

METAMORPHIC ROCKS OF THE CAPE HINODE DISTRICT, EAST ANTARCTICA

Satoshi KANISAWA

*Department of Earth Sciences, College of General Education,
Tohoku University, Kawauchi, Sendai 980*

and

Keizo YANAI

National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173

Abstract: Microprobe analyses of amphiboles, biotites, clinopyroxenes, feldspars, garnets and Fe-Ti oxides in various metamorphic rocks of the Cape Hinode district, East Antarctica are presented. The analytical results of these minerals show that they crystallized under the condition of amphibolite facies. The composition of hornblendes belongs to a low pressure type, and indicates that they might have crystallized at about 5 kb or lower. Garnet-biotite geothermometry reveals that the estimated temperature is about 650°C. Biotite included in garnet crystal in sillimanite-garnet-biotite gneiss has the composition rich in Mg and poor in Ti and might have been formed at lower temperature than matrix ones.

1. Introduction

The Cape Hinode district, East Antarctica, 160 km northeast of Syowa Station, is composed of various metamorphic rocks belonging to amphibolite facies, and many granitic rocks and pegmatites. Geology of the district has been investigated by YANAI and ISHIKAWA (1978), and major element chemistry has been reported by KANISAWA *et al.* (1979b). In the present study, we will describe the results of microprobe analyses of minerals of these metamorphic rocks and some consideration on the metamorphic condition of the district.

We wish to express our gratitude to Professor Ken'ichiro AOKI and to Dr. Hirokazu FUJIMAKI of Tohoku University, who kindly allowed us the use of EPMA(EDX). Thanks are also due to Professor Kazuo YAMAOKA of Tohoku University for determination of Fe-Ti oxides.

2. Petrochemical Characteristics and Mineral Assemblages of Metamorphic Rocks of the Cape Hinode District

The rocks of the Cape Hinode district are characteristically composed of biotite gneiss and garnet-biotite gneiss which has been called anorthositic gneiss

and garnet anorthositic gneiss by YANAI and ISHIKAWA (1978). Subordinate amounts of garnet gneiss, hornblende gneiss, amphibolite, granites, calc-silicate rocks are intercalated in them. The metamorphic rocks of the district are characterized by the mineral assemblages of amphibolite facies metamorphism. Both of granitic rocks and metamorphic rocks are characterized by scarcity of K-feldspar. The analytical results by KANISAWA *et al.* (1979b) show that the metamorphic rocks of the district have a wide range of chemical composition, but the K_2O content is considerably low and nearly constant throughout all rock types. The K_2O/Na_2O ratio of most rocks is less than 1, being quite different from those of rocks around the Lützow-Holmbukta region. According to YOSHIDA (1978), the geology of East Antarctica can be divided lithostratigraphically into three groups, namely, Skallen, Ongul and Oku-iwa Groups from southwest to northeast, and former two have suffered granulite facies metamorphism. The rocks of the Cape Hinode district may belong to the Oku-iwa Group judging from their lithostratigraphical nature. The chemical characteristics of the rocks of the Oku-iwa Group in other districts such as Cape Ryûgû (NAKAI *et al.*, 1980) and Oku-iwa Rock (NAKAI *et al.*, 1981) are similar to those of Cape Hinode, and most of rocks of these districts have high Na_2O and low K_2O contents. Generally, the rocks of the Oku-iwa Group have low K_2O/Na_2O ratio less than 1. In the Cape Hinode district, the rocks having K_2O/Na_2O ratio larger than 1 is sillimanite-biotite-garnet gneiss only, according to the previous data. This rock occurs as thin intercalations in amphibolite and is different from other biotite-hornblende gneiss and biotite gneiss in the mode of occurrence. Moreover, this rock is rich in Al_2O_3 and poor in alkalis, suggesting a derivative from residual clay-rich sediments. Hornblende-biotite gneiss and biotite gneiss having the K_2O/Na_2O ratio less than 1 are all coarse grained and similar to sandstone or granitic rocks. If we assume that these rocks were derived from sandstone, these chemical characteristics of the rocks belong to eugeosynclinal clan by MIDDLETON (1960) or greywacke sandstone by PETTIJOHN (1963). Assuming that these metamorphic rocks were derived from igneous rocks, chemical characteristics of these rocks are similar to those of trondhjemite—tonalite suite (BARKER, 1979). Chemical characteristics of rocks of the Oku-iwa Group are quite different from K_2O -rich charnockites and other rocks of the Ongul and the Skallen Groups of the Lützow-Holmbukta region, thus the meaning of these chemical differences of rocks among these groups is very serious for considering the provenance of original sediments or the tectonic environment of igneous activities of these districts. The Fe_2O_3/FeO ratios of the Oku-iwa Group rocks are generally higher than those of the Skallen and the Ongul Groups, suggesting higher fO_2 condition in the former. There is a peculiar calc-silicate rock rich in garnet and clinopyroxene (*Sp. No. 74010112*) intercalated in hornblende gneiss. It was previously called the hedenbergite-garnet-plagioclase rock by KANISAWA *et al.* (1979b). This rock has a peculiar composition rich in Al_2O_3 and CaO and poor

in SiO_2 , MgO and alkalis. The results of EPMA analysis have revealed that the clinopyroxene in this rock is not hedenbergite but fassaite rich in Al_2O_3 and that the composition of garnet and plagioclase is Fe-rich grossular and pure anorthite respectively as shown in the subsequent section, thus the rock must be named fassaite-grossular-anorthite rock. High Al_2O_3 clinopyroxene has been reported from Cape Omega, about 80 km southwest of Cape Hinode, by SUZUKI (1979, *Sp. No.* 77010721). This pyroxene is also typical fassaite from SUZUKI's data, and its host rock which is called eclogitic rock by SUZUKI may belong to some kind of calc-silicate rocks as described above.

3. Analytical Results of Metamorphic Minerals

The samples analysed here were collected by YANAI in December 1973 and January 1974 (the 15th Japanese Antarctic Research Expedition). The analysis of minerals has been carried out by means of a scanning electron-probe micro-analyser, Hitachi Model X-560S, with a 2-channel detecting system and 38° take off angle (wave length-dispersible analytical system, WDX) with an accessory energy-dispersible analytical system (Kevex corporation, EDX), using the routine analytical procedure of Tohoku University.

3.1. Amphiboles

Amphiboles are found in amphibolite and biotite-hornblende gneiss, and most of them are common hornblende showing Z-axial colours of blue-green to green. Colourless amphiboles are rarely found in some hornblende gneiss (*Sp. No.* 74010701). They are irregular in shape and are associated with common hornblende and have an actinolitic composition poor in Al and Na. However, amphiboles of this kind are restricted locally, so they are not the products of retrogressive or progressive metamorphism but those of intrusion of pegmatite or granite. In these parts, the composition of amphiboles varies in a wide range on Na and Al. However, except these parts, the compositional range in a single crystal or one hand specimen is not very wide as shown in Table 1. The ranges of *mg*-value of all analysed hornblendes and of host rocks are restricted within 0.52–0.58 and 0.49–0.51 respectively and not much variable. The Al^{IV} range of amphiboles on the anhydrous basis of $\text{O}=23$ is 1.04–1.55, and the Al^{VI} range of them is 0.48–0.77, so amphiboles of the present study are plotted on slightly lower side of 5 kb line in the Si– Al^{VI} relation (RAASE, 1974) as shown in Fig. 1, or slightly higher than $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}=2.0$ line dividing the low pressure metamorphic hornblende and the high pressure one (FLEET and BARNET, 1978). The crossite content in Ca-amphibole, Na in M4, representing high pressure metamorphism is not calculated or very scarce in the present study. The Ti content of amphiboles is lower than 0.17 corresponding to medium- or lower-grade amphibolite facies (RAASE, 1974). The relation between total(A) and Al^{IV} of amphiboles is also

Table 1. EPMA analyses of representative hornblendes.

	74010104 (n=9)		73123113 (n=7)		73123103 (n=6)		74010606 (n=7)		74010701 (n=7)		74010701* (n=7)	
SiO ₂	44.22	0.38***	44.60	0.77	43.99	1.17	44.12	0.38	46.15	1.86	54.42	1.23
TiO ₂	0.73	0.11	1.26	0.12	0.90	0.14	1.34	0.10	0.28	0.33	0.02	0.04
Al ₂ O ₃	12.04	0.43	10.69	0.53	11.37	1.09	11.14	0.53	10.41	1.48	3.45	1.04
FeO**	15.52	0.41	16.62	0.51	16.87	0.92	15.04	0.19	14.97	0.85	10.67	0.39
MnO	0.29	0.06	0.38	0.09	0.43	0.05	0.30	0.03	0.61	0.02	0.75	0.18
MgO	11.10	0.25	10.36	0.43	10.35	0.87	11.34	0.18	11.88	1.02	16.57	0.88
CaO	11.74	0.15	11.89	0.16	12.00	0.16	12.13	0.10	12.08	0.16	11.69	0.65
Na ₂ O	1.25	0.17	1.16	0.17	1.03	0.27	1.10	0.16	0.76	0.17	0.43	0.08
K ₂ O	0.71	0.13	1.20	0.11	1.10	0.13	1.42	0.04	0.95	0.27	0.23	0.06
Total	97.61	1.01	98.16	0.93	98.04	1.10	97.93	0.91	98.09	0.83	98.23	0.13
	Anhydrous basis of O=23											
Si	6.568		6.649		6.575		6.562		6.796		7.711	
Al	1.432		1.351		1.425		1.438		1.204		0.289	
(Tet)	8.000		8.000		8.000		8.000		8.000		8.000	
Al	0.677		0.527		0.578		0.514		0.606		0.288	
Fe ²⁺	1.784		2.030		2.05		1.822		1.756		1.212	
Mg	2.457		2.302		2.306		2.514		2.607		3.497	
Ti	0.082		0.141		0.101		0.150		0.031		0.003	
Mn	—		—		—		—		—		—	
(M ₁ -M ₃)	5.000		5.000		5.000		5.000		5.000		5.000	
Ca	1.820		1.899		1.853		1.914		1.836		1.775	
Mn	0.036		0.048		0.054		0.038		0.076		0.091	
Fe	0.144		0.042		0.093		0.048		0.088		0.052	
Na	—		0.011		—		—		—		0.082	
(M ₄)	2.000		2.000		2.000		2.000		2.000		2.000	
Ca	0.048		—		0.069		0.019		0.070		—	
Na	0.361		0.324		0.299		0.317		0.217		0.037	
K	0.134		0.228		0.210		0.269		0.178		0.043	
(A)	0.543		0.552		0.578		0.605		0.465		0.080	

* Actinolite. ** Total Fe as FeO. *** Standard deviation.

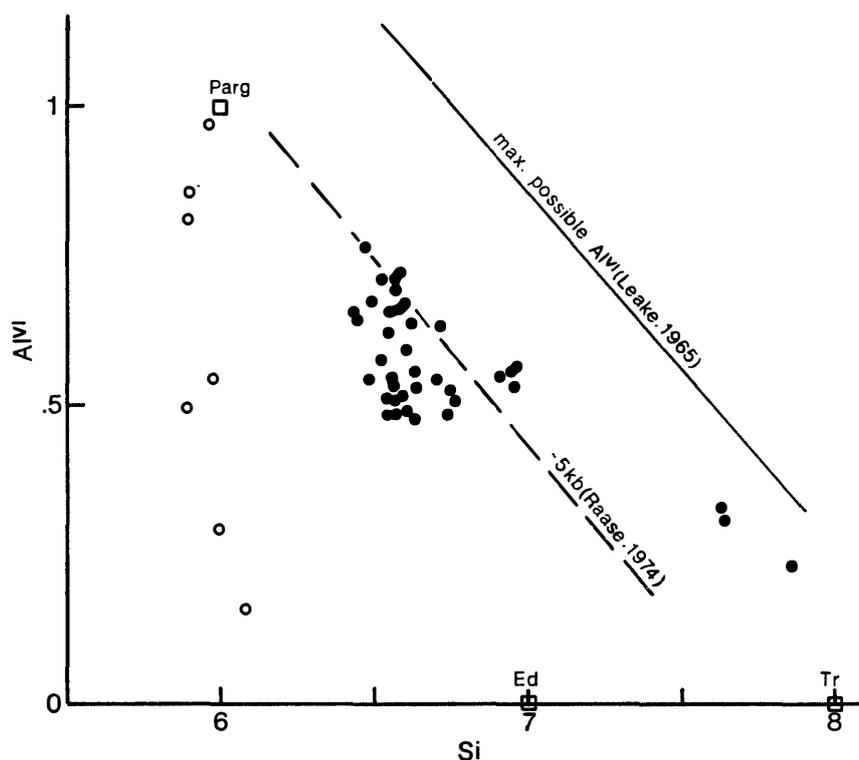


Fig. 1. Relationship between Si and Al^{VI} of Ca-amphiboles. Solid circle: Amphiboles of Cape Hinode. Open circle: Hornblendes of the Lützow-Holmbukta region. Tr, Ed and Parg represent tremolite, edenite and pargasite end member respectively.

about 1:2 (Fig. 2). The 2:1 relations between total(A) and Al^{IV} , and Al^{IV} and Al^{VI} as shown in Figs. 1 and 2, reveal that the substitution of $Na \cdot 2Al^{IV} \rightleftharpoons 2Si$, namely tremolite \rightleftharpoons pargasite substitution, is characteristic of the district. Hornblendes of the present district are clearly poorer in Al^{IV} than those from the Lützow-Holmbukta region (KANISAWA *et al.*, 1979a), while pargasites from the latter region have a wide range of the Al^{VI} content as shown in Figs. 1 and 2.

3.2. Clinopyroxenes

Clinopyroxene sometimes coexists with hornblende (ex. Sp. No. 73123113) having the composition of $Wo_{57-49}En_{36-35}Fs_{17-16}$. The Mg-Fe distribution of coexisting hornblende and clinopyroxene in Sp. No. 73123113 has $K_D = (MgO/FeO)_{cpx} / (MgO/FeO)_{hor} = 2.04$, and the value is higher than that of amphibolite facies (KRETZ and JEN, 1978). Generally K_D of coexisting hornblende and clinopyroxene tends to become large with increase of Al^{IV} of hornblende, so the large K_D of this rock may account for the high content of Al^{IV} ($=1.35$) of the hornblende.

Fassaite in fassaite-grossular-anorthite rock (Sp. No. 74010112) shows

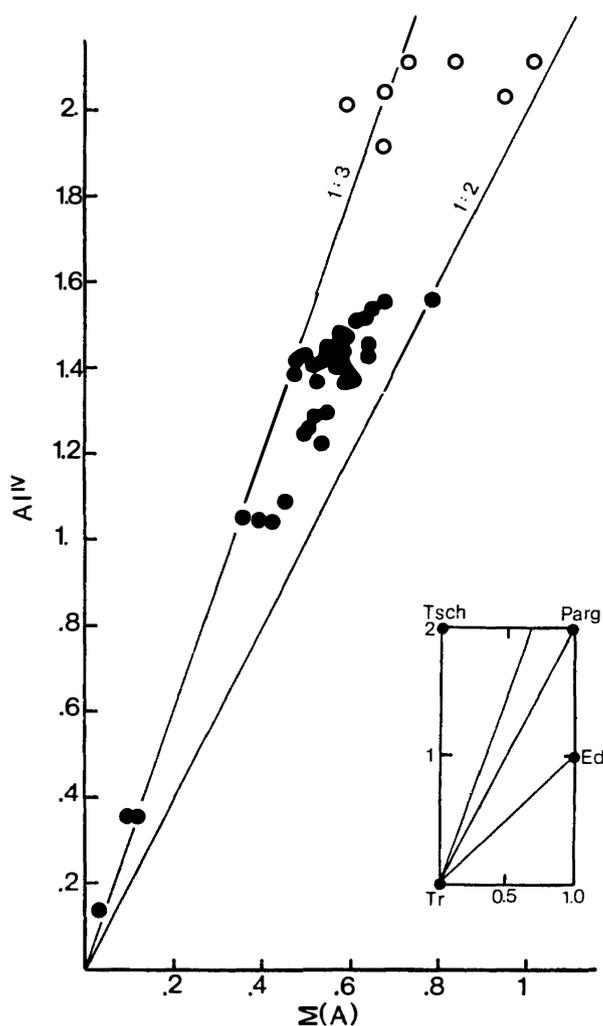


Fig. 2. Relationship between total(A) and Al^{IV} of Ca-amphiboles. Tsch represents tschermakite end member, and other symbols are the same as those in Fig. 1.

Table 2. EPMA analyses of clinopyroxene.

	1 (n=5)		2	3
SiO_2	52.83	0.84**	45.95	43.42
TiO_2	0.11	0.06	0.11	0.34
Al_2O_3	2.00	0.29	6.30	9.67
FeO^*	9.38	0.29	15.63	16.20
MnO	0.59	0.04	0.21	0.12
MgO	11.97	0.31	7.17	6.46
CaO	22.37	0.21	23.73	23.77
Na_2O	0.60	0.12	0.17	0.38
K_2O	—	—	—	—
Total	99.85	1.15	99.27	100.35
O=6 and R=4.000 in fassaite				
Si	1.979		1.782	1.662
Al^{IV}	0.021		0.218	0.338
Al^{VI}	0.068		0.070	0.097
Ti	0.003		0.003	0.097
Fe^{3+}	—		0.103	0.167
Fe^{2+}	0.294		0.404	0.352
Mn	0.019		0.007	0.004
Mg	0.668		0.414	0.368
Ca	0.898		0.986	0.974
Na	0.044		0.013	0.028
K	—		—	—
Total	3.994		4.000	4.000

* Total Fe as FeO.

** Standard deviation.

1. Sp. No. 73123113.

2 and 3. Sp. No. 74010112.

anhedral irregular shape and strong pleochroism with X=bluish green and Z=yellowish green and high dispersion of $r > v$, and has high Al_2O_3 content of 5.86–9.19% and small amounts of TiO_2 and Na_2O . It shows strong zonal structure with Al-rich core and Al-poor rim. Compositional variation of $CaFe^{3+}AlSiO_6$ (FATs) mol ranges from 5.97 to 13.56, and of $CaAl_2SiO_6$ (CaTs) mol from 9.43 to 13.62% respectively. A detailed discussion of fassaite-bearing rock will be given in the future. The analytical results of clinopyroxene are shown in Table 2.

Table 3. EPMA analyses of representative biotites.

	74010104 (n=7)	73123113 (n=6)	73123103 (n=5)	74010606 (n=7)	74010701 (n=7)	74010113 (n=5)	73123106 (n=5)							
SiO ₂	37.71	0.17*	37.22	0.26	37.49	0.50	37.42	0.65	37.33	0.31	37.35	0.32	36.56	0.18
TiO ₂	3.45	0.20	3.71	0.82	3.73	0.11	4.60	0.17	4.19	0.37	2.97	0.61	3.71	0.43
Al ₂ O ₃	15.37	0.45	14.64	0.28	15.43	0.36	15.18	0.50	15.76	0.48	15.97	0.37	15.43	0.35
FeO**	15.94	0.22	18.13	0.83	17.93	0.25	15.87	2.14	16.74	0.58	16.94	0.66	17.99	0.21
MnO	—	—	0.10	0.04	0.23	0.02	0.19	0.06	0.40	0.04	0.15	0.06	0.41	0.07
MgO	14.31	0.33	12.68	1.03	12.42	0.27	13.73	0.97	12.41	0.33	13.28	0.72	11.52	0.21
CaO	0.15	0.04	0.22	0.02	0.15	0.05	0.15	0.06	0.16	0.05	0.13	0.03	0.18	0.06
Na ₂ O	0.37	0.09	0.24	0.08	0.18	0.11	0.22	0.06	0.24	0.09	0.21	0.11	0.20	0.11
K ₂ O	9.04	0.09	9.29	0.23	9.58	0.17	9.49	0.40	9.66	0.14	9.49	0.07	9.32	0.17
Total	96.34	0.49	96.23	0.92	97.14	1.28	96.85	1.17	96.89	0.62	96.50	0.76	95.32	0.29
							Anhydrous basis of O=22							
Si	5.578	5.592	5.573	5.528	5.540	5.557	5.552							
Al ^{IV}	2.422	2.408	2.424	2.472	2.460	2.443	2.448							
Al ^{VI}	0.257	0.184	0.275	0.171	0.296	0.357	0.314							
Ti	0.385	0.419	0.417	0.511	0.468	0.332	0.423							
Fe ²⁺	1.971	2.277	2.229	1.961	2.079	2.107	2.285							
Mn	—	0.013	0.029	0.024	0.051	0.019	0.052							
Mg	3.155	2.839	2.752	3.023	2.745	2.945	2.606							
Ca	0.024	0.035	0.024	0.024	0.026	0.021	0.030							
Na	0.106	0.070	0.052	0.063	0.070	0.061	0.060							
K	1.706	1.780	1.817	1.789	1.829	1.801	1.806							
Total	15.604	15.617	15.595	15.566	15.564	15.643	15.576							
mg	0.615	0.554	0.549	0.604	0.563	0.581	0.527							

* Standard deviation. ** Total Fe as FeO.

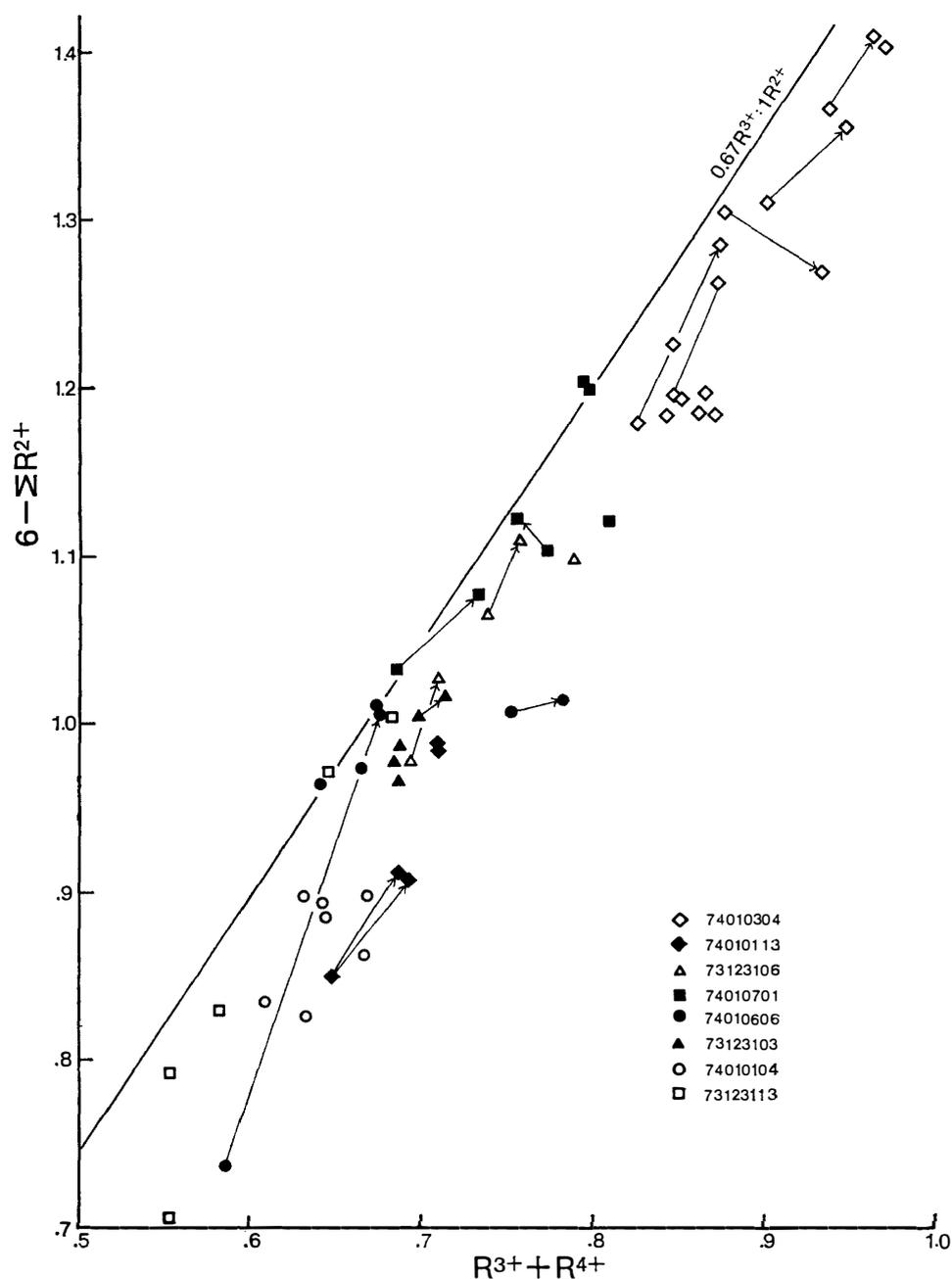


Fig. 3. Relationship between $(R^{3+} + R^{4+})$ and $(6 - \Sigma R^{2+})$ of biotites. Arrow indicates the composition from core to rim in single crystal.

3.3. Biotites

Biotite is the most widely distributed mafic mineral, but its compositional variation is not so distinct. Its pleochroism is generally X=pale yellow and Z=dark brown. Its *mg*-value ranges from 0.53 to 0.65, and Si on the anhydrous basis

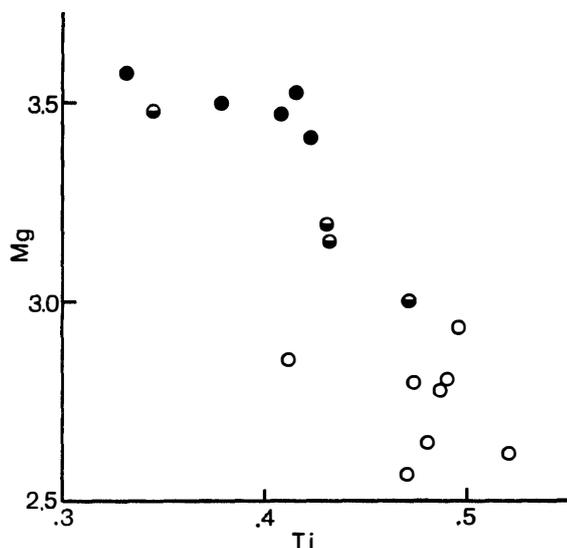


Fig. 4. Ti and Mg contents of biotites in sillimanite-biotite-garnet gneiss (Sp. No. 74010304). Solid circle: Biotites included in garnet. Half solid circle: Biotites in contact with garnet rim. Open circle: Matrix biotite outside of garnet.

of $O=22$ ranges from 5.43 to 5.62, and the Ti range is 0.54–0.28 (Table 3). The relation between $(6-\Sigma R^{2+})$ and $(R^{3+}+R^{4+})$ is shown in Fig. 3. It is clear from Fig. 3 that these values tend to increase in the order of amphibolite through biotite-hornblende gneiss to biotite gneiss, and also tend to increase from core to rim within a single crystal. In the sillimanite-biotite-garnet gneiss (Sp. No. 74010304), biotite included in garnet is lower in the values of $6-\Sigma R^{2+}$ and $(R^{3+}+R^{4+})$ than matrix biotite. Moreover, the former biotite is richer in Mg and poorer in Ti than the latter (Fig. 4). This phenomenon indicates the difference of physical condition of crystallization between the two modes of occurrence of biotites.

3.4. Garnets

Garnet is found in garnet-biotite gneiss, sillimanite-biotite-garnet gneiss and calc-silicate rocks. Garnet in garnet-biotite gneiss is nearly euhedral to subhedral granular crystal and has the composition of almandine rich in MnO as shown in Table 4. It shows weak zonal structure with slightly decreasing MnO and MgO and increasing CaO. Inclusions are scarcely observed, and sometimes ore minerals occur along its cracks. Garnet in sillimanite-biotite-garnet gneiss shows irregular shape and poikiloblastic texture having many inclusions of quartz, biotite and ore in the core, but scarce in the rim. This garnet shows a considerably homogeneous almandine composition having narrow ranges of MnO 0.61–0.75%, MgO 6.4–7.5% and CaO 0.88–1.1%. The Al content on the basis of $O=12$ is nearly 2.00, thus most Fe may occupy as Fe^{2+} in the Y-site. Garnet coexisting with fassaite in Sp. No. 74010112 shows irregular poikiloblastic texture including fassaite, anorthite and magnetite. Compositional variation is narrow and nearly homogeneous showing $And_{31.9}Gro_{49.9}Alm_{14.2}Sp_{1.7}Pyr_{2.3}$ (Table 4).

Table 4. EPMA analyses of representative garnets.

Sp. No.	74010113				74010304				74010112	
	Rim (n=4)		Core (n=7)		Rim (n=6)		Core (n=7)		(n=7)	
SiO ₂	38.02	0.29*	38.47	0.20*	38.58	0.16*	38.57	0.26*	37.85	0.26*
TiO ₂	—	—	—	—	—	—	—	—	0.14	0.05
Al ₂ O ₃	21.39	0.32	21.38	0.17	21.60	0.48	21.51	0.18	13.44	0.66
FeO	24.89	0.55	25.44	0.11	30.62	0.45	31.02	0.51	17.30	0.51
MnO	6.81	0.11	7.02	0.12	0.71	0.04	0.66	0.03	0.77	0.14
MgO	5.00	0.35	5.38	0.32	7.20	0.13	6.96	0.35	0.57	0.13
CaO	3.28	0.13	2.48	0.16	0.98	0.04	0.95	0.07	28.96	0.26
Total	99.38	0.26	100.16	0.49	99.69	0.55	99.67	0.38	99.03	0.56
Fe ₂ O ₃									12.04**	0.76
FeO									6.47**	0.37
Total									100.24	0.53
Si	3.014		3.025		3.018		3.024		3.004	
Al	1.998		1.981		1.992		1.986		1.257	
Ti	—		—		—		—		0.008	
Fe ³⁺	—		—		—		—		0.719	
Fe ²⁺	1.650		1.673		2.003		2.034		0.429	
Mn	0.457		0.467		0.047		0.044		0.052	
Mg	0.590		0.630		0.840		0.814		0.068	
Ca	0.279		0.209		0.082		0.080		2.462	
Total	7.988		7.984		7.982		7.982		8.000	

* Standard deviation. ** Fe₂O₃ and FeO were calculated as R=8.000.

3.5. Feldspars

K-feldspar is very scarce in metamorphic and granitic rocks of the district. In sillimanite-garnet-biotite gneiss, K-feldspar occurs as independent crystals having the composition Or_{80.3-88.3}Ab_{12.8-18.5}An_{1.2-1.7}. In other rocks, however, K-feldspar occurs only as antiperthite in plagioclase. Antiperthitic K-feldspar shows the composition Or_{87.7-92.2}Ab_{10.9-8.4}An_{0.9-1.6}. Porphyroblastic crystals of plagioclase frequently develop in amphibolite and these are slightly rich in An mol compared with the matrix plagioclase. Plagioclase in fassaite-grossular-anorthite rock is nearly pure anorthite. The analytical results of feldspars are shown in Table 5.

3.6. Fe-Tioxides

In the rocks of the present study, mineral assemblages of Fe-Ti oxides are as follows: magnetite alone, ilmenite-hematite, and ilmenite-magnetite. Magnetite free from any other Fe-Ti oxides is nearly pure Fe₃O₄. The analytical results of

Table 5. EPMA analyses of feldspars.

	1	2	3	4	5	6	7	8	9	10	11	12
SiO ₂	55.69	60.33	60.09	60.34	59.54	63.64	60.09	63.08	64.51	65.02	65.43	43.59
Al ₂ O ₃	28.07	25.86	25.34	24.92	25.53	19.26	24.89	23.36	18.84	18.67	18.90	35.39
FeO	—	—	—	0.17	0.04	—	0.01	0.04	—	—	—	0.18
CaO	10.41	7.26	6.88	7.19	7.20	0.18	6.74	4.63	0.32	0.23	0.24	20.16
Na ₂ O	5.89	7.26	6.88	7.63	7.20	0.80	7.67	8.82	0.78	1.40	2.04	0.18
K ₂ O	0.36	0.11	0.18	0.20	0.39	15.25	0.35	0.41	15.18	14.38	13.47	0.06
Total	100.41	100.82	100.12	100.45	100.15	99.13	99.76	100.35	99.63	99.70	100.08	99.56
	O=32											
Si	10.007	10.650	10.691	10.721	10.618	11.838	10.738	11.135	11.926	11.969	11.958	8.124
Al	5.944	5.380	5.314	5.218	5.367	4.223	5.241	4.861	4.104	4.052	4.070	7.773
Fe	—	—	—	0.025	0.006	—	0.002	0.006	—	—	—	0.028
Ca	2.004	1.374	1.312	1.368	1.375	0.036	1.290	0.876	0.063	0.045	0.047	4.025
Na	2.050	2.487	2.630	2.630	2.577	0.290	2.657	3.019	0.281	0.500	0.724	0.065
K	0.083	0.024	0.041	0.046	0.089	3.618	0.080	0.093	3.579	3.377	3.140	0.013
Total	20.088	19.915	19.988	20.008	20.032	20.005	20.008	19.990	19.953	19.943	19.939	20.028
An	48.4	35.4	32.9	33.8	34.0	0.9	32.0	22.0	1.6	1.2	1.2	98.1
Ab	49.6	64.0	66.0	65.0	63.8	7.3	66.0	75.7	7.2	12.8	18.5	1.6
Or	2.0	0.6	1.0	1.1	2.2	91.8	2.0	2.3	91.2	86.1	80.3	0.3

1. Sp. No. 74010104. Porphyroblastic plagioclase core, 2. Porphyroblastic plagioclase rim, 3. Martix plagioclase showing granoblastic texture.
4. Sp. No. 73123113. Plagioclase showing granoblastic texture.
5. Sp. No. 74010606. Plagioclase, 6. Antiperthitic K-feldspar included in plagioclase of No. 5.
7. Sp. No. 74010701. Plagioclase.
8. Sp. No. 74010113. Plagioclase, 9. Antiperthitic K-feldspar included in plagioclase of No. 8.
10. and 11. Sp. No. 74010304. K-feldspar.
12. Sp. No. 74010112. Anorthite.

some Fe-Ti oxides are listed in Table 6. Detailed discussion on Fe-Ti oxides will be given in another paper.

4. Garnet-Biotite Geothermometry

For the estimation of the metamorphic condition of the Cape Hinode district, the Mg-Fe distribution of coexisting garnet and biotite pairs of sillimanite-biotite-garnet gneiss (*Sp. No. 74010304*) and garnet-biotite gneiss (*Sp. No. 74010113*) was used as a geothermometer. The relation between biotite inclusion in garnet and immediately adjacent garnet pairs in sillimanite-biotite-garnet gneiss shows the value of $K_D = (\text{Mg/Fe})_{\text{gar}} / (\text{Mg/Fe})_{\text{bio}} = 0.16$, which is similar to those of staurolite-kyanite zone, chloritoid-staurolite zone or kyanite zone reported by LYONS

Table 6. EPMA analyses of Fe-Ti oxides.

	1	2	3	4
TiO ₂	46.69	47.23	0.25	0.30
FeO	50.35	46.93	92.05	92.24
MnO	1.32	3.80	0.37	0.53
V ₂ O ₃	0.89	1.02	—	—
Cr ₂ O ₃	—	—	—	—
Total	99.25	98.98	92.66	93.07
Fe ₂ O ₃	10.78	9.24	68.14	68.33
FeO	40.65	38.62	30.73	30.75
Total	100.33	99.91	99.49	99.90

1. Sp. No. 74010104. Ilmenite. 3. Sp. No. 74010113. Magnetite.
 2. Sp. No. 74010606. Ilmenite. 4. Sp. No. 74010112. Magnetite.

and MORSE (1970), HIETANEN (1969) and BALTATZIS (1979), and the equilibrium temperature of the pairs is 525–570°C, 499–521°C (assumed to be $P=5$ kb), and 520–582°C by the equations of THOMPSON (1976), GOLDMAN and ALBEE (1977), FERRY and SPEAR (1978) respectively. The relation between the matrix biotite outside of garnet and the rim of garnet shows $K_D=0.29$, and the value is nearly equal to that of sillimanite zone presented by LYONS and MORSE (1970). The equilibrium temperature is calculated as 700°C, 631°C ($P=5$ kb), and 777°C by the equations of the above authors respectively. From the composition of garnet rim and associated biotite pairs of garnet-biotite gneiss (Sp. No. 74010113), the equilibrium temperature is calculated as 670°C, 613°C and 723°C respectively and $K_D=0.26$. The results of calculation are shown in Table 7. The Mg-Fe distribution of garnet-biotite is shown in Fig. 5. The results calculated by the method of FERRY and SPEAR (1978) indicate somewhat higher values than those by THOMPSON (1976) and GOLDMAN and ALBEE (1977), because the effects of Ti in biotite and Ca and Mn in garnet have not been taken into account in the equation of the former. Therefore, THOMPSON's and GOLDMAN and ALBEE's equations are suitable to apply the garnet-biotite geothermometry to natural rock systems. The estimated temperature, calculated by THOMPSON's and GOLDMAN and ALBEE's equations from the garnet rim and matrix biotite pair in sillimanite-biotite-garnet gneiss, is nearly equal to that of biotite-garnet rim pair in garnet-biotite gneiss, and is 613–700°C averaging 650°C. The Mg-Fe distribution between inclusion biotite in garnet and immediately adjacent garnet in sillimanite-biotite-garnet gneiss indicates the temperature of 500–570°C. The composition of biotite included in garnet is richer in Mg and poorer in Ti than that of matrix biotite as shown in Fig. 4, indicating lower temperature than the latter. This is com-

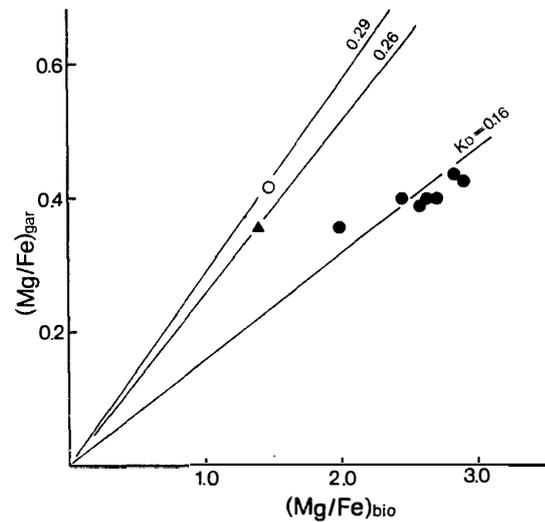
Table 7. Garnet-biotite geothermometry.

	1	2	3	4	5	6	7	8	9
Garnet									
Mg/Fe	0.387	0.439	0.426	0.397	0.397	0.400	0.358	0.419	0.358
X _{Mn}	0.015	0.014	0.015	0.014	0.015	0.015	0.016	0.016	0.154
X _{Ca}	0.025	0.028	0.026	0.026	0.028	0.026	0.030	0.028	0.094
Biotite									
Mg/Fe	2.586	2.821	2.879	2.685	2.610	2.440	1.993	1.466	1.398
X _{Fe}	0.279	0.262	0.258	0.271	0.277	0.291	0.334	0.406	0.583
X _{Ti}	0.061	0.074	0.058	0.066	0.072	0.074	0.076	0.085	0.058
X _{Al^{VI}}	0.093	0.077	0.094	0.087	0.079	0.075	0.074	0.079	0.062
T°C									
THOMPSON (1976)			525	—	570			700	670
GOLDMAN and ALBEE (1977)	503	511	509	499	501	512	521	631	613
FERRY and SPEAR (1978) (Assumed to be P=5 kb)	524	535	521	520	528	552	582	777	723

- 1-7. Biotite inclusion and immediately adjacent garnet. } Sillimanite-biotite-garnet gneiss (Sp. No. 74010304).
 8. Matrix biotite and garnet rim.
 9. Garnet biotite gneiss (Sp. No. 74010113).

Fig. 5. The distribution of Mg and Fe between coexisting biotite and garnet.

Solid circle: The relation between biotite inclusion in garnet and immediately adjacent garnet. Open circle: The relation between matrix biotite and garnet rim (Sp. No. 74010304). Solid triangle: The relation between biotite and garnet rim (Sp. No. 74010113).



patible with the above estimated temperature. Garnet shows strong zonal structure in lower metamorphic grade, but it is compositionally homogenized and its zoning disappears with increasing grade because of diffusion of elements under high temperature condition. The disappearance of zoning is thought to have taken place

at about 600–650°C (YARDLEY, 1977; WOODSWORTH, 1977). Garnet of the present study is nearly homogeneous and does not show strong zonal structure. Taking account of the above-mentioned facts, garnet of the district has become homogeneous and original zoning has disappeared. Therefore, it can not be said that the relation between inclusion biotite and immediately adjacent garnet is in equilibrium. However, it is probable that garnet core and inclusion biotite in it were formed at lower temperature than the one for the formation of garnet rim and matrix biotite.

Petrology of the metamorphic rocks of Cape Ryûgû, 60 km ENE of Cape Hinode, has been carried out by YOSHIKURA *et al.* (1979). According to them, temperature of metamorphism in the district has been estimated at about 600°C, if the pressure is assumed to be 5 kb. The metamorphic condition of Cape Hinode was nearly the same as or somewhat higher in temperature than that of Cape Ryûgû.

5. Conclusion

The chemical composition of metamorphic minerals of the Cape Hinode district reveals that they crystallized in the amphibolite facies condition. Hornblende shows the composition of low pressure metamorphic one or slightly lower side of 5 kb line in Si–Al^{VI} relation (RAASE, 1974). Aluminum-rich clinopyroxene fassaite is found in some calc-silicate rock intercalated in hornblende gneiss. The estimated temperature, calculated by THOMPSON's (1976) and GOLDMAN and ALBEE's (1977) equations from garnet rim–matrix biotite pairs in sillimanite-biotite-garnet gneiss and garnet-biotite gneiss, is 613–700°C and averages 650°C. Garnet of the district became homogeneous and its zonal structure disappeared during progressive metamorphism. In sillimanite-biotite-garnet gneiss, garnet core and biotite inclusion were formed at lower temperature than that of garnet rim and matrix biotite respectively.

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Note added after submission of the manuscript: A rock having the association kyanite-andalusite-sillimanite was found from the Cape Hinode district by Dr. Y. HIROI (personal communication). This association is very important for the estimation of PT-condition of the district.