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PYROXENES IN THE BASALT AND ANDESITE SUITE FROM TOTTORI PREFECTURE, WEST JAPAN

by

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(with 2 tables and 5 text-figures)

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Abstract

Olivine tholeiite (transitional type between alkaline and tholeiitic basalt), quartz tholeiite and calc-alkaline andesite suite of Pliocene age are widely distributed in the central part of Tottori Prefecture, west Japan. Pyroxenes in this volcanic suite were analysed with the electron microprobe. From olivine tholeiite to quartz tholeiite, Ca-rich clinopyroxenes become rich in Fe and poor in Ca with progressive crystallization. Ca-rich clinopyroxenes in the andesites are similar to, or higher in Mg and Ca contents than those in the basalts. Ca-poor pyroxenes in the andesites have higher 100Mg/(Mg+Fe+Mn) ratios than those in the basalts. These features are considered to be characteristic in the calc-alkaline volcanic suite and probably reflect constant oxygen fugacity during the crystallization of the pyroxenes.

Introduction

Crystallization trends of pyroxenes in volcanic rocks have been investigated by many authors. These investigators have dealt mainly with the pyroxenes in the tholeiite and alkaline volcanic series. Little attention has been given to the calc-alkaline volcanic suite. Recently, detailed discussions of pyroxenes from the calc-alkaline volcanic suite were presented by Smith and Carmichael (1968), Lowder (1970, 1973), Fodor (1971), Ewart (1976b) and others. They found that Fe content of the Ca-rich clinopyroxene is essentially constant throughout the suite of basalt-andesite-rhyolite, and discussed the mechanism for the restriction of iron enrichment.

In this paper, the compositional variation of the pyroxenes in the basalt and calc-alkaline andesite suite from Tottori Prefecture, west Japan, is described, and the conditions of crystallization of pyroxenes are briefly discussed.

Geological Setting

The Misasa Group, a late Miocene to Pliocene formation, is widely distributed in the central part of Tottori Prefecture, west Japan. The voluminous lava flows and associated pyroclastics are the main constituents of the group, which cover unconformably the Sangun metamorphic rocks, Cretaceous granitic rocks, and Miocene Tottori Group.

According to Fujita (1972, 1973), the Misasa Group is divided into three formations, the Ningyo-toge, Togo and Aba Formations.

The present writer has made a geological and petrological study of the volcanic rocks in the Togo Formation. The stratigraphic sequence and geological map prepared by the writer are shown in Table 1 and Fig. 1. As shown in Table 1, the Togo Formation is subdivided into seven members.

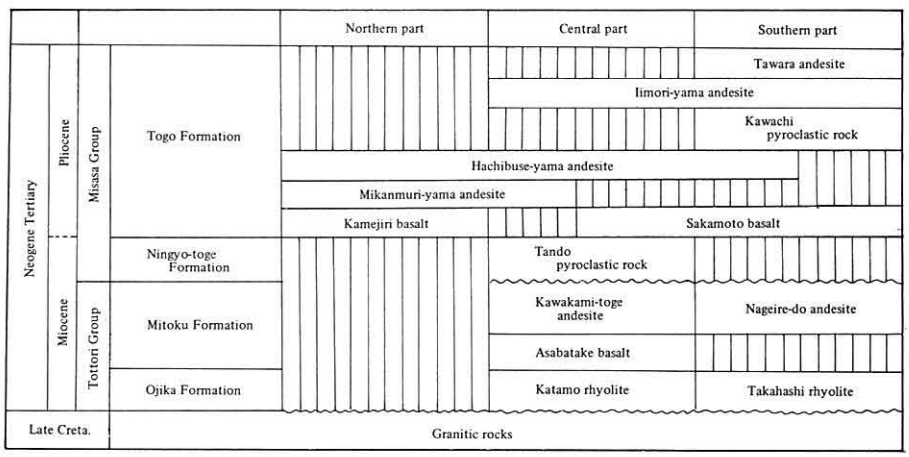
The Kamejiri basalt is exposed in the northern part of the district. This basalt can be subdivided into three units, KB1, KB2, and KB3, by stratigraphic and petrographic features. The KB1 unit is composed of olivine basalt lava, whereas KB2 and KB3 consist of lava flows of clinopyroxene-olivine basalt or dolerite.

The Sakamoto basalt is distributed in the southern part of the district. It is composed of lavas of aphyric basalt or olivine-clinopyroxene dolerite.

The Mikanmuri-yama andesite occurs in the central and northern parts of the district. It is made up of clinopyroxene-orthopyroxene-hornblende andesite and hornblende-orthopyroxene andesite.

The Hachibuse-yama andesite is widely distributed in the district. The lava flows are composed of aphyric andesite and clinopyroxene-orthopyroxene andesite.

Table 1. Stratigraphic sequence in the central part of Tottori Prefecture, West Japan.



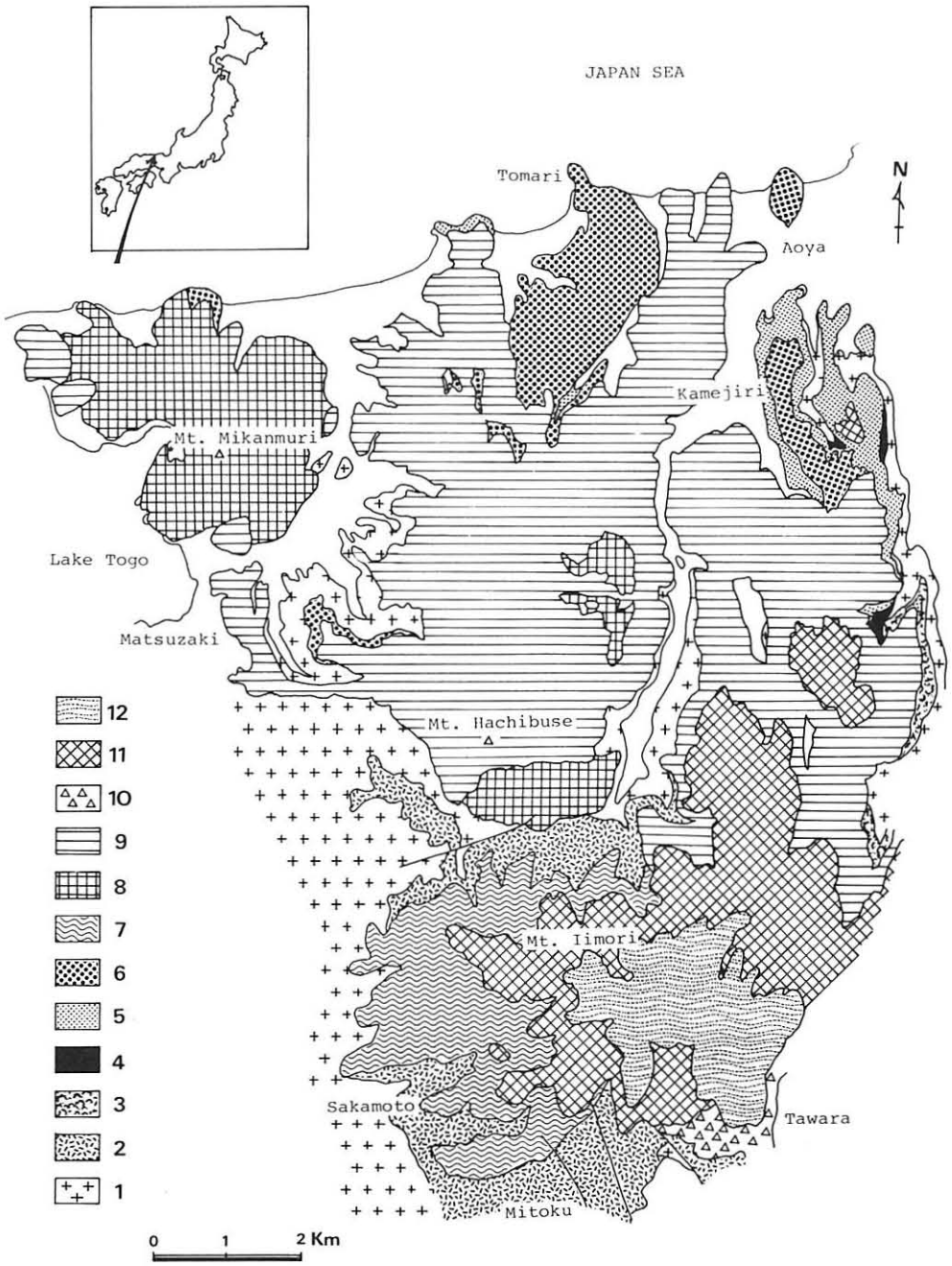


Fig. 1. Geological map of the central part of Tottori Prefecture, West Japan.
1. Cretaceous granitic rocks, 2. Tottori Group, 3. Ningyo-toge Formation, 4. Kamejiri basalt (KB1), 5. Kamejiri basalt (KB2), 6. Kamejiri basalt (KB3), 7. Sakamoto basalt, 8. Mikanmuri-yama andesite, 9. Hachibuse-yama andesite, 10. Kawachi pyroclastic rock, 11. Iimori-yama andesite, 12. Tawara andesite.

The Kawachi pyroclastic rock consisting of hornblende andesitic tuff breccia is exposed in the southern part of the district.

The Iimori-yama andesite is widely distributed in the southern and eastern parts of the district. It consists of voluminous lava flows of clinipyroxene-orthopyroxene andesite, and hornblende-orthopyroxene andesite and small amount of pyroclastics.

The Tawara andesite is exposed in the southern part of the district. It is made up of aphyric andesite.

Petrography

Kamejiri basalt: KB1, KB2, and KB3.

As mentioned above, the Kamejiri basalt is divided into the following three units, KB1, KB2 and KB3.

KB1: Olivine basalt (IIIb*)

Phenocrystic plagioclase and olivine are always present. Plagioclase is usually more abundant than olivine. The groundmass shows intergranular texture and consists of lath-shaped plagioclase, fine grained olivine and short prismatic clinopyroxene. Iron-titanium oxide is scattered throughout the groundmass. Interstitial glass is also seen.

KB2: Clinopyroxene-olivine basalt (IVb)

The rock is porphyritic or doleritic in texture. Phenocrystic minerals are plagioclase, olivine and clinopyroxene. Clinopyroxene sometimes shows sector zoing. The groundmass shows intersertal texture and is composed of plagioclase, olivine, clinopyroxene, iron-titanium oxide and a small amount of glass.

KB3: Olivine-clinopyroxene basalt (IVb)

Essential constituent minerals of the rock are the same as KB2. However, this basalt is more porphyritic than the KB2, and orthopyroxene is rarely found in the groundmass.

Sakamoto basalt: Aphyric basalt (d)

Essential constituent minerals are plagioclase, olivine clinopyroxene, orthopyroxene, and iron-titanium oxide. Plagioclase is most abundant, and shows lath or tabular form. The fine grained and short prismatic mafic minerals and iron-titanium oxide occur interstitially among plagioclases.

Mikanmuri-yama andesite: Clinopyroxene-orthopyroxene-hornblende andesite and orthopyroxene-hornblende andesite (VId, VIId).

The rock shows porphyritic texture. Phenocrysts consist mainly of plagioclase, hornblende and orthopyroxene. A small amount of clinopyroxene

* In parenthesis rock type defined by Kuno (1950) is given.

is also observed. A quartz xenocryst is rounded and irregular in shape and surrounded by minute grains of clinopyroxene. The groundmass is hyalo-ophitic and composed of lath-shaped plagioclase, prismatic orthopyroxene and clinopyroxene. Iron-titanium oxide is scattered throughout. A small amount of cristobalite and tridymite are observed in cavities.

Hachibuse-yama andesite: Clinopyroxene-orthopyroxene andesite (Vd, Ve)

The rock is aphyric or porphyritic. Phenocrysts are plagioclase, orthopyroxene and clinopyroxene. A glomeroporphyritic aggregate of these phenocrysts is sometimes observed. Some rocks have anhedral quartz xenocrysts. The groundmass is hyalo-ophitic or hyalopilitic. The constituent minerals are lath-shaped plagioclase, prismatic orthopyroxene, short prismatic clinopyroxene and iron-titanium oxide. Interstitial glass is also seen. Cristobalite and tridymite are rarely observed in cavities.

Iimori-yama andesite: Clinopyroxene-orthopyroxene-hornblende andesite and hornblende-orthopyroxene andesite (VId, VIId)

Plagioclase, hornblende and orthopyroxene are the essential minerals of phenocrysts. Hornblende has suffered severly from opacitization. Corroded quartz is sometimes found. The groundmass is hyalo-ophitic and composed of plagioclase, orthopyroxene, iron-titanium oxides and a small amount of glass.

Tawara andesite: Aphyric andesite (d)

This andesite is composed mainly of plagioclase, orthopyroxene and clinopyroxene, showing intergranular texture. Iron-titanium oxide occurs sporadically.

According to Kuno's (1950) definition the Kamejiri basalt belongs to the alkali rock series, but the nature of the minerals indicates that this basalt is not a typical alkaline basalt, but a transitional type. The pyroxene assemblage in the groundmass of the Sakamoto basalt, Mikanmuri-yama andesite, Hachibuse-yama andesite, Iimori-yama andesite and Tawara andesite accords with that of Kuno's hypersthenic rock series.

Chemical compositions of these volcanic rocks reported by Murayama et al. (1961) and Takamura (1973) indicate that the Kamejiri basalt and Sakamoto basalt belong to olivine tholeiite and quartz tholeiite, respectively, based on the classification of Yoder and Tilley (1962). However, the andesites have a chemical composition similar to the calc-alkaline rocks.

Analytical Procedure

Quantitative analyses were carried out at the Institute for Thermal Spring Research, Okayama University, with an electron microprobe (Japan Electron Optic Laboratory, Co., Ltd., model JXA-5A with 40° take off angle).

Instrument conditions were 15 KV accelerating potential, 0.02μA specimen current and 2 – 3μm electron beam. Other operating procedures are described in Tazaki and Hirano (1973).

The following standard materials were used; synthetic pure oxides for Ti, Al, and Mg; hematite, rhodonite, albite and adularia for Fe, Mn, Na, and K; synthetic wollastonite for Si and Ca. The correction is made by the method of Bence and Albee (1968) with correction factors given by Nakamura and Kushiro (1970).

Result

Electron microprobe analyses were carried out on the pyroxenes from the olivine tholeiite, quartz tholeiite and calc-alkaline andesite suite.

Selected microprobe analyses of pyroxenes are given in Table 2. Variation in atomic proportions Ca:Mg:Fe+Mn for each rock is plotted in Figs. 2 and 3. *Kamejiri basalt:* Except for KB2 (73081706, KB2-A), the Ca:Mg:Fe+Mn ratios in Ca-rich clinopyroxenes, both of phenocryst and groundmass, are scattered as shown in Fig. 2. In zoning of Ca-rich clinopyroxene phenocryst from KB2-A,

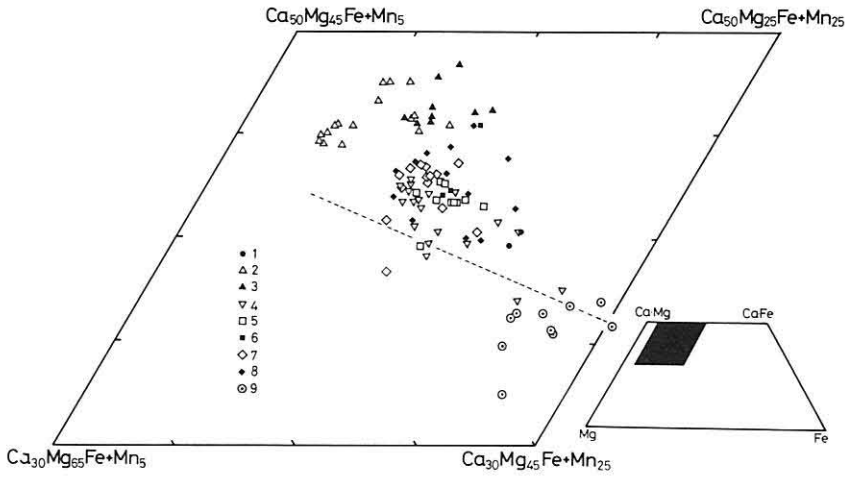


Fig. 2. Compositions of Ca-rich clinopyroxenes in the Kamejiri basalt and Sakamoto basalt.
1. Kamejiri basalt (KB1), groundmass; 2. Kamejiri basalt (KB2, 73081706), phenocryst; 3. Kamejiri basalt (KB2, 73081706), groundmass; 4. Kamejiri basalt (KB2, 73082203); 5. Kamejiri basalt (KB3, 73102508), phenocryst; 6. Kamejiri basalt (KB3, 73102508), groundmass; 7. Kamejiri basalt (KB3, 73102708), phenocryst; 8. Kamejiri basalt (KB3, 73102708), groundmass; 9. Sakamoto basalt. Dashed line: trend of Skaergaard pyroxene (Brown and Vincent, 1963).

Ca contents increase at first, whereas Fe contents remain nearly constant, and then Ca contents decrease slightly with increasing Fe contents. Groundmass Ca-rich clinopyroxenes have similar Ca:Mg:Fe+Mn ratios to those of rims of phenocrysts.

Sakamoto basalt: Ca-rich clinopyroxene ranges from $Ca_{34.8}Mg_{44.0}Fe+Mn_{21.2}$ to $Ca_{36.8}Mg_{40.2}Fe+Mn_{23.0}$ in composition. The 100Mg/(Mg+Fe+Mn) ratios of Ca-poor pyroxenes have values between 75.4 and 62.8.

Mikanmuri-yama andesite: The Ca:Mg:Fe+Mn ratios of Ca-rich clinopyroxene phenocrysts range from $Ca_{41.3}Mg_{44.1}Fe+Mn_{14.6}$ to $Ca_{40.1}Mg_{44.0}Fe+Mn_{15.9}$, whereas Ca-poor pyroxene phenocrysts have the 100Mg/(Mg+Fe+Mn) ratios varing from 81.7 to 66.2. The groundmass is usually bronzite and hypersthene in composition, however minor amounts of Ca-rich clinopyroxenes, ranging from $Ca_{43.9}Mg_{41.6}Fe+Mn_{14.5}$ to $Ca_{42.9}Mg_{43.8}Fe+Mn_{13.3}$, are also present.

Hachibuse-yama andesite: The range of groundmass Ca-rich clinopyroxene is

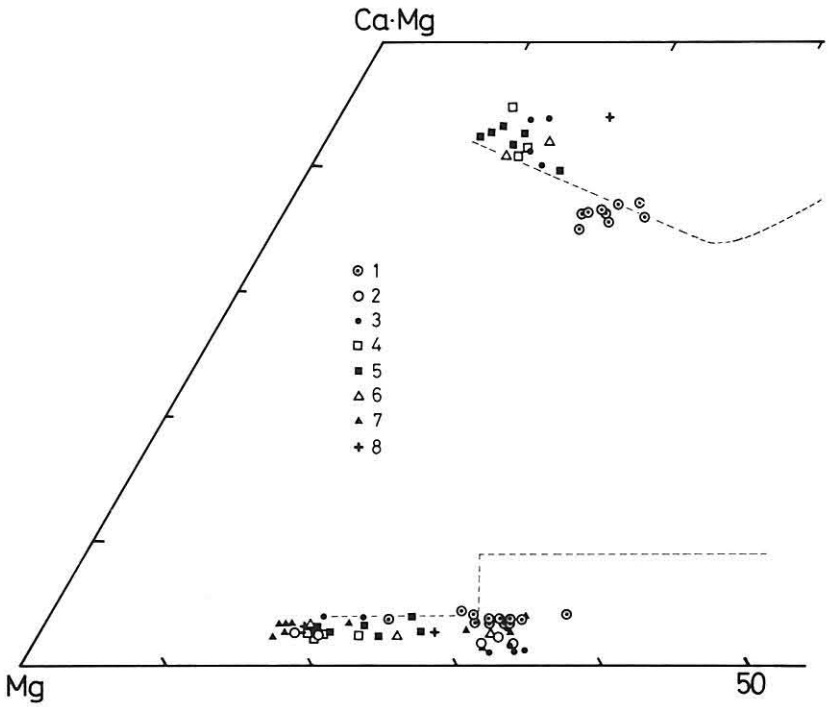


Fig. 3. Compositions of pyroxenes in the Sakamoto basalt and andesites.
1. Sakamoto basalt; 2. Mikanmuri-yama andesite, phenocryst; 3. Mikanmuri-yama andesite, groundmass; 4. Hachibuse-yama andesite, phenocryst; 5. Hachibuse-yama andesite, groundmass; 6. Iimori-yama andesite, phenocryst; 7. Iimori-yama andesite, groundmass; 8. Tawara andesite, groundmass. Dashed line: trend of Skaergaard pyroxene (Brown and Vincent, 1963).

from $Ca_{42.7}Mg_{46.3}Fe+Mn_{11.0}$ to $Ca_{39.5}Mg_{43.2}Fe+Mn_{17.3}$, showing a similar trend to Skaergaard pyroxenes (Brown and Vincent, 1963). Phenocrystic Ca-rich clinopyroxene is zoned from $Ca_{40.7}Mg_{45.5}Fe+Mn_{13.8}$ in the core to $Ca_{44.6}Mg_{43.8}Fe+Mn_{11.6}$ in the margin. Ca-poor pyroxenes in the groundmass are not homogeneous. Their 100Mg/(Mg+Fe+Mn) ratios vary from 80.3 to 72.9. Phenocrystic Ca-poor pyroxenes fall in the same area as Mg-rich groundmass pyroxenes.

Iimori-yama andesite: The wide compositional variations of Ca-poor pyroxenes are similar to those found in the Mikanmuri-yama andesite. The Ca:Mg:Fe+Mn ratios of groundmass Ca-rich clinopyroxenes are the same as the other andesite.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	50.92	51.95	50.45	50.81	51.72	50.58	51.86	50.51	52.77	52.36	53.94	53.37	55.06	54.07	55.79
TiO_2	0.95	0.79	1.45	1.22	0.71	0.63	0.52	0.71	0.37	0.44	0.21	0.17	0.14	0.19	0.11
Al_2O_3	2.07	2.86	3.56	7.14	0.54	4.53	2.98	3.45	0.71	0.77	3.43	3.01	1.69	2.47	0.99
FeO*	10.47	5.29	7.41	9.46	15.02	8.88	8.03	7.91	20.55	21.97	12.30	12.60	12.34	11.06	12.00
MnO	0.18	0.11	0.13	0.24	0.44	0.22	0.22	0.23	0.56	0.48	0.19	0.29	0.26	0.25	0.24
MgO	15.30	15.98	14.43	14.97	13.39	15.34	15.30	16.38	22.80	21.27	28.52	28.90	29.21	29.92	29.87
CaO	19.20	22.19	22.49	20.34	17.11	19.98	20.56	19.94	2.43	1.97	1.38	1.24	1.16	1.51	1.54
Na_2O	0.38	0.27	-	0.42	0.43	0.31	0.38	0.28	0.03	0.07	0.03	0.05	0.04	0.01	0.01
Total	99.47	99.54	99.92	99.60	99.36	100.47	99.85	99.41	100.22	99.33	100.00	99.63	99.90	99.48	100.53
						Numbers of Ions on the basis of 6 (O)									
Si	1.914	1.917	1.877	1.907	1.975	1.870	1.922	1.882	1.960	1.971	1.918	1.911	1.958	1.926	1.970
Al^{IV}	0.086	0.083	0.123	0.093	0.024	0.130	0.078	0.118	0.021	0.029	0.082	0.089	0.042	0.074	0.030
Al^{VI}	0.006	0.041	0.033	0.002	-	0.067	0.052	0.033	-	0.005	0.062	0.038	0.029	0.030	0.011
Ti	0.027	0.022	0.041	0.035	0.020	0.018	0.015	0.020	0.010	0.012	0.006	0.005	0.004	0.005	0.003
Fe	0.329	0.167	0.231	0.297	0.480	0.275	0.249	0.247	0.630	0.692	0.366	0.377	0.367	0.329	0.355
Mn	0.006	0.004	0.004	0.008	0.014	0.007	0.007	0.007	0.018	0.015	0.006	0.009	0.008	0.008	0.007
Mg	0.858	0.879	0.800	0.838	0.762	0.846	0.846	0.910	1.262	1.193	1.512	1.543	1.549	1.588	1.573
Ca	0.773	0.877	0.896	0.818	0.700	0.792	0.817	0.797	0.097	0.079	0.053	0.048	0.044	0.058	0.058
Na	0.028	0.020	-	0.031	0.032	0.022	0.027	0.020	0.002	0.005	0.002	0.003	0.003	0.001	0.001
Total	4.027	4.010	4.005	4.029	4.007	4.027	4.013	4.034	4.018	4.001	4.001	4.023	4.004	4.019	4.008
Ca	39.3	45.5	46.4	41.7	35.8	41.3	42.6	40.6	4.8	4.0	2.7	2.4	2.2	2.9	2.9
Mg	43.6	45.6	41.4	42.7	39.0	44.1	44.1	46.4	62.6	60.3	78.1	78.1	78.7	80.1	78.9
Fe+Mn	17.1	8.9	12.2	15.6	25.2	14.6	13.3	13.0	32.6	35.7	19.2	19.5	19.1	17.0	18.2
M**	71.9	83.7	77.3	73.3	60.7	75.0	76.8	78.2	65.8	62.8	80.3	80.0	80.5	82.5	81.3

* Total Fe as FeO

** 100 Mg/(Mg + Fe + Mn)

Table 2. Selected microprobe analyses of pyroxenes in the basalt and andesite suite.
1. Groundmass Ca-rich clinopyroxene (No. G8), Kamejiri basalt (KB1). 2. Core of phenocrystic Ca-rich clinopyroxene (No. 1-1-1), Kamejiri basalt (KB2, 73081706). 3. Groundmass Ca-rich clinopyroxene (No. G2), Kamejiri basalt (KB2, 73081706). 4. Groundmass Ca-rich clinopyroxene (No. 8), Kamejiri basalt (KB3, 73102508). 5. Groundmass Ca-rich clinopyroxene (No.G5), Sakamoto basalt. 6. Microphenocrystic Ca-rich clinopyroxene (No. G13A), Mikanmuri-yama andesite. 7. Groundmass Ca-rich clinopyroxene (No. G9-1), Hachibuse-yama andesite. 8. Groundmass Ca-rich clinopyroxene (No. G-14), Iimori-yama andesite. 9. Groundmass Ca-poor pyroxene (No. 3-3), Kamejiri basalt (KB3, 73102508). 10. Groundmass Ca-poor pyroxene (No. G13), Sakamoto basalt. 11. Groundmass Ca-poor pyroxene (No. G4), Mikanmuri-yama andesite. 12. Core of phenocrystic Ca-poor pyroxene (No. G3-1), Hachibuse-yama andesite. 13. Rim of phenocrystic Ca-poor pyroxene (No. G3-2), Hachibuse-yama andesite. 14. Groundmass Ca-poor pyroxene (No. G5-2), Iimori-yama andesite. 15. Groundmass Ca-poor pyroxene (No. G3), Tawara andesite.

Tawara andesite: The 100Mg/(Mg+Fe+Mn) ratios of groundmass Ca-poor pyroxenes vary from 81.3 to 80.7. The composition of an analysed groundmass Ca-rich clinopyroxene is $Ca_{37.6}Mg_{43.8}Fe+Mn_{18.6}$.

Discussion

For comparison between pyroxene from the basalts and andesites, all of the pyroxene analyses from each rock are plotted in Fig. 4. The results are summarized as follows:

Ca-rich clinopyroxene: A continuous variation of Ca-rich clinopyroxene from the Kamejiri to the Sakamoto basalt is observed. This trend shows a steeper decrease in Ca than in the early stage of the Skaergaard intrusion (Brown and Vincent, 1963). The Sakamoto basalt probably represents a more advanced stage of fractionation. The compositions of Ca-rich clinopyroxenes in the andesites are similar to those of the Kamejiri basalt, but the range is more restricted in the andesites than in the Kamejiri basalt. The compositions of Ca-rich clinopyroxenes in the andesites are higher in Ca and Mg than those in the Sakamoto basalt.

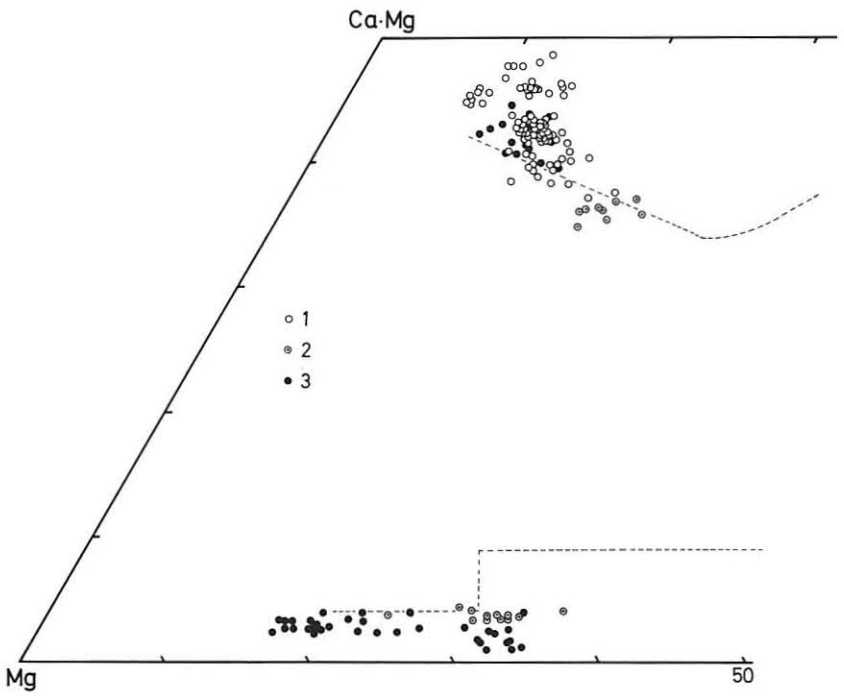


Fig. 4. Combined plot of pyroxene analyses from all the specimens.
1. Kamejiri basalt, 2. Sakamoto basalt, 3. andesites. Dashed line: trend of Skaergaard pyroxene (Brown and Vincent, 1963).

Ca-poor pyroxene: Ca-poor pyroxene is rarely found in the groundmass of the Kamejiri basalt (KB3). It is, however, abundant in the Sakamoto basalt and andesites. The 100Mg/(Mg+Fe+Mn) ratios of Ca-poor pyroxenes in the Sakamoto basalt vary from 62.8 to 75.4. Ca-poor pyroxenes in the andesites range from 63.5 to 82.9 in the 100Mg/(Mg+Fe+Mn) ratios. It is clear that Ca-poor pyroxenes in the andesites are more magnesian than those in the basalts.

From the above observations it is concluded that Ca-rich clinopyroxene of the calc-alkaline volcanic suite has a limited range in Fe content. On the other hand, Ca-poor pyroxene from the calc-alkaline volcanic suite has relatively high 100Mg/(Mg+Fe+Mn) ratios.

Smith and Carmichael (1968), Lowder (1970, 1973) and Fodor (1971) found that Fe content is essentially constant throughout a suite of basalt – andesite – rhyodacite (or latite) – rhyolite. Ewart (1976b) suggested that Ca-rich clinopyroxene compositions are concentrated within the augite field, and show no tendency to develop marked iron enrichment at any stage during precipitation in modern orogenic lavas.

These trends are different from those of the tholeiitic volcanic suite, which has iron enrichment during differentiation (Carmichael, 1967; Nicholls, 1971; Ewart, 1976a).

The available data on iron-titanium oxide in the groundmass of this volcanic suite are given in the f_{O_2}-temperature diagram, after Buddington and Lindsley (1964) (Fig. 5). For comparison, the data for calc-alkaline lavas of Talasea, New Britain (Lowder, 1970) and the margin of the Great Basin,

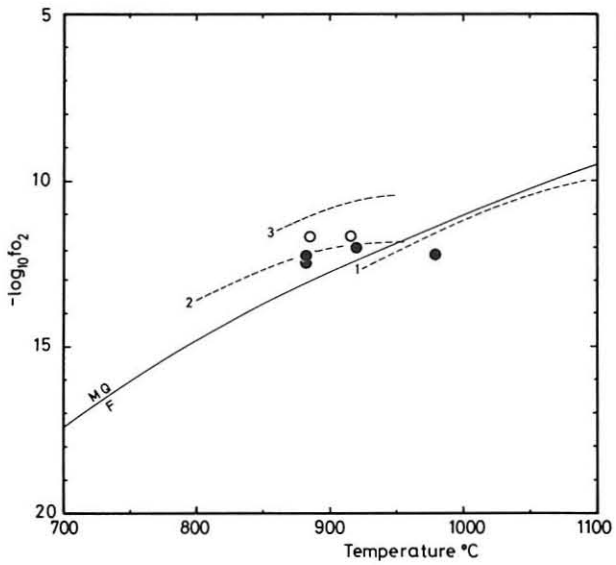


Fig. 5 Log f_{O_2} – temperature diagram. Solid circles: basalt. Open circles: andesite.
Dashed line: 1. Tholeiitic volcanic suite of Thingmuli, Iceland (Carmichael, 1967), 2. transitional alkali olivine–tholeiitic basalt and andesite of the Great Basin, Utah (Lowder, 1973), 3. calc-alkaline lavas of Talasea (Lowder, 1970). QM/F: quartz-fayalite-magnetite buffer (Eugster and Wones, 1962).

Southwest Utah (Lowder, 1973) are also shown in the same figure. The data studied here indicate that the f_{O_2} is slightly higher in the andesites than the basalts, and the f_{O_2} keeps rather constant with decreasing temperature. This implies that magnetite was precipitated and removed from those lavas just before eruption (Osborn, 1959). Consequently, Fe may not be available enough amounts to form more Fe rich pyroxenes than those in the basalts.

If this is the case in the volcanic rocks, phenocrystic or xenocrystic magnetite might be expected as pointed out by Lowder (1970). However, no such magnetite was observed in the basalts and basic andesites in question.

More data are necessary to elucidate the mechanism for the formation of the characteristic pyroxenes of the calc-alkaline volcanic suite.

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