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Amphiboles in the Paleogene Namariyama Granophyres, Eastern San'in District, Southwest Japan

By

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with 2 Tables, 17 Text-figures

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Abstract: In the eastern San'in district, a volcano-plutonic complex of the late Paleogene age is widely developed. The Namariyama granophyres belonging to the Namariyama intrusive rocks are one of the main constituting members of the complex. Judging from the mode of occurrence and textures, amphiboles in the granophyres are inferred to be classified into the following three groups, that is, amphiboles -I, II and III in the order of crystallization. Amphibole-I is scarsely zoned, and is titaniferous ferroan pargasite to titaniferous ferroan pargasitic honblende in composition. Amphibole-II is mainly composed of magnesio hornblende. It shows the zonal structure represented by increase of Si from core to rim in each grain. It is normally zoned in Si-poor crystal and reversely zoned in Si-rich one with respect to the mg-value. Amphibole-III is actinolitic hornblende to actinolite. It has zonal structure and Si and mg-value increases from core to rim.

In the progress of the crystallization of amphiboles, Si increases and Al, Ti, Na and K decrease. On the other hand, mg-value decreases in the early stage and increases in the late stage during the crystallization of the Namariyama granophyres.

Si enrichment in the later stage of crystallization can be explained by increase of silica activity in the liquid with crystallization. Increase of oxygen fugacity in the later stage of crystallization has resulted in the appearence of magnetite and the increase of mg-value of amphibole.

Ti/Al ratio of amphibole in the Namariyama granophyres is the highest among those in the late Cretaceous to Paleogene plutonic rocks in the Innerside of Southwest Japan. This fact indicates that amphibole in the Namariyama granophyres has been crystallized under the condition of comparatively high temperature at shallow level.

Appearence of Ti-pargasite supports the activity of basic magma has been closely connected with the genesis of the Namariyama granophyres.

Contents

I. INTRODUCTION

Amphibole is one of the most significant rock-forming minerals in the calc-alkaline plutonic suites and has been described by many workers (e.g., DODGE *et al.*, 1968; HASLAM, 1968; CZAMANSKE and WONES, 1973; de ALBUQUERQUE, 1974). Most of amphiboles reported by these workers are compositionally ranging from common hornblende to actinolitic hornblende and titaniferous amphibole is rarely described. Furthermore, it has been regarded that amphiboles in the high level intrusions which often form a volcano-plutonic complex are generally poor in Al, Na+K and Ti. Recently, numerous analytical data of amphiboles in the late Cretaceous to Paleogene plutonic rocks in the innerside of Southwest Japan have been accumulated with reference to the zonal distribution of plutonic rocks (KANISAWA, 1975, 1976; TAINOSHO *et al.*, 1979; MURAKAMI, 1981; CZAMANSKE *et al.*, 1981). They claim that the the amphiboles in the San'in zone have the highest mg-value and the lowest Al-content among the Ryoke, Sanyo and San'in zone which are zonally distributed in that order from south to north. Especially in the Tamagawa plutonic rocks of the San'in zone, very low Al-content of amphibole have been reported (MURAKAMI, 1969, 1981).

Namariyama granophyres now studied are situated in the San'in zone and seem to be high level intrusions forming a volcano-plutonic complex closely associated with Kijiyama volcanic rocks and Shimokoya granite. Judging from isotopic ages, rock facies and mutual relations of plutonic rocks, the Namariyama granophyres have been correlated with the Tamagawa plutonic rocks (SASADA *et al.*, 1979). Through the mineralogical studies by EPMA analyses for the amphiboles, the present author has found Ti-pargasite in spite of their acidic rock composition and come to the rather different conclusions on the petrogenesis from previous works.

This paper presents the description of the amphiboles in the Namariyama granophyres and their equivalents, comparing especially with those of the other plutonic suites in the Innerside of Southwest Japan and the petrogenetic significance of the occurrence of Ti-pargasite will be discussed.

II. GEOLOGICAL SETTING

Generallized geological map in the Okutsu-Misasa area eastern San'in district is shown in Fig. 1. The greater part of the area is occupied by the late Cretaceous to early Paleogene igneous rocks. Mutual relations among these igneous rocks are shown in Fig. 2. They have been divided into the Cretaceous volcanic rocks, Imbi intrusive rocks, Paleogene volcanic rocks and Namariyama intrusive rocks in the order of the activity (SASADA *et al.*, 1979).

The Cretaceous volcanic rocks are made up mainly of andesitic to rhyolitic pyroclastic rocks with lesser amounts of lava. They are intruded by the Imbi intrusive rocks and the Namariyama intrusive rocks.

The Imbi intrusive rocks are further divided into the late Cretaceous plutonic rocks (stage 1) and the early Paleogene plutonic rocks (stage 2) (SAKIYAMA and IMAOKA, 1981; SAKIYAMA, 1983). The activity of the Imbi intrusive rocks of stage 1 began with tonalitic small stocks succeeded by the emplacement of granitic batholith. Based on the K–Ar

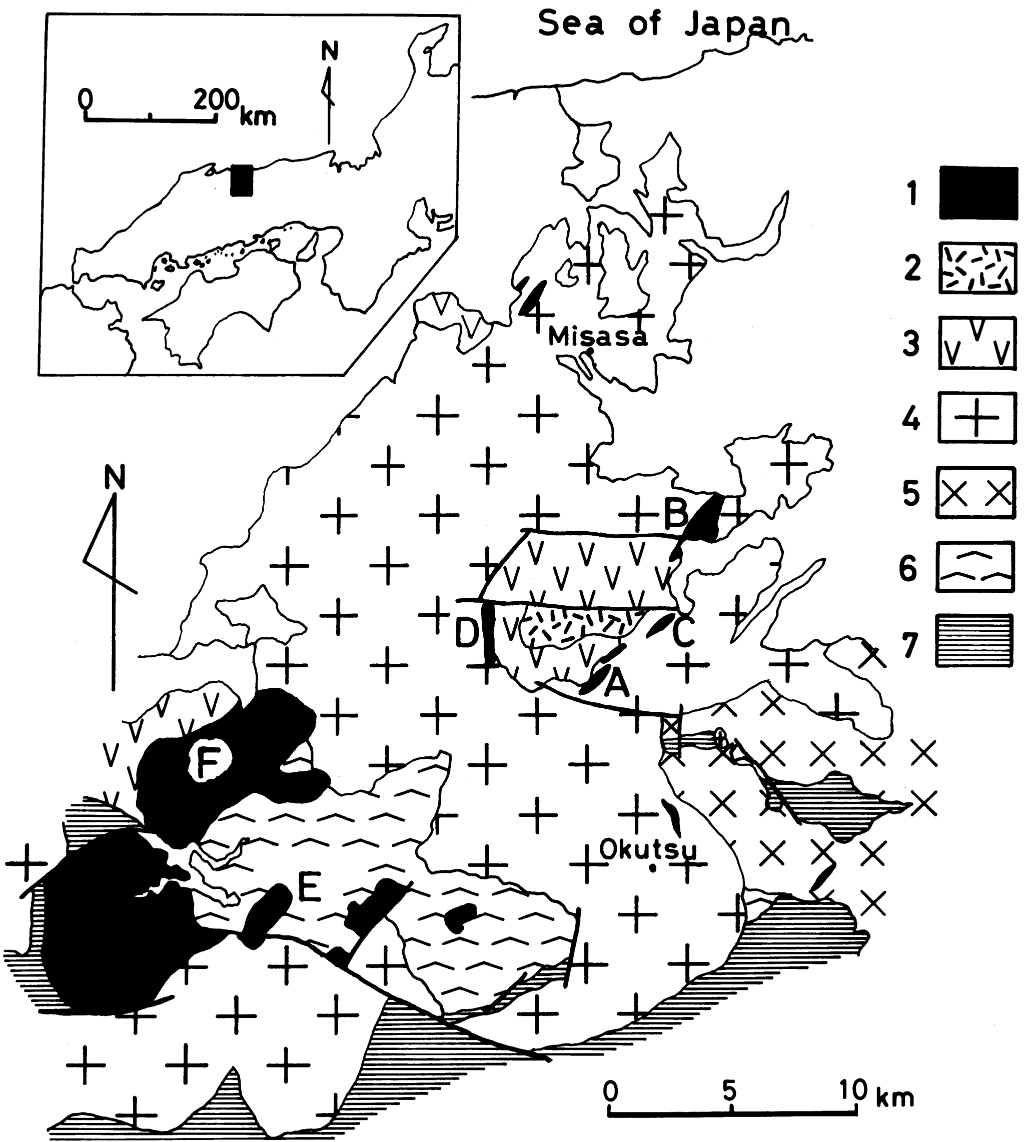

Fig. 1. Generallized geological map of Okutsu-Misasa area, eastern San'in district. (modified from Sasada *et al.* (1979)).

1 and 2: Namariyama intrusive rocks (1. Namariyama granophyres, 2. Shimokoya granite), 3. Paleogene volcanic rocks, 4. Imbi intrusive rocks stage-2, 5. Imbi intrusive rocks stage-1, 6. Cretaceous volcanic rocks, 7. "Paleozoic".

A to D are the main masses of Namariyama granophyres. (A. Ningyōsen mass, B. Namariyama mass, C. Ningyōtōge mass, D. Takamaruyama mass), E. Amagoisen mass, F. Yubarako granophyre intrusion.

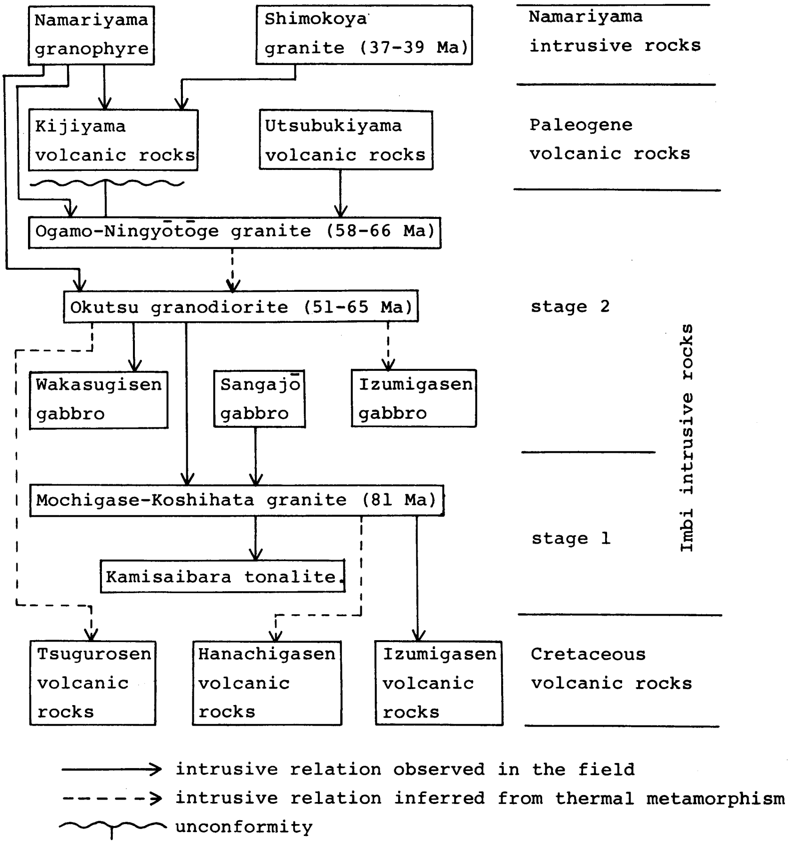

FIG. 2. Mutual relation of the igneous rocks in the Okutsu-Misasa area.
( ): K–Ar age data from Shibata and Yamada (1965),
Kawano and Ueda (1966) and Shibata (1979).

age and mineralogy, they are correlated with Hiroshima plutonic rocks in the Sanyo zone (SHIBATA, 1979; SAKIYAMA, 1982a). The activity of the Imbi intrusive rocks of stage 2 began with the intrusion of gabbroic small stocks, through the tonalitic to granodioritic stocks often forming a zoned pluton and succeeded by the emplacement of granitic batholith. The K–Ar ages of these intrusive rocks are 66–51 Ma (SHIBATA and YAMADA, 1965; KAWANO and UEDA, 1966; SHIBATA, 1979).

The Paleogene volcanic rocks unconformably overlie on the Imbi intrusive rocks and are intruded by the Namariyama intrusive rocks. The Kijiyama volcanic rocks, having the largest exposure among the Paleogene volcanic rocks in the area, are made up mainly of andesitic to dacitic lava with lesser amounts of pyroclastic rocks.

The Namariyama intrusive rocks are composed of various rock types indicating the hypabyssal facies such as fine-grained granite to granodiorite, granite porphyry, granophyre and plagiophyre. The Shimokoya granite, one of the Namariyama intrusive rocks, is composed of fine-grained biotite granite to hornblende biotite granodiorite. The K–Ar determinations on the biotite in the Shimokoya granite suggest the emplacement during middle Paleogene (37–39 Ma) (SHIBATA and YAMADA, 1965; KAWANO and UEDA, 1966). The Namariyama granophyres are main rock facies in the Namariyama intrusive rocks and already have been described by MURAYAMA and OZAWA (1961), YAMADA (1961), SUGIYAMA (1965) and HONMA (1975). They occur as dykes or small stocks. The Namariyama granophyres and Shimokoya granite intrude into the Kijiyama volcanic rocks. It has been inferred that the intrusive rocks form a volcano-plutonic complex associating with the Kijiyama volcanic rocks. Some granophyric masses correlated with the Namariyama granophyres are exposed in the Yubara area. The Yubarako granophyre has the largest exposure in the studied area and has been described in detail by SASADA *et al.* (1982). According to them, it is occupied mainly by leucocratic porphyritic rocks composed of granophyre, granite porphyry and fine-grained granophyre and their emplacement was preceded by the intrusion of small bodies of the granodiorite porphyry. The Amagoisen mass and other intrusive ones distributed to the east are composed mainly of granophyre and granite porphyry and intrude the Tsugurosen volcanic rocks belonging to the late Cretaceous· volcanic rocks (UEDA, 1979). These granophyric masses are arranged in the direction of NE–SW, showing the distinct contrast to that trending E–W of the Imbi intrusive rocks.

III. PETROGRAPHY

The main facies of the Namariyama granophyres are classified into the facies-1 and facies-2 on the basis of their mineral assemblages and the texture of groundmass.

The facies-1 is composed of plagiophyre. Phenocrysts of this rock facies are composed of plagioclase, brownish amphibole, magnetite and ilmenite with or without clinopyroxene and orthopyroxene. Glomero-porphyritic aggregates of pyroxene, plagioclase and magnetite are often observed. Groundmass of this rock facies is composed of fine-grained plagioclase lath with interstitial quartz or graphic intergrowth of quartz and alkali-feldspar. Minute magnetite is despersed throughout the groundmass. Greenish amphibole rarely occupies interspace of plagioclase lath.

The facies-2 is composed of granophyre, granite porphyry, quartz diorite porphyry and so forth. Phenocrysts of this rock facies are composed mainly of plagioclase, greenish amphibole, magnetite and ilmenite with or without biotite and quartz. Groundmass is composed of graphic intergrowth of quartz and alkali-feldspar, magnetite and ilmenite. Pale green to colorless amphibole rarely occupies interspace of groundmass felsic minerals. Dark inclusions with angular shape ranging in diameter from a few centimeters to 2 meters often occur in the facies-2.

As have been seen easily in Fig. 3, the facies-1 and -2 are situated in the outer and the inner parts of the intrusive body, respectively. Both facies are gradually changed in the Ningyōsen mass (A in Fig. 3). On the other hand, they have sharp contact in the Namariyama (B) and Takamaruyama (D) masses, and the facies-1 has been thermally metamorphosed by intrusion of the facies-2. The Ningyōtōge mass (C) is composed only facies-1.

IV. WHOLE ROCK CHEMISTRY

Chemical compositions of rocks bearing analysed amphiboles are listed in Table 1.

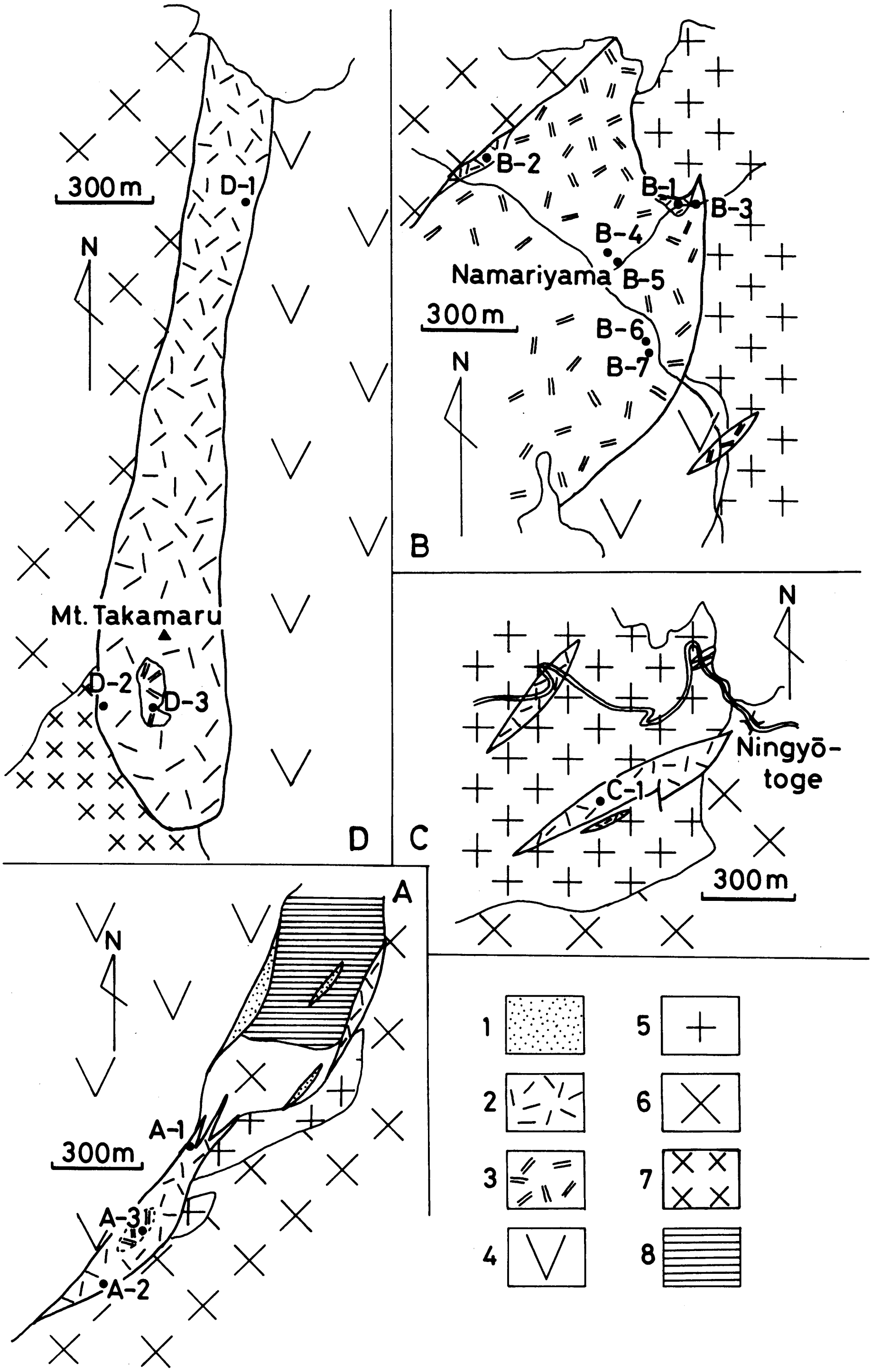
300m
N
D-1
Mt. Takamaru
D-2
D-3
D
B-2
B-1
B-3
B-4
Namariyama
B-5
300m
B-6
B-7
N
B
N
Ningyō-
toge
C-1
C
300m
A
N
A-1
300m
A-3
A-2
1
2
3
4
5
6
7
8

TABLE 1. CHEMICAL COMPOSITIONS OF ROCKS CONTAINING ANALYZED AMPHIBOLES

No.	A-1*	A-3**	B-2*	C-1*	D-2**	D-3**	E-1*
Facies	1	2	1	1	1	2	2
SiO_2	65.52	63.13	73.28	75.29	72.21	68.52	74.18
TiO_2	0.80	0.88	0.30	0.27	0.40	0.57	0.34
Al_2O_3	15.94	16.73	14.21	13.77	14.71	15.82	13.93
FeO_t	4.73	5.66	1.97	1.80	2.43	3.83	2.12
MnO	0.18	0.32	0.07	0.06	0.04	0.06	0.05
MgO	1.80	2.41	0.56	0.30	0.31	0.93	0.57
CaO	4.17	4.51	1.71	1.27	1.41	2.63	1.64
Na_2O	3.90	3.84	4.68	4.93	5.03	4.54	4.98
K_2O	2.58	2.38	3.25	3.14	3.41	3.06	3.09
P_2O_5		0.14			0.05	0.03	
Total	99.62	100.00	100.03	100.83	100.00	99.99	100.90

analyst: T. Sakiyama

FeO_t: total Fe as FeO, * EPMA analyses ** XRF analyses, recalculated to 100% excluding water content

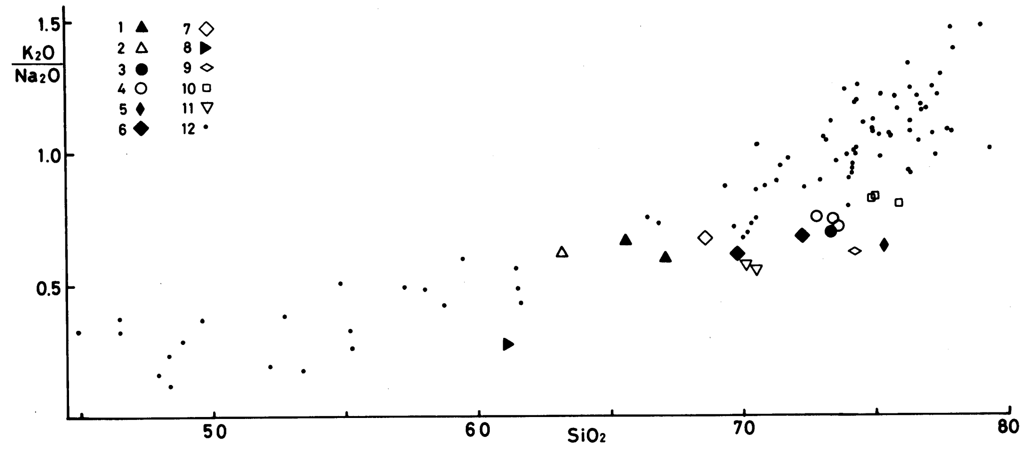

FIG. 4. SiO_2 versus K_2O/Na_2O diagram of the Namariyama granophyres.

1 to 8: Namariyama granophyres; 1 and 2: Ningyōsen mass (1. facies-1; 2. facies-2); 3 and 4: Namariyama mass (3. facies-1; 4. facies-2); 5: Ningyō-tōge mass (facies-1); 6 and 7: Takamaru-yama mass (6. facies-1; 7. facies-2); 8: minor dyke rock in the Kijiyama volcanic rocks (facies-1); 9: Amagoisen granophyre; 10 and 11: Yubarako granophyre (10. leucocratic porphyritic rocks; 11. granodiorite pophyry); 12: Imbi intrusive rocks.

FIG. 3. Geological map of Namariyama granophyres and localities of analyzed samples.

1 to 3: Namariyama granophyres (1: felsite; 2: facies-1; 3: facies-2); 4: Kijiyama volcanic rocks; 5 to 7: Imbi intrusive rocks (5: coarse-grained biotite granite; 6: coarse-grained hornblende biotite granite; 7: medium-grained hornblende biotite granodiorite); 8: "Paleozoic".

A to D are the same as in Fig. 1.

Some samples were analysed by the electron probe micro analyzer JXA–5A in the Hiroshima University. Fusion of rock samples was made by the Iridium-strip heater in the Institute for Thermal Spring Reserch, Okayama University according to the method established by Nicholls (1974) and reformed by Sakiyama *et al.* (1978). The data were corrected by the method proposed by Bence and Albee (1968). Other samples were analysed by X-ray fluorescence JSX-6037 in the Shimane University according to the method by Kobayashi *et al.* (1981).

Chemical compositions of the Namariyama granophyres range from 61 to 75 wt. % in SiO_2 content and are different among the masses, however the compositional range is narrow in each mass. That is, SiO_2 content is 63 to 67 wt. % in the Ningyōsen mass, 69 to 72 wt. % in the Takamaruyama mass, 73 to 74 wt. % in the Namariyama mass and 75 wt. % in the Ningyōtōge mass. Generally speaking, SiO_2 content of facies 1 is slightly higher than that of facies 2 in each mass as shown in Fig. 4.

As have already been pointed out by many workers, the K_2O/Na_2O ratio of the middle to late Paleogene igneous rocks in the San'in zone is lower than that of late Cretaceous to early Paleogene igneous rocks (Imaoka and Murakami, 1979; Murakami, 1981; Sakiyama and Imaoka, 1981; Sasada *et al.*, 1982). The K_2O/Na_2O ratio of the Namariyama granophyres have a general character of the middle to late Paleogene igneous rocks in the San'in zone.

V. Mode of Occurrence and Chemical Compositions of Amphiboles

Typical modes of occurrence of amphiboles in the Namariyama granophyres are shown in Fig. 5. Some amphiboles were chemically analysed by the electron probe micro analyzer. The selective data are listed in Table 2 and $Al^{IV}-Na+K$, mg–Si, Al^{IV}–Al^{VI} and Ti–Al diagrams are shown in Figs. 6, 7, 8 and 9, respectively.

As mentioned below, three kinds of amphiboles called I, II and III in the order of crystallization sequence are observed in the Namariyama granophyres. Amphibole-I is brownish and generally occurs as euhedral to subhedral phenocryst in the facies-1 with no relation to the whole rock composition (Fig. 10). They often have opacite rim or are replaced by amphibole-II at their marginal part. Moreover, the amphibole-I also occurs as irregularly-shaped core of amphibole-II phenocryst in the facies-2 (Fig. 5). These amphiboles are titaniferous ferroan pargasite to titaniferous ferroan pargasitic hornblende by the Leake's nomenclature (Leake, 1968). They are scaresely zoned and each crystal has different composition with each other in a sample. In this paper, the amphibole-I is called Ti-pargasite for convenience.

Amphibole-II is greenish and mainly occurs as euhedral to subhedral phenocryst in the facies-2. Furthermore, it rarely occurs as interstitial crystal in the groundmass of the facies-1. These amphiboles are mainly magnesio hornblende by Leake's nomenclature and have lower mg-value than the amphibole-I. They have zonal structure, increasing in Si and decreasing in Al, Ti, Na and K from core to rim. On the other hand, Si poor crystals are normally zoned and Si rich crystals are reversely zoned with respect to mg-value.

Amphibole-III is pale green to colorless. It rarely occurs in the groundmass of the facies-2 and is interstitial against quartz and alkali-feldspar. It is mainly actinolitic hornblende to actinolite by Leake's nomenclature and has still higher mg-value than the amphibole-II. It has distinct zonal structure, increasing in Si and mg-value (Fig. 11) and decreasing in Al, Ti, Na and K from core to rim.

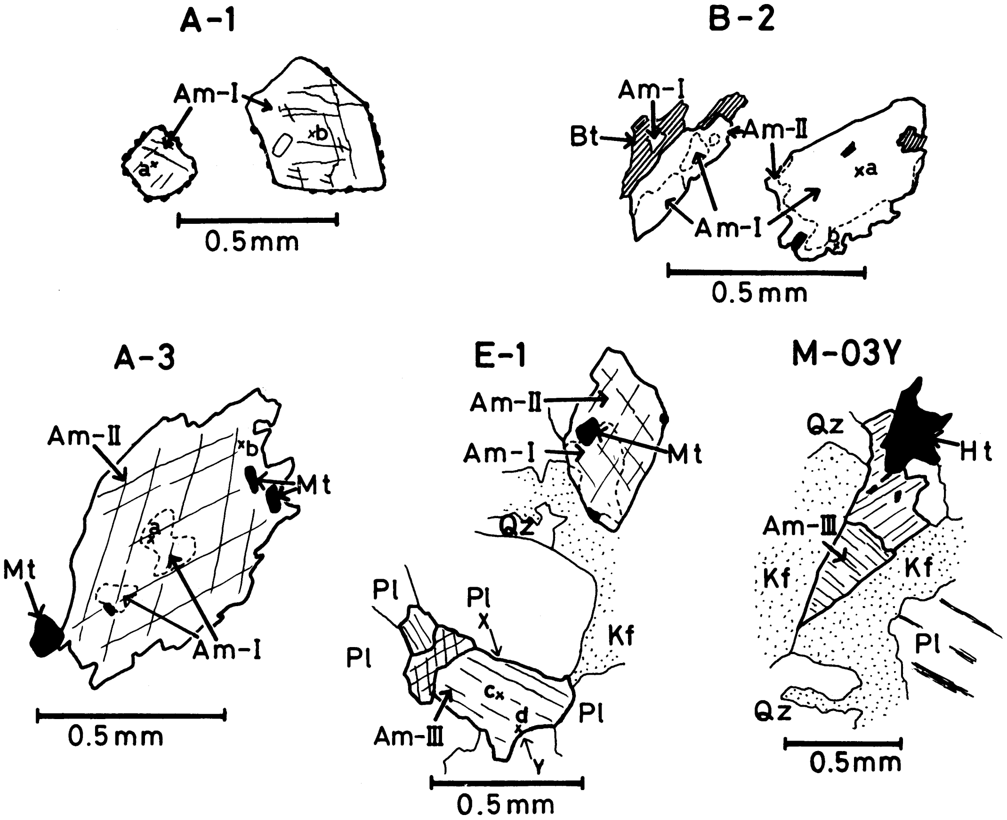

FIG. 5. Sketches showing the mode of occurrence of amphiboles.
A–1, A–3, B–2 and E–1 are same as in Fig. 3.

A–1: amphibole-I phenocryst with opacite rim, facies-1 of Namariyama granophyres. A–3: Amphibole-II phenocryst with relic of amphibole-I, facies-2 of Namariyama granophyres. B–2: Amphibole-I phenocryst replaced by amphibole-II at the marginal part, facies-1 of Namariyama granophyres. E–1: Amphiboles in the Amagoisen granophyre. Amphibole-II phenocryst includes the amphibole-I at the core part. Amphibole-III is interstitial against plagioclase and alkali feldspar. X–Y shows the traverse line given in Fig. 11. M–03Y: Amphibole-III in the Yubarako granophyre intrusion. Data are listed in SASADA *et al.* (1982). Amphibole-III is interstitial against alkali feldspar and quartz.

Am: amphibole, Bt: biotite, Pl: plagioclase, Qz: quartz, Kf: alkali feldspar, Mt: magnetite, Ht: hematite, cross: analyzed point.

TABLE 2. SELECTED AMPHIBOLE ANALYSES IN THE NAMARIYAMA GRANOPHYRES.

No.	A–1a	A–1b	A–1c	A–3a	A–3b	B–2a	B–2b	C–1a	D–2a	D–2b	D–3a	E–1a	E–1b	E–1c	E–1d
Stage	I	I	I	I	II	I	II	I	I	II	II	I	II	III	III
SiO_2	42.77	45.13	43.37	41.85	51.30	41.85	47.58	43.96	45.00	47.13	45.67	46.13	47.55	50.96	51.82
TiO_2	3.88	2.10	3.02	3.77	1.03	3.56	1.18	2.80	2.23	0.70	1.97	1.90	1.34	0.37	0.32
Al_2O_3	10.79	7.74	9.74	11.35	4.19	10.25	4.57	9.58	8.02	4.44	7.26	6.46	5.07	3.28	2.52
FeO_t	12.23	16.38	13.47	12.66	14.47	12.20	11.27	11.85	16.20	20.73	16.71	15.71	16.82	16.23	14.48
MnO	0.31	0.56	0.43	0.29	0.47	0.32	0.98	0.18	0.37	1.03	0.60	0.53	0.74	1.03	0.85
MgO	14.34	12.96	13.85	12.19	14.90	14.64	17.32	14.70	12.26	10.88	12.11	13.55	13.26	13.57	15.05
CaO	11.06	10.84	10.81	11.55	11.07	10.75	10.70	11.30	10.86	9.37	10.63	10.91	10.49	11.91	12.12
Na_2O	2.82	2.27	2.80	2.76	1.68	2.97	1.85	2.26	2.44	1.79	2.00	2.15	1.68	0.93	0.60
K_2O	0.32	0.56	0.42	0.53	0.33	0.43	0.60	0.50	0.52	0.50	0.51	0.47	0.44	0.29	0.24
Total	98.52	98.54	97.91	96.95	97.54	96.97	96.95	97.13	97.90	96.57	97.46	97.81	97.39	98.57	98.00
	Numbers of ions on the basis of 23 (0)														
Si	6.261	6.707	6.421	6.257	7.376	6.245	7.073	6.496	6.721	7.242	6.850	6.871	7.116	7.475	7.565
Ti	0.427	0.234	0.337	0.424	0.111	0.399	0.132	0.311	0.250	0.080	0.223	0.213	0.150	0.041	0.036
Al^{IV}	1.739	1.293	1.579	1.743	0.624	1.754	0.800	1.504	1.279	0.758	1.150	1.129	0.884	0.525	0.434
Al^{VI}	0.123	0.063	0.122	0.257	0.086	0.050		0.164	0.133	0.047	0.134	0.005	0.010	0.043	
Fe	1.497	2.035	1.668	1.584	1.740	1.522	1.410	1.465	2.023	2.665	2.097	1.957	2.105	1.991	1.767
Mn	0.038	0.070	0.054	0.036	0.058	0.041	0.124	0.022	0.047	0.134	0.076	0.067	0.093	0.129	0.105
Mg	3.129	2.870	3.054	2.717	3.192	3.256	3.836	3.237	2.728	2.491	2.708	3.009	2.958	2.966	3.274
Ca	1.736	1.726	1.715	1.850	1.705	1.718	1.705	1.789	1.737	1.543	1.709	1.741	1.682	1.872	1.895
Na	0.800	0.654	0.804	0.799	0.469	0.859	0.534	0.648	0.707	0.534	0.581	0.622	0.489	0.265	0.169
K	0.060	0.107	0.079	0.101	0.061	0.081	0.114	0.094	0.100	0.099	0.097	0.090	0.084	0.054	0.044
mg	0.671	0.577	0.644	0.627	0.640	0.676	0.716	0.685	0.569	0.471	0.555	0.598	0.574	0.583	0.636

FeO_t: total Fe as FeO. mg=Mg/Fe+Mn+Mg Analyst: T. Sakiyama

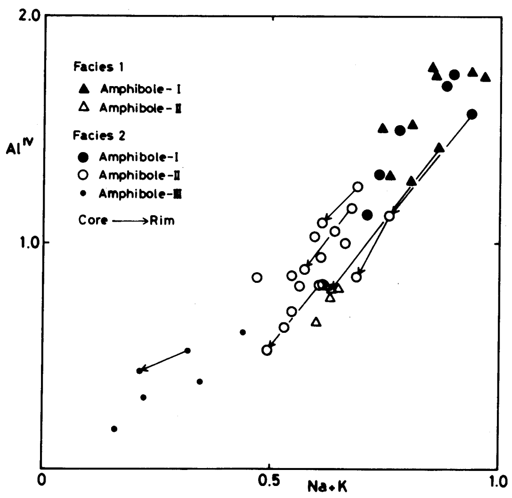

FIG. 6. Al^{IV} versus Na+K diagram of amphiboles in the Namariyama granophyres.

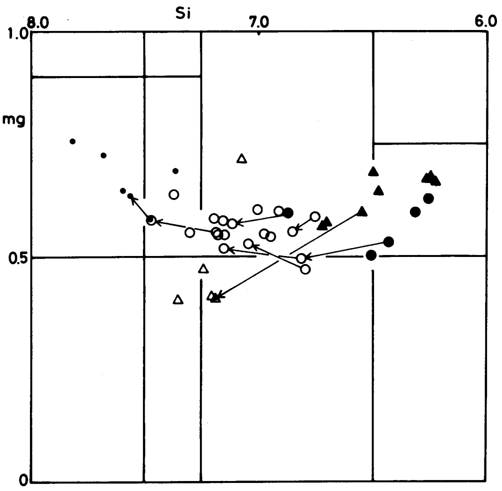

FIG. 7. mg versus Si diagram of amphiboles in the Namariyama granophyres. Symbols are same as in Fig. 6.

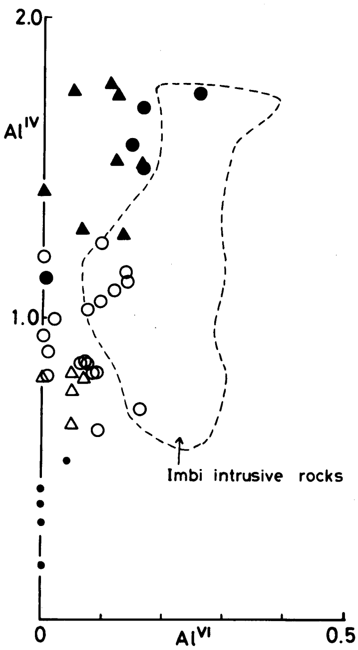

FIG. 8. Al^{IV} versus Al^{VI} diagram of amphiboles in the Namariyama granophyres. Symbols are same as in Fig. 6.

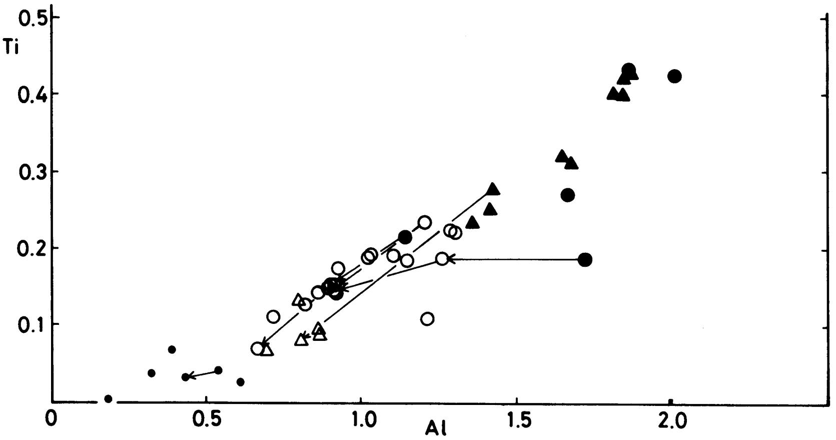

FIG. 9. Ti versus Al diagram of amphiboles in the Namariyama granophyres. Symbols are same as in Fig. 6.

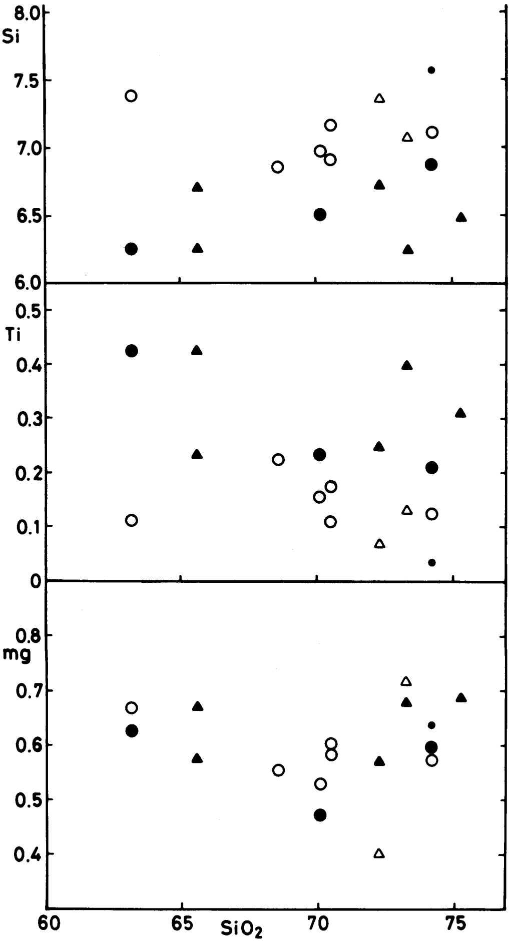

FIG. 10. Relation between SiO_2 content of whole rock and Si, Ti and mg of the amphiboles. Symbols are same as in Fig. 6.

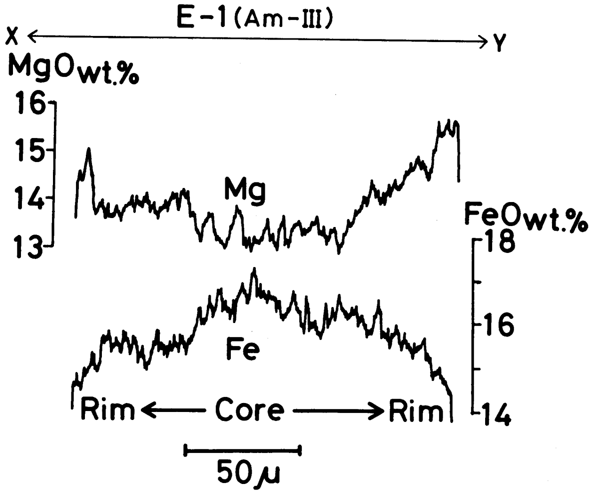

FIG. 11. Scanning profile of amphibole-III in the Amagoisen granophyre.

X–Y: traverse line shown in Fig. 5.

VI. DISCUSSION

A. Relation between Si-content and mg-value of amphiboles

Judging from the mode of occurrence and microscopic textures of the amphiboles, it is inferred that Ti-pargasite, magnesio hornblende and actinolite have been crystallized in that order. That is Al (espacially Al^{IV}), Ti, Na and K decrease and Si increases with the crystallization process. TAINOSHO (1974) has shown that Si-content of amphibole decreases with crystallization in the Ibaragi granitic complex. Furthermore, KANISAWA (1974) has described the zoned hornblende whose Si decreases and Al increases from core to rim in the Numabukuro plutonic mass. The trend of compositional change with the crystallization of amphiboles in the Namariyama granophyres is in contrast to those informations, while is rather similar to that described in the Neogene Yoshida complex by SAWADA (1978).

It must be noted that the mg-value decreases in the early stage and increases in the late stage during the crystallization of the Namariyama granophyres. KANISAWA (1976), MURAKAMI (1977, 1981) and TAINOSHO *et al.* (1979) have pointed out a distinct negative correlation between Al^{IV} and mg-value and suggested the intimate correlation of Al^{IV} in amphibole with oxygen fugacity during the crystallization. This tendency does not necessarily coincide with that of the Namariyama granophyres. In the Namariyama granophyres, variational trend of amphibole composition is linear in the Al^{IV}—Na+K and Ti–Al diagrams but is not linear in the mg-Si diagram. These facts indicate that the factor controling the variation of the Al^{IV} (or Si) may be different from that of mg-value.

Increase in temperature or oxygen fugacity has been considered to be the cause of reverse zoning on mg-value (SAKUYAMA, 1979; MASON, 1978). SAKUYAMA (1979) described the reversely zoned hornblende in andesite of Shirouma-Oike volcano, central Japan. He suggested that the reverse zoning can result from increase in temperature accompanied with magma mixing. According to him, mg-value, Al, Ca, Na and K increase and Si decreases from core to rim of amphibole in the Shirouma-Oike volcano. This tendency differs from that of the Namariyama granophyres. As mentioned above, composition of amphibole increases in Si and decreases in Al, Ti, Na and K with the crystallization in the Namariyama granophyres. On the other hand, it has generally been considered that Al (especially Al^{IV}), Ti, Na and K of amphibole increase with temperature (KOSTYUK and SOBOLEV, 1969; HELZ, 1973; RAASE, 1974). Accordingly, increase of temperature is out of harmony with the tendency of compositional variation of amphiboles in the Namariyama granophyres. Crystallization of magnetite is the most suitable way to raise only the mg-value without changing the variational trend of other elements. Magnetite is included neither in amphibole-I nor the core of amphibole-II but is often found in outer part of amphibole-II and amphibole-III as minute grains. Furthermore, magnetite is ubiquitously dispersed throughout the groundmass. From these facts, it seems that the increase of mg-value in the amphibole with crystallization mainly owes to appearence of magnetite at the comparatively later stage (amphibole-II and -III). As stated by MASON (1978), perhaps, increase of oxygen fugacity in the later stage of crystallization resulted in magnetite appearance and reverse zoning of amphibole. Recent experimental studies have suggested that mg-value increases and Al^{IV} and Ti contents decrease with the increase of oxygen fugacity (GILBERT, 1966; HELZ, 1973; POPP *et al.*, 1977). These results of experiments are consistent with above consideration.

Si enrichment in the later stage of crystallization can be explained by the increase of silica activity in the liquid with crystallization. Phenocrysts in most of Namariyama granophyres are composed mainly of amphibole and plagioclase and quartz occurs only in groundmass. This fact indicates that silica activity in the liquid becomes higher in the later stage.

In the Namariyama granophyres, Ti-pargasite occurs as liquidus mineral. On the other hand, amphibole is preceded by pyroxenes in the Ibaragi granitic complex in which amphiboles decrease in Si with crystallization (TAINOSHO, 1974). It may have resulted in increase of silica activity in the liquid that Ti-pargasite is more dominantly crystallized than pyroxene as liquidus phase in the Namariyama granophyres.

B. Ti and Al contents of amphiboles in the calc-alkaline plutonic rocks

Ti–Al diagram of amphiboles in the late Cretaceous to Paleogene plutonic rocks in the Chugoku district is shown in Fig. 12. Amphiboles of intrusive rocks in the Ryoke zone have high Al-content. Ti-content of amphiboles of intrusive rocks in the Sanyo zone (containing the Imbi intrusive rocks of stage-1) are the lowest among the late Cretaceous to Paleogene intrusive rocks in the Chugoku district. As can be seen in the figure, the variational trends of Ryoke and Sanyo zones are continuous with each other. Ti/Al gradient of amphiboles in the Imbi intrusive rocks of stage-2 and Namariyama granophyres belonging to magnetite series are more steep than those of Ryoke and Sanyo zones. Furthermore, Ti-content against Al-content of amphibole is higher in the Namariyama granophyres than in the Imbi intrusive rocks of stage-2.

The trend shown by the amphiboles in the Namariyama granophyres is in agreement with that in the Ben Nevis (HASLAM, 1968), Finnmarka complex (CZAMANSKE and WONES, 1973) and Western Highland of Papua New Guinea (MASON, 1978) which have been considered to be the high level intrusions (Fig. 13). On the other hand, those of Ryoke and Sanyo zones are in agreement with the Sierra Nevada (Dodge *et al.*, 1968) and

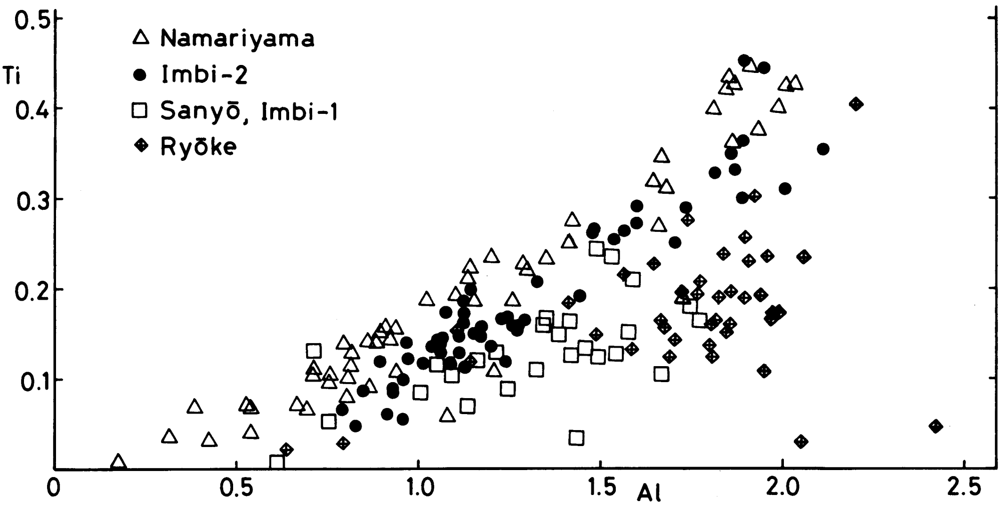

FIG. 12. Ti versus Al diagram of amphiboles in the late Cretaceous to Paleogene plutonic rocks in the Innerside of Southwest Japan. Data from TAINOSHO *et al.* (1979), SASADA (1979a), IZUMI (1979), MURAKAMI (1981), CZAMANSKE (1981), SASADA *et al.* (1982), SAKIYAMA (unpublished) and this work.

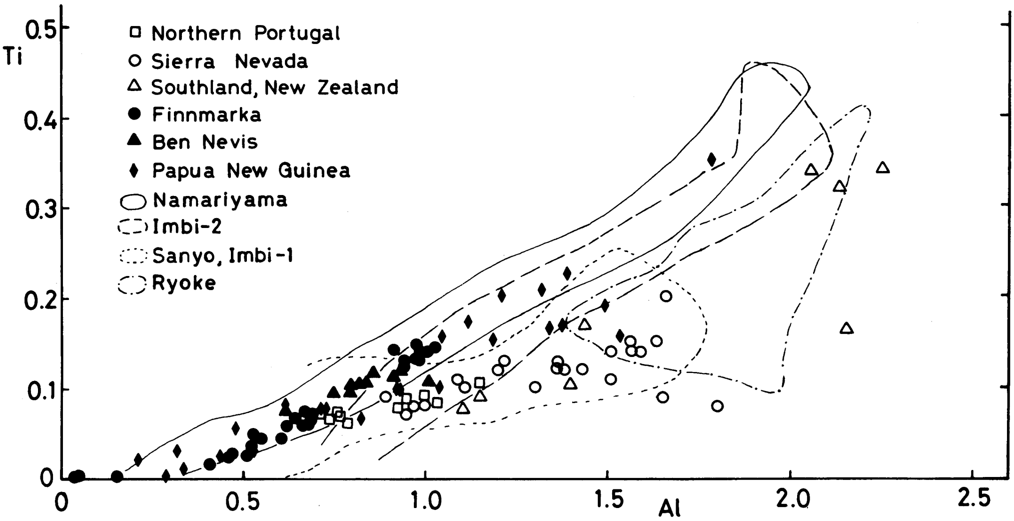

FIG. 13. Ti versus Al diagram of amphiboles in some calc-alkaline plutonic suites.
Data from DODGE *et al.* (1968), HASLAM (1968), CZAMANSKE and WONES (1973), de ALBUQUERQUE (1974), PRICE and SINTON (1978) and MASON (1978).

Northern Portugal (de ALBUQUERQUE, 1974) forming the huge batholith (Fig. 13). Ti–Al trend of the amphibole observed in the Namariyama granophyres may be a general property of the high level intrusion.

Whole rock composition, temperature, pressure and oxygen fugacity have been considered to be the factors controling the composition of amphiboles. Fig. 14 shows relation between TiO_2 and Al_2O_3 of the late Cretaceous to Paleogene intrusive rocks in the Chugoku district. In this figure, TiO_2 and Al_2O_3 content of the Namariyama granophyres is similar to that of other intrusive rocks except for some samples in the Imbi intrusive rocks of stage-2 and intrusive rocks in the Ryoke zone which have high Al_2O_3 and low TiO_2 contents. Accordingly, it is inferred that the effect of whole rock composition on Ti and Al contents of amphibole is little.

High temperature or low oxygen fugacity can be given as the factor of high Ti-content of amphibole (HELZ, 1973; RAASE, 1974). While, it has been generally considered that Al^{IV}-content of amphibole increases with rising of temperature and Al^{VI}-content is high in the amphibole formed under the high pressure condition (KOSTYUK and SOBOLEV, 1969; HELZ, 1973; RAASE, 1974). It seems that the oxygen fugacity during the crystallization of the Namariyama granophyres was comparatively high, owing to the high mg-value of mafic silicates, high Fe_2O_3 and $MnTiO_3$ molecule in the ilmenite and appearance of numerous magnetite (SAKIYAMA, 1982a). As mentioned before, the amphiboles in the Namariyama granophyres range in composition from Ti-pargasite to actinolite but

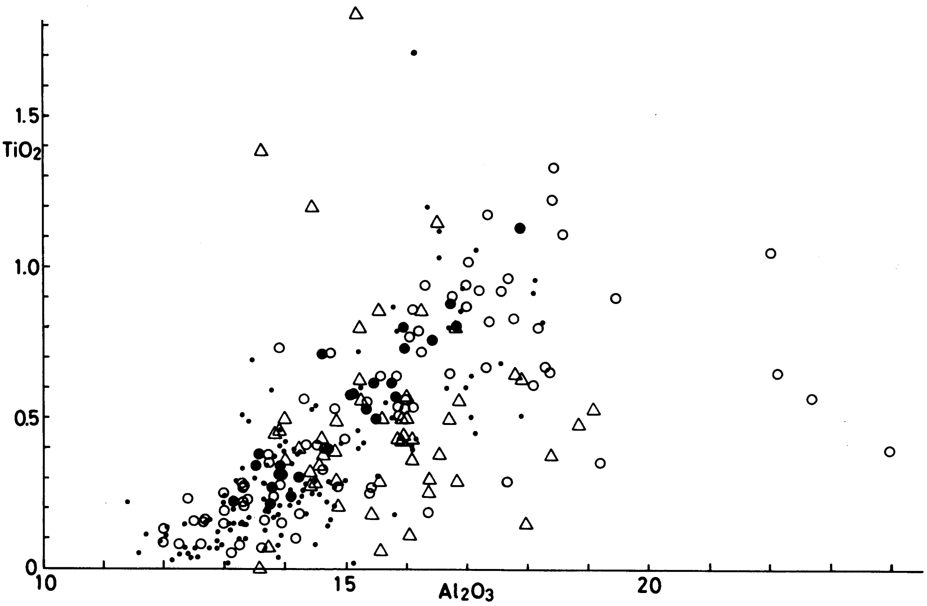

FIG. 14. TiO_2 versus Al_2O_3 diagram of late Cretaceous to Paleogene plutonic rocks in the Chugoku district.

Solid circle: Namariyama granophyres (from SASADA *et al.*, 1982; SAKIYAMA, unpublished; this paper).

Open circle: Imbi intrusive rocks stage-2 (from SHIBATA and SAYAMA, 1959; YAMADA, 1961; SASADA, 1979a, b; KUTSUKAKE *et al.*, 1979; IIZUMI, 1979; CZAMANSKE *et al.*, 1981; SAKIYAMA, unpublished).

Dot: Intrusive rocks in the Sanyo zone and Imbi intrusive rocks stage-1 (TAINOSHO, 1971; TOMONARI, 1974, 1976; SHIRAKAWA, 1975; KUTSUKATE *et al.*, 1979; MURAKAMI, 1981; CZAMANSKE *et al.*, 1981; SAKIYAMA, unpublished).

Triangle: Intrusive rocks in the Ryoke zone (HONMA, 1974; KUTSUKAKE *et al.*, 1979; MURAKAMI, 1981; CZAMANSKE *et al.*, 1981).

Al^{VI}-content is always low (Fig. 8).

All things considered, it is inferred that the amphiboles in the Namariyama granophyres were crystallized under the condition of comparatively high temperature at shallow level.

C. Genetic consideration of Ti-pargasite

As already mentioned, amphibole-I is Ti-pargasite and is commonly observed in the Namariyama granophyres in spite of their acidic compositions. Such Ti rich pargasite has been reported from some gabbroic rocks in the Imbi intrusive rocks and that in the Ryoke zone (Tainosho, *et al.*, 1979; Sasada, 1979; Kamiya and Harayama, 1982), but it has not been observed in the acidic rock except the plagiophyre in the Asagiridani granodioritic stock belonging the Imbi intrusive rocks (Iizumi, 1979).

In terms of appearance of opacite rim or replacement of amphibole-II, it seems that the amphibole-I has not equilibrate the melt represented by the whole rock composition and has been crystallized before intrusion of the Namariyama granophyres. The following four hypotheses can be advanced to explain the appearance of such incongruous mineral with whole rock composition:

(1) accidental xenocryst derived from country rocks;
(2) refractory residue carried up from the zone of partial melting;
(3) cumulate material that has been disrupted and reincorporated into the magma;
(4) phenocryst of basic magma which injected to acidic magma and disrupted during the mixing of magmas.

It seems disadvantageous to accidental xenocryst that the Ti-pargasite (amphibole-I) universally occurs in the facies-1 of every masses among the Namariyama granophyres. Furthermore, the amphibole shows a linear correlation with amphiboles-II and -III in the Al^{IV}—Na+K and Ti-Al diagrams. Ti-Al diagram of metamorphic amphiboles listed in Leake's catalogue (Leake, 1968) is shown in Fig. 15. As already stated by Raase (1974), Ti-contents of amphiboles in the metamorphic rocks increase with the metamorphic grade. Ti-content of the amphibole-I is rather higher than that of the general metamorphic rocks of granulite facies. These evidences suggest that the magmatic

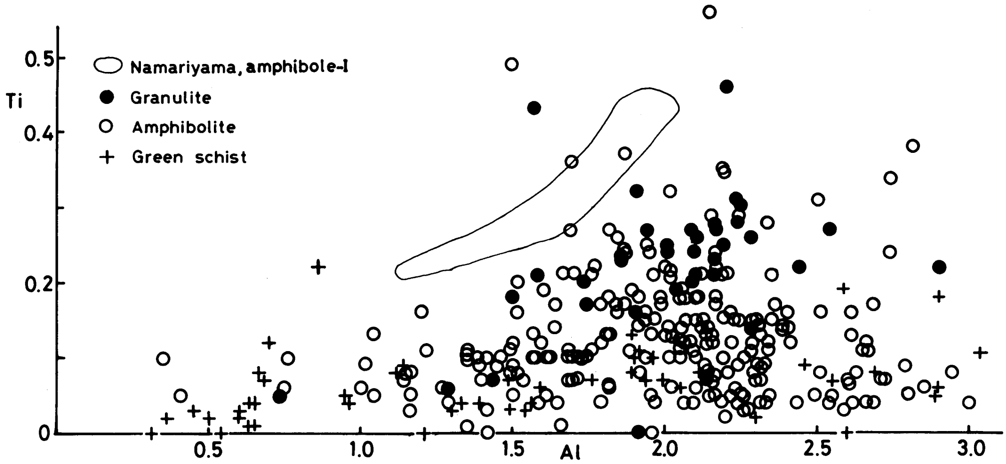

Fig. 15. Ti versus Al diagram of amphiboles in metamorphic rocks. Data from Leake (1968).

origin is more suitable than the exotic metamorphic origin in order to explain the appearance of the Ti-pargasite. While, amphibole data from the calc-alkaline andesite are plotted in Ti–Al diagram (Fig. 16). As shown in this figure, most of amphiboles in andesite are generally poorer in Ti than the amphibole-I in the Namariyama granophyres having andesitic to rhyolitic composition. Generally, Ti rich amphibole is suitable to basic magma and rare in intermediate to acidic magma. Therefore, it is not unreasonable to consider that amphibole-I was crystallized from basic magma, with the composition similar to gabbroic rocks in the Imbi intrusive rocks, in which Ti-pargasite is often found.

It is suitable for the linear correlation of amphibole composition to regard the Ti-pargasite as the early formed mineral from basic magma. However, appearance of the Ti-pargasite is not concerned to the whole rock composition. When the Ti-pargasite is regarded as the early formed mineral, it may be considered that cumurous phase precipitated in a zoned magma chamber were dispersed and disequiliblium mineral assemblage remained.

Two types of plagioclase phenocrysts showing different mode of occurrence, composition and zonal structural aspects are observed in the facies-1 of the Namariyama granophyres (Sakiyama, 1982b). Type-A of plagioclase with high An-content shows simple normal

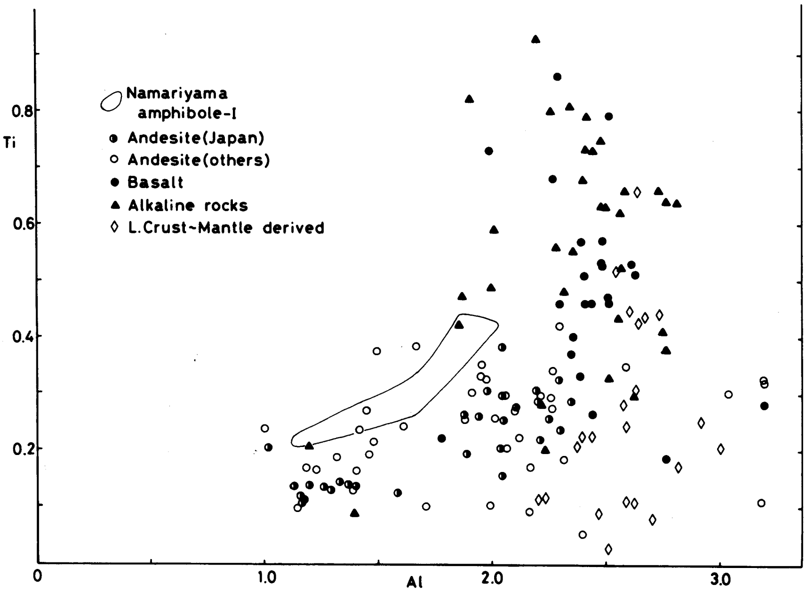

Fig. 16. Ti versus Al diagram of amphiboles in volcanic rocks and mantle or lower crust derived amphiboles.

Andesite (Japan): Ui (1971), Ujike (1972), Oshima (1975), Ujike and Onuki (1976), Togashi (1977), Sakuyama (1978).

Andesite (others): Carmichael (1967), Leake (1968), Wise (1969), Nicholls (1971), Wilkinson (1971), Stewart (1975), Flood *et al.* (1977), Luhr and Carmichael (1980).

Besalt and alkaline rocks: Leake (1968).

Lower crust-mantle derived: Yamazaki *et al.* (1966), Aoki and Shiba (1973), Best (1974).

zoning and rarely aggregates with Ti-pargasite. Type-B of plagioclase with low An-content shows complex patchy or reverse zoning and often aggregates with pyroxenes. These evidences suggest that a basic magma containing type-A plagioclase and Ti-pargasite and more acidic magma containing type-B plagioclase and pyroxenes may have been mixed. If so, it has not yet been clarified whether such two type magmas are cognate or not. In any case, appearance of Ti-pargasite in the Namariyama granophyres can not be explained by at least the simple crystallization from parental basic magma. Namariyama granophyres have andesitic to rhyolitic composition and basic rock does not crop out at the surface. However, it is presumed by the appearance of Ti-pargasite that the activity of basic magma has been closely connected with the generation of the Namariyama granophyres.

Helz (1973) made experimental study on the basaltic rocks at $P_{H_2O}=5$ kb and pointed out that Ti-content in amphibole increases with temperature and decreases with oxygen fugacity, independently of bulk rock composition. The amphibole-I is slightly poor in Al than that appeared at 1000°C and QFM-buffer in the experiments by Helz (1973). On the other hand, Allen *et al.* (1975) determined the stability of amphiboles in an andesite, three basalts and an olivine nephelinite at $P_{H_2O}=10$ kb and more. Amphiboles appeared as near liquidus phase in the experiments by Allen *et al.* (1975) are richer in Al, especially Al^{VI}, and poorer in Ti than that in the experiments by Helz (1973) (Fig. 17). Furthermore, Al increases and Ti decreases with P_{H_2O} through the experiments by Allen *et al.* (1975). While, the amphiboles derived from mantle or deeper level of lower crust are generally rich in Al (Yamazaki *et al.*, 1966; Aoki and Shiba, 1973; Best, 1974) (Fig. 16). From these data, it may be inferred that Ti-content decreases and Al-content

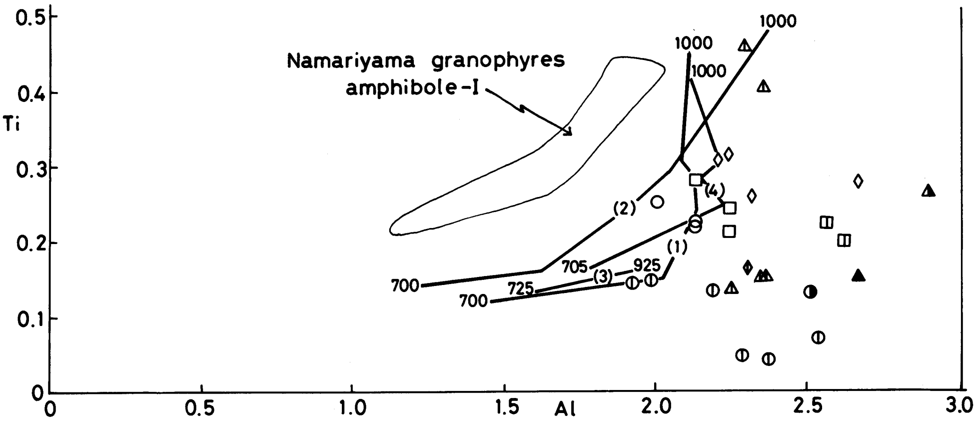

Fig. 17. Ti versus Al diagram of synthetic amphiboles in andesite and basalts.

Solid lines: experiments at $P_{H_2O}=5$ kb by Helz (1973)

1000–700: temperature (°C), (1): quartz tholeiite (QFM buffer), (2): olivine tholeiite (QFM buffer), (3): olivine tholeiite (HM buffer), (4): alkali basalt (QFM buffer).

Symbols: experiments at $P_{H_2O}=10$ kb and more by Allen *et al.* (1976).

circles: andesite; squares: quartz tholeiite; triangles: olivine tholeiite; diamonds: alkali basalt; open symbols: 10 kb; open symbols with bar: 13 kb; half solid symbols: 18 kb; solid symbols: 20 kb.

increases with pressure. Accordingly, the amphibole-I in the Namariyama granophyres has not been derived from very deep level such as mantle or lower crust but has probably been derived from a basic magma intruding into the magma chamber or cumulous phase precipitated in a zoned magma chamber.

Hitherto, it has been regarded by the wet chemical analyses of minerals that the amphiboles of the middle to late Paleogene plutonic rocks represented by the Tamagawa plutonic rocks have low Al, Ti and Na+K contents. In the facies-2 of the Namariyama granophyres which is similar to the rock facies of Tamagawa plutonic rocks, Ti-pargasite occurs as relic included by magnesio hornblende. Ti-pargasite will farther be discovered from the middle to late Paleogene plutonic rocks in the other areas through the detailed petrographical study and EPMA analyses.

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