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PETROGRAPHY AND MINERALOGY OF XENOLITHS FROM
THE YATSUGATAKE VOLCANIC CHAIN,
CENTRAL JAPAN I. Ti-GARNET

by

Takanobu Oba and Shimpei Kawachi

(with 5 text-figures and 4 tables)

Abstract

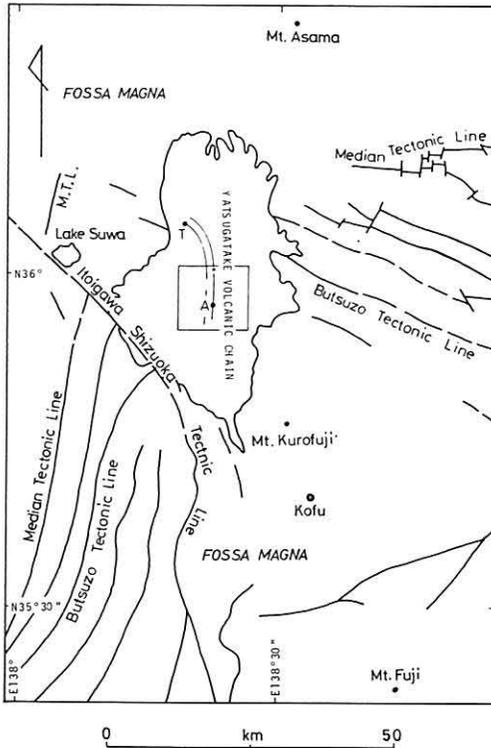
Calc silicate xenoliths from the Yatsugatake Volcanic Chain have representative mineral assemblage of Ti-garnet + fassaitic pyroxene + anorthite + sphene ± iron ores ± vesuvianite ± wollastonite ± corundum ± calcite. Garnet is schorlomite ($\text{TiO}_2 = 11.87$ wt %) with the formula of $\text{Ca}_{2.85} \text{Mn}_{0.02} \text{Fe}_{0.39}^{2+} \text{Mg}_{0.12} \text{Fe}_{0.74}^{3+} \text{Al}_{0.61} \text{Ti}_{0.74} \text{Si}_{2.52} \text{O}_{12}$. Chemical composition of fassaitic pyroxene shows a range between $\text{Ca}_{0.98} \text{Fe}_{0.03}^{2+} \text{Mg}_{0.48} \text{Fe}_{0.33}^{3+} \text{Ti}_{0.06} \text{Al}_{0.57} \text{Si}_{1.52} \text{O}_6$ and $\text{Ca}_{1.00} \text{Fe}_{0.26}^{2+} \text{Mn}_{0.01} \text{Mg}_{0.37} \text{Fe}_{0.27}^{3+} \text{Ti}_{0.05} \text{Al}_{0.45} \text{Si}_{1.60} \text{O}_6$. Unit-cell dimension for schorlomite is determined, $a = 12.046 \text{ \AA}$. Genesis of the xenoliths is briefly discussed.

Introduction

The Yatsugatake Volcanic Chain (Text-fig.1; Highest point at Mt. Akadake, 2,899 m) is one of the major stratovolcanic massifs in Japan. It is situated near the junction of the Median Tectonic Line and the Itoigawa-Shizuoka Tectonic Line. It consists of more than twenty centers of volcanic activity aligned on two major north-south arcs of about 21 km in length convex to the east. The volcanic chain is straddling over the Honshu (Japan Sea side) and the Shimanto provinces (Pacific side) separated by the Butsuzo Tectonic Line. Coarse-grained volcanic ejecta derived from the volcanic chain thickly cover an area about 60 km north-south by 35 km east-west. The volcanic chain has been active since early Pleistocene. The rocks of the chain are mainly composed of calc-alkaline andesites with minor tholeiitic basalts.

The geology of the volcanic chain has been described in detail by Kawachi (1961, 1972, 1974-75, 1977) and Kawachi and Aramaki (1979).

The basement rocks of the volcanic chain can only be studied through xenoliths. Kawachi collected thousands of xenoliths from the entire volcanic chain and classified them into 19 types under the microscope (Kawachi, 1979). He drew a north-south upper crustal profile of the central Fossa Magna region based mainly on characteristic occurrence of schist xenoliths in the southern chain and the contrasting lack of them in the northern chain, the boundary of southern and northern chain being located at around the Natsuzawa Pass (see Text-fig. 1). The history of the Yatsugatake Volcanic Chain is divided into two major periods: the older and the younger (Kawachi, 1961). Ti-garnet-bearing xenoliths are only found in the rocks belonging to the older period. In this paper we describe Ti-garnet-bearing xenoliths and their paragenetic minerals.



Text-fig. 1 Location of the Yatsugatake Volcanic Chain.

A: Mt. Akadake T: Mt. Tsteshinayama
The square around A corresponds to Fig. 2.

Host rocks of xenoliths

Xenoliths are mainly collected from river boulders. Based on the nature of the host rocks geologic horizons from which they are derived can be identified with reasonable certainty. Ti-garnets are found in 9 xenoliths (Table 1).

The host rocks include Shinkyojiyama lava, Tatsubadani lava, Gongendake pyroclastics, and Kawamata lava. Simplified distribution of host rocks is shown in Text-fig. 2. Except for Kawamata lava the host rocks are hypersthene-augite (glassy) andesites. The Kawamata lava has phenocrystic olivines and hornblendes in addition to other constituents common to other host rocks. The groundmass minerals comprise plagioclase, augite, hypersthene, opaque mineral, apatite, silica mineral, biotite, and glass. Except for Gongendake pyroclastics, the host rocks have small amount of K-feldspar. Wet chemical analyses of Tatsubadani lava and Shinkyojiyama lava are given in Table 2. All the host rocks belong to common calc-alkaline andesites.

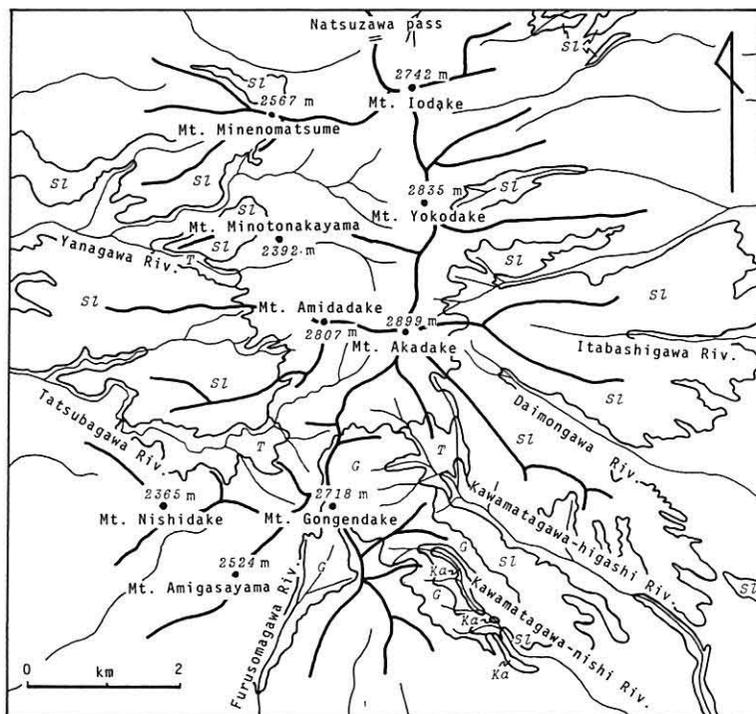
Description of the xenoliths

Ti-garnet-bearing xenoliths are subangular to angular, up to 8 cm across, and vary from fine-grained (sample 1668) to medium-grained (others). Most xenoliths show mosaic texture (Text-fig. 3). Banded nature of original rocks is recognizable to some extent in some

Table 1 Localities of Ti-garnet-bearing xenoliths

sample no.	locality	host rock (older period)	
935	Daimongawa River	Shinkyojiyama lava	* hyp -aug glassy andesite
1668	Furusomagawa River	Gongendake pyroclastics	hyp -aug glassy andesite
2241	Itabashigawa River	Shinkyojiyama lava	hyp -aug glassy andesite
2411	Tatsubagawa River	Tatsubadani lava	hyp -aug andesite
2458	Tatsubagawa River	Gongendake pyroclastics	hyp -aug glassy andesite
2530	Tatsubagawa River	Gongendake pyroclastics	hyp -aug glassy andesite
4695	Yanagawa River	Shinkyojiyama lava	hyp -aug andesite
5078	Kawamatagawa -higashi River	Kawamata lava	ol-hor-hyp -aug andesite
5329	Kawamatagawa -nishi River	Gongendake pyroclastics	hyp -aug glassy andesite

*aug; augite, hor: hornblende, hyp: hypersthene, ol: olivine.



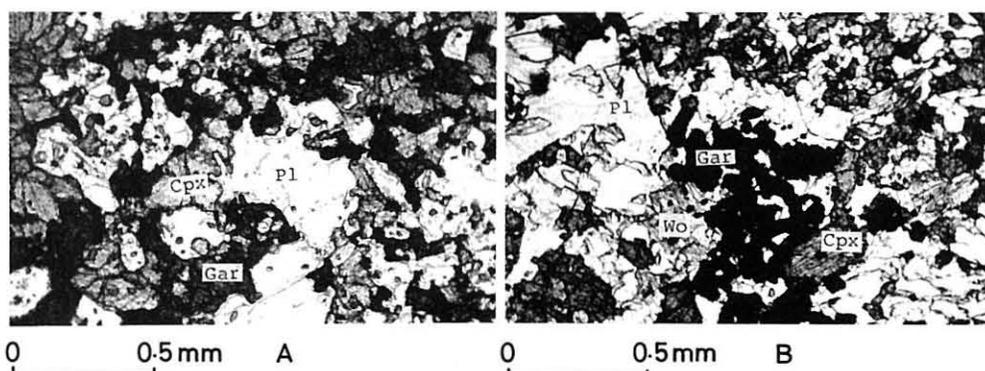
Text-fig. 2 Distribution of the host rocks of the Ti-garnet-bearing xenoliths.

G: Gongendake pyroclastics Ka: Kawamata lava Sl: Shinkyojiyama lava T: Tatsubadani lava
Ridges are shown by thick lines.

	Tatsubadani lava	Shinkyojiyama lava	Xenolith
Sample no.	11	3762	2530
SiO ₂	52.94	52.55	39.23
TiO ₂	1.19	1.36	2.62
Al ₂ O ₃	18.21	18.30	17.49
Fe ₂ O ₃	4.02	3.73	11.76
FeO	4.68	5.34	
MnO	0.15	0.15	0.15
MgO	4.24	4.72	4.28
CaO	9.04	9.15	25.12
Na ₂ O	3.17	3.16	0.08
K ₂ O	1.15	0.92	0.06
P ₂ O ₅	0.29	0.23	—
H ₂ O ⁺	0.32	0.62	
H ₂ O ⁻	0.40	0.07	
Total	99.80	100.36	100.37
Analyst	Omori & Omori	Haramura	Yamamoto

Table 2

Selecteu bulk chemical compositions of host rocks and sample 2530 xenolith



Text-fig. 3 Photomicrographs of Ti-garnet-bearing xenoliths. They show mosaic texture.

A: sample 2530, B: sample 2411, Abbreviations: Cpx: clinopyroxene, Pl: plagioclase, Gar: Ti-garnet, Wo: wollastonite.

samples.

Vesiculation is observed in samples 2241 and 4695. Iron ores form 7 to 8 mm thick rim around xenolith 4695.

Bulk composition of a xenolith (sample 2530) is shown in Table 2. SiO₂ was determined by conventional wet method, while TiO₂, Al₂O₃, FeO, MgO, CaO, Na₂O and K₂O by atomic absorption method, and MnO and P₂O₅ by colorimetric analysis. The composition of xenolith 2530 is high in CaO suggesting a decarbonated calcareous sediment as its source. It is also rich in TiO₂, and poor in SiO₂ and alkali as compared with host andesite. The boundary between the xenolith and the host rock is sharp.

Xenoliths are intensely affected by magma. However, it is unlikely that the metamorphic reactions have reached equilibrium. There is a subtle difference in mineral

Table 3 Summary of paragenetic mineral assemblages in Ti-garnet-bearing xenoliths from the Yatsugatake Volcanic Chain

Sample no.	Ti-gar	Cpx	Pl	Wo	Ac	Ves	Sph	Cc	Co	Ap	Op	Gl
935a	+	+	+	-	+	-	+	-	+	-	+	-
935b	+	+	+	-	-	-	+	-	-	+	+	-
935c	+	-	-	+	-	-	-	+	+	-	-	+
1668	+	+	+	-	-	-	+	-	-	-	+	-
2241	+	+	+	-	-	-	+	-	-	-	-	+
2411	+	+	+	+	-	+	-	+	-	-	-	-
2458	+	+	+	-	-	-	-	-	+	-	-	+
2530	+	+	+	-	-	-	+	-	-	-	+	-
4695	+	-	+	-	-	-	-	+	-	-	-	+
5078	+	+	+	-	-	-	-	-	-	-	-	-
5329	+	+	+	-	-	-	+	-	-	-	+	-

+: present -: absent

Abbreviations: Ac = Actinolite, Ap = Apatite, Cc = Calcite, Co = Corundum, Cpx = Clinopyroxene, Gl = Glass, Op = Opaque mineral, Pl = Plagioclase, Sph = Sphene, Ti-gar = Ti-garnet, Ves = Vesuvianite, Wo = Wollastonite.

assemblages within one and the same xenolith as shown in sample 935 (Table 3).

The convention that only when the minerals are in mutual contact they are said to be in paragenetic relations is employed. Paragenetic assemblages of calcareous rocks are shown in Table 3. Garnet, clinopyroxene, and plagioclase are invariably present, while other phases such as calcite, vesuvianite, actinolite, wollastonite, corundum, and glass may or may not occur.

Ti-garnet generally occurs as subhedral to anhedral crystals, and is often included poikilistically in clinopyroxene or in plagioclase. It is about 0.5 mm across in sample 935 c, but generally about 0.2 mm in others. The color of most Ti-garnets is brown to deep brown, but a range from yellow brown to dark brown is observed in samples 935 a, c, 2241, 2458, 4695, 5078, and 5349.

Unit-cell dimensions of Ti-garnet in sample 2530 is $a = 12.046 \text{ \AA}$. It is determined by using the following reflections; (642), (521), (422), (332), and (420). Silicon was used as an external standard. This value is close to unit-cell dimension of andradite ($a = 12.053 \text{ \AA}$).

Clinopyroxene occurs as clustered anhedral crystals. It is partly zoned. The size ranges from 0.5 to 1 mm. Pleochroism is X = yellowish green and Z = grass green. Unit-cell dimensions of the pyroxene are determined: $a = 9.794 \text{ \AA}$, $b = 8.935 \text{ \AA}$, $c = 5.282 \text{ \AA}$, $\beta = 105.59^\circ$ and $V = 445.2 \text{ \AA}^3$.

Plagioclase occurs as subhedral grains twinned commonly on Albite and Carlsbad laws. Plagioclase in xenolith 2530 is mostly pure anorthite (An_{99}).

Wollastonite in samples 935 c and 2411 occurs as tabular subhedral crystals.

Vesuvianite in sample 2411 is subhedral in form aligned in a radial fashion. It is slightly pleochroic with X = pale brownish yellow and Z = pale gray to pale brownish yellow. The mineral can easily be distinguished by its extremely high refractive indices.

Clustered euhedral corundums are observed in samples of 935 a, c and 2458.

Chemical compositions of minerals in sample 2530

Minerals in xenolith 2530 are analysed with an electron microprobe analyzer (JEOL JXA-50A). Averaged chemical compositions of more than three spot analyses are listed in Table 4 together with structural formulae. The amounts of Fe^{2+} in garnet and clinopyroxene are estimated assuming stoichiometry. Ilmenite composition is recalculated after the method of Carmichael (1967b).

Ti-bearing Ca-Fe garnet (andradite) is called melanite or schorlomite depending on Ti contents, schorlomite being more Ti rich. Howie and Wooley (1968) proposed the boundary between melanite and schorlomite to be placed at 0.5 Ti in formula unit calculated on the basis of 12 oxygens: this would amount to a TiO_2 content of approximately 8%. The proposal was supported by the evidence that garnets in the middle TiO_2 range, 5 to 8% are relatively rare. However, this gap does not seem to be present as shown in Text-fig. 4. According to this nomenclature, the Ti-garnet of the present study is schorlomite ($\text{TiO}_2 = 11.87$ wt %). Chemical composition of this ti-garnet is similar to those from contact metamorphosed impure calcareous sediments and alkali rocks (Howie and Wooley, 1968;

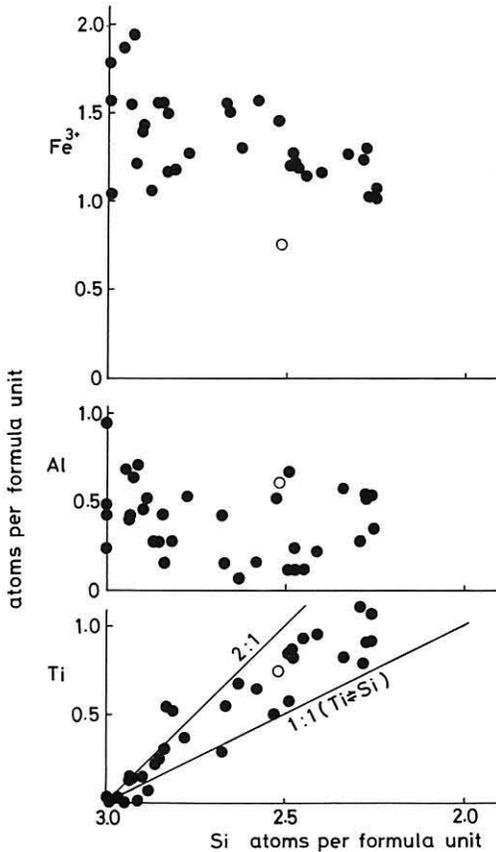
Table 4 Composition of minerals in sample 2530 xenolith

	Ti-gar	Pl	Cpx-1	Cpx-2	Sph	Il
SiO_2	30.23	43.12	39.79	41.18	30.33	0.05
TiO_2	11.87	0.02	2.68	1.61	38.34	47.98
Al_2O_3	6.23	36.36	12.75	9.76	1.61	0.31
Fe_2O_3	18.10	0.52	12.49	18.12	1.00	53.15
MnO	0.22	0.02	0.10	0.18	0.05	0.38
MgO	0.97	—	8.50	6.33	0.01	2.13
CaO	31.99	20.22	23.98	23.94	27.52	0.11
Na_2O	0.02	0.06	0.03	0.03	—	—
K_2O	0.01	0.01	0.01	—	—	—
Cr_2O_3	0.04	—	0.23	0.07	0.03	0.05
Total	99.70	100.33	100.56	101.22	98.89	105.14
Fe_2O_3	11.86		11.51	9.30		9.85
* FeO	5.61		0.88	7.84		38.88
Total	99.07		100.46	100.24		99.74
Structural formulae						
Si	2.517	1.998	1.520	1.601	0.999	0.002
Ti	0.743	0.001	0.057	0.047	0.949	1.802
Al	0.611	1.983	0.574	0.447	0.062	0.018
Fe^{3+}	0.743	0.018	0.331	0.272	0.025	0.370
Fe^{2+}	0.391	—	0.028	0.258	—	1.624
Mn	0.015	0.008	0.003	0.006	0.001	0.016
Mg	0.121	—	0.484	0.367	0.001	0.158
Ca	2.854	1.003	0.981	0.997	0.949	0.006
Na	0.002	0.005	0.002	0.002	—	—
K	0.001	0.001	—	—	—	—
Cr	0.003	—	0.007	0.002	0.003	0.002

*See text.

Analyst: Y. Kawachi.

Kusachi et al., 1972; Huggins et al., 1977b). There is virtually no variation in analysed compositions of Ti-garnet of this study. The formula is $\text{Ca}_{2.85}\text{Mn}_{0.02}\text{Fe}_{0.39}^{2+}\text{Mg}_{0.12}\text{Fe}_{0.74}^{3+}\text{Al}_{0.61}\text{Ti}_{0.74}\text{Si}_{2.52}\text{O}_{12}$.



Text-fig. 4 Diagrams showing numbers of Si against those of Ti, Al and Fe^{3+} on the basis of 12 oxygens for Ti-bearing garnets. Solid circles indicate garnets from literature (Howie and Wooley, 1968; Kusachi et al., 1972; Huggins et al., 1977b), while open circle from present study. The diagonal lines indicate the slopes for 1:1 and 1:2 replacement of Si by Ti, respectively.

Text-fig. 4 is constructed using analyses taken from the literatures (Howie and Wooley, 1968; Kusachi et al., 1972; Huggins et al., 1977b) and present study. The bottom diagram shows that most garnet analyses plot between lines representing replacement of 1:1 and 2:1. Ti content increases with decreasing Si content, while distinct variation trend of Fe^{3+} and Al against Si content does not seem to be present. The strong negative correlation between Si and Ti suggests that the following substitution has to be invoked to account for the Ti substituted into the garnet: $\text{Ti} \rightleftharpoons \text{Si}$. It appears that Ti is placed in the tetrahedral site.

Moore and White (1971) and Dowty (1971) suggested that the optical and infrared vibration spectra could actually be better interpreted as Al or Fe^{3+} replacing Si in the tetrahedral sites. The results of a Mössbauer study of synthetic and natural garnet suggest that the relative preference for the tetrahedral site is in the order Al, Fe^{3+} and Ti^{4+} (Huggins et al. 1977a, b). On the other hand, Schwartz et al. (1980) suggested from

Mössbauer spectra that the preferential enrichment in the tetrahedral site for high temperature garnets of nonmetamorphic origin is Fe^{3+} followed by Al or Ti^{4+} . These results indicate that the substitution $\text{Ti}^{\text{IV}} (\text{Fe}^{3+}, \text{Al})^{\text{VI}} \rightarrow \text{Ti}^{\text{VI}} (\text{Fe}^{3+}, \text{Al})^{\text{IV}}$ is present in the garnet structure.

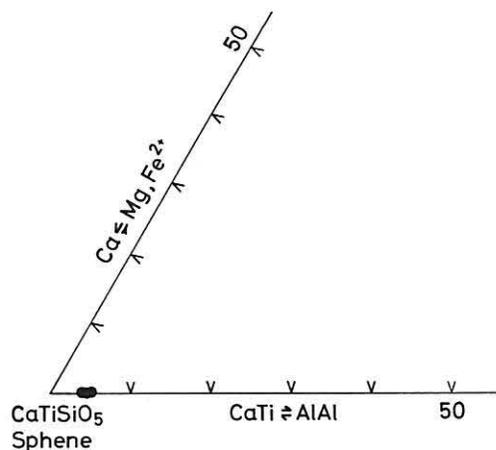
Presence of Ti^{3+} in Ti-rich garnets is suggested by wet-chemical analyses and optical absorption spectra (Moore and White, 1971; Burns, 1972) and wet-chemical analyses (Howie and Wooley, 1968). Schwartz et al. (1980) reported that substantial Ti^{3+} in some natural Fe-Ti garnets is present on the basis of discrepancies between calculated Fe^{2+} / total Fe ratios from Mössbauer and wet-chemical analyses.

Therefore, the exact role of Ti in these garnets still remains unsolved.

The chemical analyses of two clinopyroxenes (Cpx) are listed in Table 4. Although clinopyroxene is not zoned, it shows wide range of composition even within one and the same thin section. Cpx-1 is richer in MgO than other spot analyses, while Cpx-2 is richer in FeO and MnO than others. Total Fe/ Mg + total Fe ratio varies from 0.43 (Cpx-1) to 0.59 (Cpx-2). The molecular proportions of the end-members are calculated according to Akasaka and Onuma (1980). Cpx-1 is composed of 0.2 mole % acmite (Ac), 47.2 mole % diopside (Di), 2.7 mole % hedenbergite (Hd), 32.1 mole % $\text{CaFe}^{3+}\text{AlSiO}_6$ (FATs), 12 mole % Tschermak's molecule (CaTs) and 5.6 mole % $\text{CaTiAl}_2\text{O}_6$ (Tp). Cpx-2 has the composition $\text{Ac}_{0.2}\text{Di}_{35.4}\text{CaMnSi}_2\text{O}_{60.6}\text{Hd}_{24.8}\text{FATs}_{26.0}\text{CaTs}_{8.5}\text{Tp}_{4.5}$. Cpx-1 and Cpx-2 include 49.7% total Tschermak's molecule ($\text{Ts} = \text{CaTs} + \text{FTs} + \text{FATs} + \text{Tp}$) and 39.0 %, respectively. Therefore, these clinopyroxenes are fassaitic pyroxenes.

Sphene is plotted in the CaTiSiO_5 - Al_2SiO_5 - $(\text{Mg}, \text{Fe}^{2+})\text{TiSiO}_5$ diagram (Text-fig.5). It shows that the solubility of Al_2SiO_5 content in CaTiSiO_5 is about 5 mole %.

The FeO to Fe_2O_3 ratio of ilmenite is recalculated according to Carmichael's (1967b) method. The solubility of hematite in ilmenite is approximately 10 mole %. As magnetite solid solution has not been analyzed, temperature is not obtained. However, the oxygen fugacity is estimated at about 10^{-10} at 1000°C according to the calibration curve of Hem_{10} given by Buddington and Lindsley (1964).



Text-fig. 5 Plots of composition of sphene in the CaTiSiO_5 - Al_2SiO_5 - $(\text{Mg}, \text{Fe}^{2+})\text{TiSiO}_5$ triangle.

Discussion

Hijikata and Onuma (1969) reported that $\text{CaFe}^{3+}\text{AlSiO}_6$ is stable at 1 atm and high temperature. Onuma and Yagi (1975) demonstrated that for the system $\text{CaMgSi}_2\text{O}_6$ - $\text{CaAl}_2\text{SiO}_6$ - $\text{CaFe}^{3+}\text{AlSiO}_6$ stability field of clinopyroxene increased with increasing $\text{CaFe}^{3+}\text{AlSiO}_6$ component at atmospheric pressure. $\text{CaAl}_2\text{SiO}_6$ is stable as pyroxene at 1250°C and above 11 kb (Hijikata and Yagi, 1967) or above 12.5 kb (Hays, 1966). Ohashi and Hariya (1975) reported that the maximum pressure of the stability field of $\text{CaFe}^{3+}\text{AlSiO}_6$ is about 43 kb at 1300°C under conditions of high oxidation. Diopside at high pressures has been investigated by Yoder (1952), Boyd and England (1963), and Williams and Kennedy (1969). The melting point at 50 kb is about 2000°C. Hedenbergite is stable below $f_{\text{O}_2} = 10^{-13}$ bar at 800°C and 2 kb (Gustafson, 1974). These experimental results suggest that Cpx-1 and Cpx-2 in the present study are stable under wide physical conditions. Therefore, we can not precisely delimit the conditions of formation of Cpx-1 and Cpx-2 by their chemical compositions.

Investigations of Huckenholz (1969) and Hölzl (1975) for the system $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ - $\text{Ca}_3\text{Fe}_2^{3+}\text{Si}_3\text{O}_{12}$ - $\text{Ca}_3\text{Al}_2\text{Ti}_3\text{O}_{12}$ - $\text{Ca}_3\text{Fe}_2^{3+}\text{Ti}_3\text{O}_{12}$ at 1 atm suggest that Ti-garnet in this study has a stability field in the wide temperature range.

The mineral assemblage of wollastonite + fassaitic pyroxene + vesuvianite indicates that these minerals are products of the contact metamorphism. It is known that the CaO is contained mainly in anorthite molecule in pelitic rocks of the amphibolite and higher facies. The coexistence of anorthite + grandite + fassaitic pyroxene + actinolite suggest that the formation of these minerals belongs to the low-pressure amphibolite facies. Also the presence of glass supports that these xenoliths in volcanic rocks were intensely affected by magmatic heat as wall rocks and as inclusions in the magma.

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