		23		22
La		25.9	39.1		44.9		33.7		34.0
Ce		50.2	73.7		88.7		64.4		64.4
Nd		28.0	42.7		41.7		32.2		31.1
Sm		5.14	7.33		9.09		7.00		6.62
Eu		1.86	2.37		2.71		2.48		2.39
Tb		0.77	0.89		1.02		0.78		0.91
Yb		2.27	2.39		2.25		1.60		2.60
Lu									
Hf		3.90	5.91		6.86		5.80		5.00
Ta		2.40	3.30		4.40		3.30		3.40
Nb									
Th		3.42	4.86		6.92		3.66		5.48

suite belonging to OTG, and obtained a whole-rock isochron age of 6.8 ± 0.3 Ma from ten rocks. They interpreted the age as the time of eruption. On the other hand, K-Ar ages for six rocks belonging to OTG given in this study and Fujimaki *et al.* (1989) are tightly clustered around 5.5–5.4 Ma, which are significantly younger than the Rb-Sr age. As some samples are used for both K-Ar and Rb-Sr analyses, it should not be appropriate to consider that the OTG volcanism spanned more

than a million year from 6.8 Ma to 5.4 Ma. As the Rb-Sr age was calculated using data analyzed at two laboratories and K-Ar ages were from three laboratories, the discrepancy between the Rb-Sr and K-Ar systems should not be a matter of analytical problems, but rather be a matter of geological interpretation. Here, we claim that the K-Ar ages do represent those of eruption but the Rb-Sr age is artificial due to magma mixing between basic and acidic magmas.

Table 2. (continued)

Sample No.	OKD ⁽¹⁾	SHZ ⁽¹⁾	ET7809402 ⁽³⁾	UTG ⁽¹⁾	OMS ⁽¹⁾	ET78083107 ⁽³⁾	NGU ⁽²⁾	ET7809206 ⁽³⁾
UNIT	OBG	OTG	OTG	OTG	OTG	KF	KF	KF
AGE	3.30±0.12	5.42±0.17	5.45±0.21	5.46±0.23	5.51±0.18	18.0±0.6	18.0±0.6	19.2±0.7
SiO ₂	47.79	69.01	52.00	53.57	65.83	51.50	53.36	53.04
TiO ₂	2.39	0.30	3.12	2.24	0.68	1.15	1.04	1.16
Al ₂ O ₃	16.44	15.50	14.56	16.29	16.54	16.83	16.14	16.00
Fe ₂ O ₃	1.85	2.21		3.65	2.19		8.27	
FeO	7.14	0.19	11.28	5.45	0.68	8.59		7.66
MnO	0.15	0.03	0.17	0.17	0.06	0.11	0.17	0.13
MgO	8.63	0.19	3.61	2.57	0.27	5.64	5.53	5.57
CaO	7.66	0.53	7.25	5.55	1.44	9.88	9.29	10.11
Na ₂ O	4.12	4.55	3.67	3.96	4.36	2.84	2.76	2.81
K ₂ O	2.23	6.06	2.90	3.64	6.11	2.88	1.75	2.70
P ₂ O ₅	0.81	0.05	1.39	1.01	0.13	0.52	0.41	0.77
Total	99.21	98.76	99.95	98.10	98.29	99.94	98.72	99.95
Fe/Mg	1.02	11.47	3.12	3.40	9.82	1.52	1.35	1.38
Co	71.0	2.1	25.2	15.9	51.2	31.9	35.2	27.3
Ni	200	4.0	6.4	6.5	2.9	105	33.7	51
Sc	18.0	3.9	19.4	17.3	5.12	32.0	27.4	29.4
Cr	210		34	0.7	—	232	116	116
V			174			258		244
Rb	49	181	55	73	138	45	24	57
Cs			0.17			0.28		0.30
Sr	680	21	680	570	177	745	630	821
Ba	690	248	1412	1530	1294	1078	841	993
Zr	210	598	322	413	571	84	121	163
Y	19	34	39	33	24	19	16	20
La	38.9	83.2	61.0	68.2	61.4	10.6	16.2	17.7
Ce	75.0	124.0	130.6	130	99.6	22.3	33.2	38.3
Nd	27.7	46.5	54.9	59.8	44.9	12.9	14.3	15.5
Sm	7.34	8.57	11.9	11.3	7.13	3.02	3.56	4.48
Eu	2.33	0.79	4.66	4.03	1.34	1.21	1.10	1.47
Tb	0.74	1.13	2.47	1.34	0.84	0.72	0.39	0.88
Yb	2.43	3.28	2.50	2.86	2.73	1.62	1.68	1.73
Lu			0.35			0.23		0.25
Hf	5.78	15.50	7.76	10.0	13.9	2.26	3.42	3.97
Ta	4.20	4.14	3.20	4.15	3.45	0.1>	0.33	0.27
Nb			48			3.6		5.2
Th	5.61	25.60	6.59	10.10	16.7	0.83	3.67	2.79

⁽¹⁾Major elements: wet chemistry (by H. Haramura), trace elements: INAA and XRF (Univ. Toronto).

⁽²⁾Major elements: XRF (Univ. Toronto), trace elements: INAA and XRF (Univ. Toronto).

⁽³⁾Major elements: XRF (Univ. Tokyo), trace elements: INAA and XRF (GSJ).

It is always cautioned in the text books of isotope geology that one should be very careful in discriminating a real isochron from a two-component mixing line in the isochron diagram (see Chapter 9 of Faure, 1986). A $^{87}\text{Sr}/^{86}\text{Sr}$ -1/Sr diagram is commonly used to identify whether a linear line in a $^{87}\text{Sr}/^{86}\text{Sr}$ - $^{87}\text{Rb}/^{86}\text{Sr}$ isochron diagram is a real isochron or just a mixing line. If a suite

of rocks initially had a same $^{87}\text{Sr}/^{86}\text{Sr}$ ratio but has various $^{87}\text{Rb}/^{86}\text{Sr}$ ratios, it should not necessarily form a single line in a $^{87}\text{Sr}/^{86}\text{Sr}$ -1/Sr diagram after the Rb-Sr clock started. On the other hand, if a suite of rocks is formed by binary mixing between two end members with different $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, it should make a linear line not only in a $^{87}\text{Sr}/^{86}\text{Sr}$ - $^{87}\text{Rb}/^{86}\text{Sr}$ diagram but also in a $^{87}\text{Sr}/$

Fig. 4. Chondrite-normalized REE patterns. Shaded zones in (b) and (c) show the variational range for the younger basalts in (a). Chondrite values are from Nakamura (1974).

^{86}Sr -1/Sr diagram (Faure, 1986). In the case of the Rb-Sr system of OTG, it naturally has an actual age component at least of 5.5 Ma. We, thus, should consider the correlation of “excess” com-

ponent of the system; i.e., $^{87}\text{Sr}/^{86}\text{Sr}$ ratios at 5.5 Ma (solid squares in Fig. 5(a)). A straight mixing line is drawn between mugearites-trachytes and rhyolites in a $^{87}\text{Sr}/^{86}\text{Sr}$ -1/Sr diagram (Fig. 5(b)).

Fig. 5. Diagrams showing the evidence of magma mixing for mugearites, trachytes and rhyolites belonging to OTG. a): Rb-Sr isochron diagram. Open squares show the present day $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ($^{87}\text{Sr}/^{86}\text{Sr}_p$), giving the age of $6.8 \pm 0.3 \text{ Ma}$ (Iwata et al., 1988), while solid squares are ratios at 5.5 Ma [$^{87}\text{Sr}/^{86}\text{Sr}_{(5.5 \text{ Ma})}$]. b): $^{87}\text{Sr}/^{86}\text{Sr}_{(5.5 \text{ Ma})}$ vs. $1/\text{Sr}$ relationship. Solid tick marks with plain texts show mixing ratios between a mugearite with 50 wt% SiO_2 and a rhyolite with 72 wt% SiO_2 , while dotted marks with italic texts are those between trachytes with 66–67 wt% SiO_2 and a rhyolite. c): Sr vs. Rb concentration relationship. d): $^{87}\text{Sr}/^{86}\text{Sr}_{(5.5 \text{ Ma})}$ vs. SiO_2 relationship. Solid line is a calculated binary mixing line between basic and acidic end members. e): Silica variation diagrams for selected oxides (K₂O, TiO₂ and Na₂O). All data plotted in these diagrams are for the same samples used to calculate the Rb-Sr isochron age by Iwata et al. (1988). $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and Rb and Sr contents are taken from Iwata et al. (1988), and major element concentrations are from Kurasawa (1984), this study and unpublished data of E. Takahashi. Mixing line shown in b)–e) is a calculated one between two end members, having maximum and minimum $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (No. 9 and No. 14 of Iwata et al., 1988).

Solid tick marks with plain texts show mixing ratios between a mugearite with 50 wt% SiO₂ and a rhyolite with 72 wt% SiO₂, while dotted marks with italic texts are those between trachytes with 66–67 wt% SiO₂ and a rhyolite. Since there is a negligible variation between mugearites and trachytes in Figs. 5(a) and 5(b), the basic end member which actually mixed with rhyolites could be either mugearites or trachytes. In addition to this diagram, a binary mixing line should be drawn in any element-element diagrams in the case of magma mixing. Some diagrams are also shown in Figs. 5(c)–(e). Clear mixing lines are again drawn among these volcanic rocks except for K₂O. In the K₂O variation, a relatively good correlation exists between trachytes and rhyolites. This might suggest that the real magma mixing could have happened between trachytes and rhyolites but not between mugearites and rhyolites. Further petrographic studies should be necessary to determine which is the basic end member for magma mixing, mugearite or trachyte. Nevertheless, magma mixing between mugearites or trachytes and rhyolites is proved to be a possible mechanism to form a pseudo-isochron in the Rb-Sr isotopic system.

Basaltic magma influx for the composite magma eruptions

Mugearites, differentiated basaltic rocks having 50–52 wt% SiO₂, in Oki-Dogo Island were once considered to belong to the OBG (Uchimizu, 1966; Xu, 1988). Iwata *et al.* (1988) was the first to recognize the genetic relationship between such mugearites and trachyte-rhyolites of OTG based on their Rb-Sr isotopic study. Fujimaki *et al.* (1989, 1991), on the other hand, considered that these mugearites should compose an independent volcanic group stratigraphically between OTG and OBG. Our current study, however, elucidated that these mugearites should be included into OTG as was already mentioned. It should be emphasized that basaltic magmas, even though moderately differentiated in mafic minerals, had played an important role on the evolution and eruption of highly differentiated trachyte and alkali rhyolite

magmas. These mugearites, erupted between older LILE-enriched basalts and younger OIB-type basalts, are very important in considering the temporal variations of basalt geochemistry in Oki-Dogo Island.

“ARC-TYPE” VOLCANICS WITH HIGH LILE/HFSE RATIOS AND ITS TECTONIC SIGNIFICANCE

As was mentioned above, basalts and andesites of 18–19 Ma have high LILE/HFSE ratios, which are usually believed to be a characteristic signature for volcanic rocks erupted in the subduction zone. There are, however, some lines of circumstantial evidence to suggest that these volcanic rocks did not erupt in the tectonic setting of active subduction zone but rather inside the back-arc rift system:

(1) As was already reviewed, the existence of Early Proterozoic gneiss in Oki-Dogo Island is considered to indicate that this island is one of continental fragments, which was left behind the Japanese Island during the opening of the Japan. There is an E-W trending volcano-tectonic graben, named Shindi folded belt, between Oki-Dogo Island and the mainland SW Japan, and it represents the southernmost end of the back-arc rift system related to the opening of the Japan Sea. The Japan Sea was supposed to be in the middle of active opening when HFSE-depleted basaltic rocks erupted at 18–19 Ma in Oki-Dogo Island. The HFSE-depleted basaltic rocks in Oki-Dogo are, thus, considered to have erupted on the structural high inside the back-arc rift system during the extensional basin and range formations.

(2) Far southward in Shikoku Island, closer to the Nankai Trough, CO₂-rich lamprophyre dikes intruded at 17.7 ± 0.5 Ma (Uto *et al.*, 1987), almost at the same time when the HFSE-depleted alkalic rocks erupted in Oki-Dogo. These dike rocks are highly SiO₂ undersaturated alkalic rocks, carrying abundant ultramafic nodules (Goto and Arai, 1987). No HFSE depletion nor LILE enrichment in these lamprophyres (Uto, unpublished) excludes the possibility of the supply of the LILE-enriched fluids from the downgoing oceanic slab

to the wedge mantle of Southwest Japan at 18 Ma. Uto *et al.* (1987) suggested that the northern Philippine Sea Plate was under the final stage of spreading and should not have subducted beneath Southwest Japan when the lamprophyre dikes intruded into Shikoku Island. The boundary between the Philippine Sea Plate and Southwest Japan was considered to be a transform fault (Uto *et al.*, 1987).

(3) The occurrence of HFSE-depleted and LILE-enriched basalts is not necessarily limited to subduction zones and some of such basalts do occur in non-island-arc tectonic environments, such as in extensional continental interior (e.g., Rio Grande Rift: Dungan *et al.*, 1986; Big Pine volcanic field: Ormerod *et al.*, 1991; Colorado River Trough: Bradshaw *et al.*, 1993). Geochemical characteristics of the 18–19 Ma basalts in Oki-Dogo should not be enough to define the tectonic setting of the island when these basalts erupted. In addition, the basaltic rocks of KF are enriched only in K₂O and Ba, but not in Rb, Cs, LREE and Th, comparing with alkalic basalts in the active island-arc.

What is the origin for the high LILE/HFSE ratios in alkali volcanic rocks in Oki-Dogo? The following may be one possible mechanism.

The upper mantle lithosphere beneath the Oki-Dogo Island had been contaminated by subduction fluids for long time at the Asian continental margin before the opening of the Japan Sea. Hydrous minerals like phlogopite and/or amphibole should have been formed due to the metasomatic reaction between lithospheric mantle and subduction fluids. Phlogopite is a mineral known to be very rich in K and Ba, but not in LREE, Th and HFSE (Giannetti and Luhr, 1990). Menzies *et al.* (1987; Fig. 5(d)) showed the normalized trace-element pattern enriched in K, Ba and Sr but not in LREE, Th and HFSE for a glimmerite; "phlogopite-rich nodule with variable amounts of clinopyroxene and/or ilmenite" (Erlank *et al.*, 1987). If subduction-related fluid reacted with lithospheric mantle to form phlogopite, Ba, K and Sr should have been selectively trapped in phlogopite-bearing peridotites, but LREE, Th and HFSE should not. During

formation of many horst and graben systems in the back-arc region, the continental lithosphere should have been stretched and thinned. Thinned lithosphere should also have been heated by the upwelling asthenosphere as is now observed in the Basin and Range region in western USA. When contaminated mantle was heated, it might have partially melted and supplied Ba- and K-enriched magmas to the surface or at least contaminated Ba and K easily during the ascent of magmas originated from the asthenosphere. Similar process is suggested to explain the origin of Nb- and Ta-depleted basalts in the Basin and Range region, United States (Ormerod *et al.*, 1991; Bradshaw *et al.*, 1993).

TEMPORAL VARIATION IN BASALT GEOCHEMISTRY

There are five volcanic groups accompanying eruptions of alkali basaltic rocks in Oki-Dogo Islands; KF, OTG, OBG, SBG and MBG. Xu (1988) and Fujimaki *et al.* (1991) made geochemical studies on these basaltic rocks in term of trace element and Sr isotopes. Their main observations are; (1) significant difference in geochemistry, especially of LILE/HFSE ratios between basalts of KF and those of younger three basalt groups, (2) the occurrence of some basaltic rocks having high Na₂O/K₂O ratios only in OMB, (3) general geochemical similarities between mugearites and younger basalts, and (4) ⁸⁷Sr/⁸⁶Sr initial ratios of volcanics generally decrease with the decreasing age of eruption.

In the current study, we clarified the age relationships of these basalts. In addition, we added concentrations of some trace elements, especially of REE, which Xu (1988) did not present. The temporal variations of some element/element ratios are shown in Fig. 6. Spidergrams of these rocks are also shown in Fig. 7. From these diagrams, followings are significant:

(1) There is a big gap not only in geochemistry but also in ages of activity between KF and younger four volcanic groups. As younger volcanic groups are geochemically similar to each other

Fig. 6. Temporal variations in some element/element ratios for basaltic rocks in Oki-Dogo Island. Solid circles: KF, open triangles: OTG, open squares: OBG, SBG, and MBG.

including mugearites of OTG, the temporal variation in basalt geochemistry in Oki-Dogo Island should be appropriately expressed as the geochemical discontinuity between Early Miocene

basalts and Pliocene-Pleistocene ones.

(2) Mugearites of OTG have element/element ratios similar to younger basalt groups, suggesting that a parental basalt magma for chemically diverged OTG is similar to younger ones, but is different from the Miocene basalts.

(3) Even though there are significant differences in some LILE/HFSE ratios, such as K_2O/TiO_2 , Ba/Ta and Ba/La , some ratios like Th/Zr , La/Th and La/Hf show no significant variations between the basalts of KF and younger basalts.

(4) Basalts with high Na_2O/K_2O ratios are not restricted to OBG as suggested by Xu (1988), but also appear in younger SBG and MBG.

Since all elements, except for Na_2O , plotted in Fig. 6 are moderately to highly incompatible ones, these element/element ratios may have not been modified significantly during fractional crystallization from a single parental magma. The variation of such ratios, thus, should roughly reflect that of primary magmas. In addition, there is a large difference in TiO_2/K_2O , Ba/Ta and Ba/La between older and younger basalts even though Th/Zr , La/Th and La/Hf ratios are generally similar between the two. This suggests that the source mantle materials are significantly different between older and younger basalts especially in terms of Ba and K_2O .

As has already been suggested by Nakamura *et al.* (1989), the Pliocene-Pleistocene alkali basalts in Oki-Dogo Island have intraplate geochemical affinity (Fig. 7) and have been little affected by subduction-related fluids. On the other hand, the Early Miocene basalts have high ratios in some LILE/HFSE ratios similar to those of subduction-related Quaternary basalts in NE Japan. These Early Miocene basalts, however, are not considered to have erupted in an active subduction zone as mentioned in the previous chapter. It is, thus, considered that the temporal variation in the source mantle materials should not be due to the recent addition or subtraction of subduction-related fluids to the originally homogeneous mantle.

As has been mentioned before, the volcanic rocks of KF erupted in the middle of back-arc

Fig. 7. Primitive mantle-normalized spidergrams. Primitive mantle values are from Sun and McDonough (1989). Shaded zones in (b) and (c) show the variational range for younger basalts in (a).

opening while the younger basalts did considerably after the cessation of the opening. The big difference in basalt geochemistry should somewhat reflect the difference in tectonic environment when these basalts erupted. According to Ormerod *et al.* (1991) and Bradshaw *et al.* (1993), there are time progressive chemical variations from the high LILE/HFSE syn-extensional basalts with high $^{87}\text{Sr}/^{86}\text{Sr}$ to the low LILE/HFSE post-extensional basalts with lower $^{87}\text{Sr}/^{86}\text{Sr}$ at some basaltic provinces in the Basin and Range, western United States. These authors suggest the time progressive change in source materials from the lithospheric mantle to the asthenospheric mantle. Such a relationship might also be the case for the origin of temporal difference in source mantle geochemistry in Oki-Dogo Island, because the island is built on the Proterozoic continental lithosphere. The Miocene basalts might be originated from the lithospheric mantle when the lithospheric thinning was proceeding during the active back-arc rifting, while the Pliocene-Pleistocene basalts are from the asthenospheric mantle or the deeper plume mantle (Nakamura *et al.*, 1989) after the thinned lithosphere has cooled sufficiently not to contaminate the upwelling magmas.

As for the origin of $\text{Na}_2\text{O}/\text{K}_2\text{O}$ variation among younger basalts, there should have been conditions of magma generation at multiple depths beneath Oki-Dogo Island during Pliocene-Pleistocene time. This is because that Na_2O content in primary magmas generated from mantle peridotite varies significantly depending on the P - T conditions of partial melting (e.g., Takahashi and Kushiro, 1983).

CONCLUSIONS

(1) Alkalic volcanism took place discontinuously for four times in Oki-Dogo Island; 19–18 Ma, 5.5–5.4 Ma, 4.3–2.4 and 1.3–0.6 Ma, and there was a significantly long repose period of volcanic activity between 18–5.5 Ma.

(2) Chemically diverged magmas from mugearites to alkali rhyolites erupted in a relatively short period at 5.5 Ma. The previously reported

Rb-Sr whole rock age of 6.8 Ma does not represent the age of eruption, but rather has some pseudo-isochron component, which is due to the magma mixing between mugearite/trachyte and rhyolite. Simultaneous eruption of mugearites, differentiated alkali basalt magmas, with trachytes and rhyolites suggests that a basaltic magma influx was important for the formation and eruption of compositionally diverged magmas.

(3) There is a big difference in geochemistry between the 19–18 Ma basalts and younger basalts; the former have LILE/HFSE ($\text{K}_2\text{O}/\text{TiO}_2$, Ba/Ta etc.) ratios significantly higher than the latter.

(4) Basalts of 19–18 Ma erupted on a structural high made up of Proterozoic lithosphere inside the back-arc rift system, when the opening of the Japan Sea was ongoing and no oceanic plate was subducting beneath the Oki-Dogo. LILE-enriched characteristics of these basalts may be due to the considerable contribution of phlogopite-enriched continental lithosphere, which had been contaminated by subduction-related fluids for a considerable time at the Asian continental margin.

(5) Pliocene-Pleistocene basalts, erupted considerably after the cessation of the opening of the Japan Sea, may be derived from the asthenosphere or the deeper plume mantle geochemically similar to the source materials for Oceanic Island Basalts.

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