PETROLOGY AND GEOTHERMOMETRY
OF THE CLINOPYROXENE-GARNET ROCK FROM CAPE RYÛGÛ, EAST ANTARCTICA

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Abstract: In Cape Ryûgû, the most abundant rocks are biotite gneiss, garnet-biotite gneiss and hornblende-biotite gneiss, none of which show any obvious indication of their more detail metamorphic condition from their mineral parageneses.

Petrology of the clinopyroxene-garnet rock occurring as thin intercalation in biotite gneiss of this area is described to determine the physical condition of metamorphism.

Assuming the pressure during the metamorphism to be 5 kb, the temperature estimated from the distribution coefficient of Fe and Mg between coexisting garnet and clinopyroxene obtained from microprobe analyses using the Råheim and Green's calibration is about 590°C.

Råheim and Green suggested that the distribution coefficient, Kd_{Fe-Mg}^{Ga-Cpx} value, varies with grossular content in the garnet and thus with bulk rock composition. As the bulk rock chemistry of the investigated rock is different from the composition of starting materials used in their experiment, Råheim and Green's calibration cannot applied to this rock without reservation.

To check the effect on the Kd_{Fe-Mg}^{Ga-Cpx} value of Ca content in the garnet, this estimated temperature is compared with the temperature determined on the basis of the Kd_{Fe-Mg}^{Ga-Bi} geothermometer and the "plagioclase-garnet-Al_2SiO_5-quartz geothermometer" from staurolite-bearing sillimanite-garnet-biotite gneiss which is considered to have been formed under an isophysical condition.

The calculated temperature based on the Kd_{Fe-Mg}^{Ga-Cpx} well agrees with those determined by the other methods.

The temperature condition is also consistent with mineral chemistry of low

Al_2O_3 content in clinopyroxene coexisting with garnet and with the field observation that this area lacks in migmatization phenomena by partial melting of the metapelites.

1. Introduction

Cape Ryûgû, situated at 67°58'S latitude and 43°55'–44°10'E longitude and about 220 km northeast of Syowa Station on East Ongul Island, is one of the wide ice-free areas along the Prince Olav Coast (Fig. 1). This area elongates about 10 km in the east-west direction with a width of 2 km.
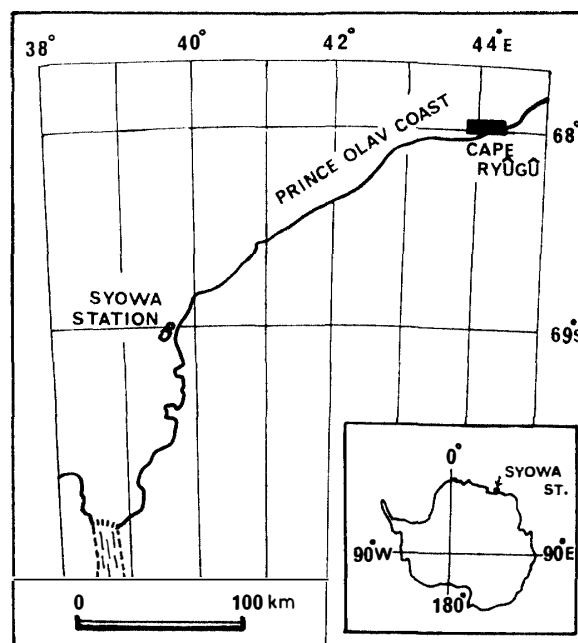

Fig. 1. Index map of the studied area.

The geological survey of this area first carried out by the present authors during the summer of 1977–1978. The basement rock of this area is composed mainly of biotite gneiss associated with minor amounts of garnet-biotite gneiss, clinopyroxene gneiss, amphibolite, hornblende gneiss, augen gneiss, crystalline limestone and pegmatite (Fig. 2). The general structure is homoclinal with an east-west trend, dipping 30°–50° south.

The metamorphism of these rocks judging from the petrographic study under the microscope, belongs probably to the amphibolite facies. But there is no critical mineral assemblage which provides more accurate fix on the metamorphic condition.

So, this paper intends to deal with the petrology of the clinopyroxene-garnet rock found in area-2 of Cape Ryûgû and to reveal the physical condition of metamorphism of this area.
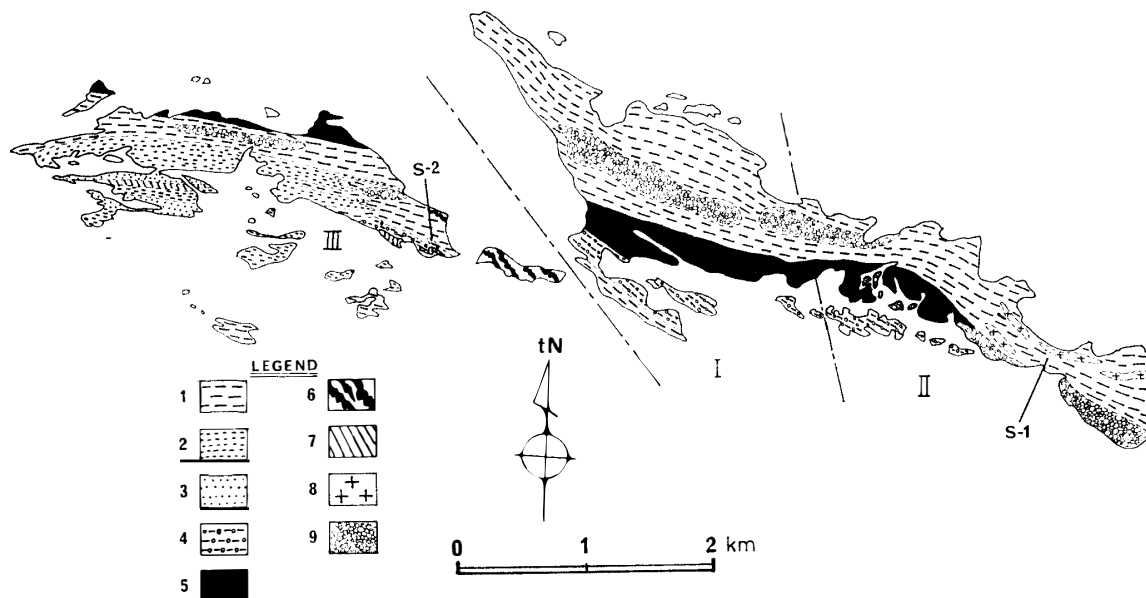
Fig. 2. *Lithofacies map of Cape Ryûgû. This area is divided into three sub-areas (area-1, area-2 and area-3) for the convenience of field survey. 1: Biotite gneiss. 2: Siliceous gneiss. 3: Leucocratic biotite gneiss. 4: Garnet-biotite gneiss, 5: Melanocratic fine-grained biotite gneiss. 6: Folded biotite gneiss. 7: Hornblende gneiss. 8: Pegmatite, aplite, granite. 9: Morain. S-1: Sampling locality of the clinopyroxene-garnet rock. S-2: Sampling locality of the staurolite bearing sillimanite-garnet-biotite gneiss. I: Area-1. II: Area-2. III: Area-3.*

2. Field Relation and Petrography

The clinopyroxene-garnet rock discussed in this paper occurs as a thin layer about 50 cm thick intercalated with the biotite gneiss in area-2 of Cape Ryûgû (Fig. 2). In hand specimen, green pyroxene and red garnet are the main constituent minerals, but the rock is partly rich in greenish black hornblende.

Under the microscope, the rock is characterized by a fine-grained granoblastic texture formed by clinopyroxene, garnet, plagioclase, quartz and accessory sphene. The clinopyroxene is fine-grained equigranular and anhedral, very faintly greenish in thin section, and shows virtually no pleochroism. The garnet has a pinkish tint and is fine-grained anhedral in shape. Most plagioclases are optically zoned and twinned according to the albite law. Subordinate green hornblende, replacing clinopyroxene as the flaky crystal, is obviously formed as a retrogressive alteration product in a subsequent stage of metamorphism.

Modal composition is given in Table 2. Bulk rock composition of this rock deduced from modal analyses and constituent mineral chemistry analyzed by means of electron probe microanalyzer shows that the rock is rich in CaO and FeO (Fig. 3, Table 2).
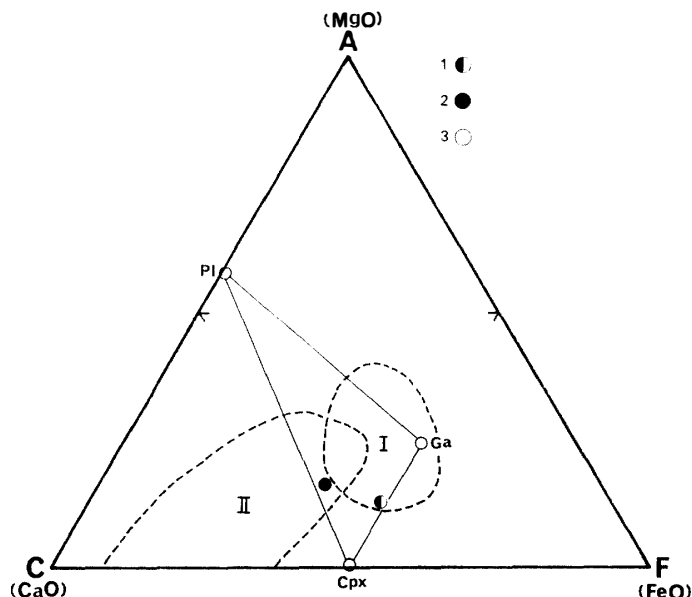
Fig. 3. *ACF diagram and MgO–FeO–CaO (wt%, total Fe as FeO) diagram of the bulk rock and constituent minerals. 1: Bulk rock composition plotted in ACF diagram. 2: Bulk rock composition plotted in MgO–FeO–CaO diagram. 3: Mineral composition plotted in ACF diagram. I: Igeous rock field (in MgO–FeO–CaO diagram). II: Sedimentary rock field (from WALKER et al., 1960).*

Although it is difficult to estimate the origin of the high grade basic metamorphic rock, this rock is plotted in the sedimentary rock field on the MgO–FeO–CaO triangular diagram used by WALKER et al. (1960) (Fig. 3). Therefore, this rock is presumed to be of sedimentary rock origin.

3. Mineral Chemistry

3.1. Analytical procedure

Chemical data on the garnet, clinopyroxene and plagioclase used in this paper were obtained by probe analyses carried out on the JEOL JXA–5A electron probe microanalyzer with 3 channel detectors and 40° take off angle. Accelerating voltage was kept at 15 kV and specimen current and beam diameter were respectively 0.02 microampere and 3–4 microns on standard periclase. Correction of the observed X-ray intensity ratio was done by the method of BENCE and ALBEE (1968) using the alpha factors given by NAKAMURA and KUSHIRO (1970). To obtain the composition of the plagioclase solid solution, the rapid quantitative microprobe analytical method proposed by YUSA (1975) was employed. The analytical results can be summarized as follows.

3.2. Garnet

Prior to the quantitative analyses at individual points on the garnet crystal,

some garnets were investigated to check the homogeneity by scanning the sample under the fixed beam for Fe, Mg and Ca across the grains.   As shown in Fig. 4, the garnets are weakly zoned to the rim of lower Ca and Mg/Fe, but the difference of the content between core and rim is always much less than 1 % in weight as CaO, MgO and FeO (Table 1).
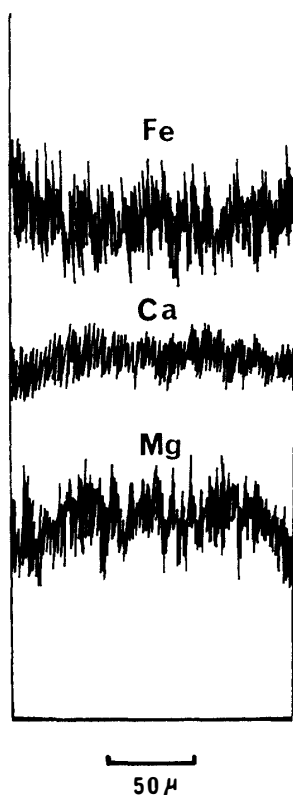

Fig. 4.   Chemical compositional zoning pattern
of the garnet.

The quantitative analyses of the garnets were made on the spot very close to associated clinopyroxene (on the outermost rim of an individual grain).   Table 1 shows the results of chemical analyses of the garnets along with their atomic proportions calculated on the basis of 12 oxygens.

It must be noted that the observed amounts of Al are always deficient to fill the Y site of the idealized Fe^{3+} free garnet formulae.   So some Fe may be fixed in the Y site as Fe^{3+}.   The Fe^{3+} content of one garnet (1–1–a) calculated after the scheme of Råheim and Green (1975) and Hamm and Vieten (1971) is 0.068 and 0.104, respectively.   The garnet is predominantly almandine with markedly higher grossular+ andradite contents and minor amounts of spessartine and pyrope.

3.3.   Clinopyroxene

Scanning analyses across some grains of the clinopyroxene indicate that the clinopyroxenes are virtually unzoned with respect to Fe, Mg and Ca.   The results of the

Table 1. *Electron microprobe analyses of garnets in the clinopyroxene-garnet rock from Cape Ryûgû (R: rim, C: core).*

	1-1-a	1-1-c	1-2-a	1-2-c	2-1-a	2-1-c	2-2-a	2-2-c	3-5-a	3-5-c	A-3-a	A-3-c	A-4-a	A-4-c
	R	C	R	C	R	C	R	C	R	C	R	C	R	C
SiO_2	37.34	37.82	37.80	37.79	37.38	36.29	36.86	36.68	37.45	37.94	37.83	37.09	37.62	37.07
TiO_2	0.05	0.07	0.05	0.04	0.06	0.06	0.02	0.11	0.02	0.05	0.04	0.04	0.03	0.04
Al_2O_3	20.68	19.92	19.87	19.77	20.34	20.70	20.83	20.32	20.73	19.84	20.72	20.03	20.64	19.87
FeO^*	21.11	21.32	22.33	22.35	21.61	21.99	20.80	21.77	22.23	21.83	22.28	22.06	22.77	22.43
MnO	5.23	5.16	5.55	5.52	5.52	5.31	5.65	5.45	5.61	5.29	5.42	5.34	5.47	5.46
MgO	2.16	2.27	2.09	2.24	2.12	2.35	2.18	2.19	2.04	2.15	2.15	2.23	2.12	2.22
CaO	12.47	12.88	11.35	11.52	12.14	12.61	12.68	12.49	12.21	11.89	11.69	11.89	11.29	11.50
Na_2O	0.02	0.01	tr	tr	tr	tr	tr	tr	tr	tr	tr	0.01	0.01	tr
K_2O	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
Total	99.06	99.45	99.04	99.23	99.17	99.31	99.02	99.01	100.29	98.99	100.13	98.69	99.95	98.59
O=12														
Si	2.988	3.018	3.036	3.031	2.997	2.920	2.957	2.956	2.976	3.042	3.001	2.994	2.996	2.999
Ti	0.003	0.004	0.003	0.002	0.003	0.003	0.001	0.007	0.001	0.003	0.002	0.003	0.002	0.003
Al	0.012	—	—	—	0.003	0.080	0.043	0.044	0.024	—	—	0.006	0.004	0.001
Al	1.938	1.874	1.880	1.868	1.918	1.883	1.926	1.886	1.917	1.874	1.936	1.899	1.933	1.894
Fe	1.142	1.423	1.499	1.499	1.448	1.479	1.395	1.467	1.477	1.463	1.478	1.489	1.516	1.517
Mn	0.354	0.349	0.377	0.375	0.374	0.362	0.384	0.372	0.377	0.359	0.364	0.365	0.369	0.374
Mg	0.257	0.270	0.250	0.268	0.253	0.282	0.260	0.263	0.241	0.257	0.253	0.269	0.251	0.267
Ca	1.069	1.101	0.976	0.989	1.043	1.086	1.090	1.078	1.039	1.021	0.994	1.028	0.963	0.997
Na	0.002	0.002	—	—	—	—	—	—	—	—	0.001	0.001	0.001	—
K	—	—	—	—	—	—	—	—	—	—	—	—	—	—

* Total Fe as FeO.

Table 2. Electron microprobe analyses of clinopyroxenes in the clinopyroxene-garnet rock, and bulk rock composition and modal composition of the clinopyroxene-garnet rock from Cape Ryûgû (R: rim, C: core).

	1-1-b	1-2-b	2-1-b	2-1-d	2-2-b	3-5-b	3-5-d	A-3-b	A-4-b	A-4-d	Bulk rock composition**	
	R	R	R	C	R	R	C	R	R	C		
SiO₂	52.07	51.41	51.68	51.53	51.48	52.41	51.70	51.84	51.54	51.43	SiO₂	45.5
TiO₂	0.10	0.14	0.18	0.36	0.11	0.13	0.10	0.16	0.06	0.10	Al₂O₃	11.2
Al₂O₃	1.28	1.40	1.46	1.33	1.25	1.33	1.28	1.46	1.36	1.40	FeO	15.6
FeO*	10.80	10.76	10.28	11.52	11.22	11.51	11.79	10.95	10.77	11.54	MnO	2.9
MnO	0.72	0.95	0.70	0.95	0.81	0.79	0.95	0.76	0.80	0.86	MgO	6.5
MgO	10.63	10.88	11.20	10.82	10.97	10.63	10.44	10.74	10.88	10.92	CaO	18.2
CaO	23.51	23.53	23.83	22.72	22.78	22.95	22.69	22.89	23.12	22.42	Na₂O	0.2
Na₂O	0.23	0.26	0.21	0.28	0.19	0.25	0.24	0.21	0.11	0.27	Total	100.1
K₂O	tr	tr	tr	0.14	tr	tr	tr	tr	tr	tr		
Total	99.33	99.33	99.54	99.65	98.82	100.00	99.19	99.01	98.64	98.94		
O=6											Modal composition	
Si	1.985	1.965	1.965	1.967	1.983	1.986	1.981	1.982	1.978	1.973	Cpx	49.3
Ti	0.003	0.004	0.005	0.010	0.003	0.004	0.003	0.005	0.002	0.003	Ga	39.0
Al	0.015	0.035	0.035	0.033	0.017	0.014	0.019	0.018	0.022	0.027	Ho	3.8
Al	0.042	0.028	0.040	0.027	0.040	0.045	0.039	0.049	0.039	0.036	Pl	2.5
Fe	0.344	0.344	0.327	0.368	0.361	0.365	0.378	0.349	0.346	0.370	Qz	3.6
Mn	0.023	0.031	0.023	0.031	0.003	0.025	0.031	0.025	0.026	0.029	Others	1.9
Mg	0.603	0.620	0.634	0.615	0.630	0.600	0.596	0.611	0.622	0.624	Total	100.1
Ca	0.960	0.963	0.970	0.930	0.940	0.931	0.931	0.937	0.950	0.921		
Na	0.017	0.019	0.016	0.021	0.014	0.018	0.018	0.016	0.008	0.020		
K	—	—	—	0.007	—	—	—	—	—	—		

* Total Fe as FeO.
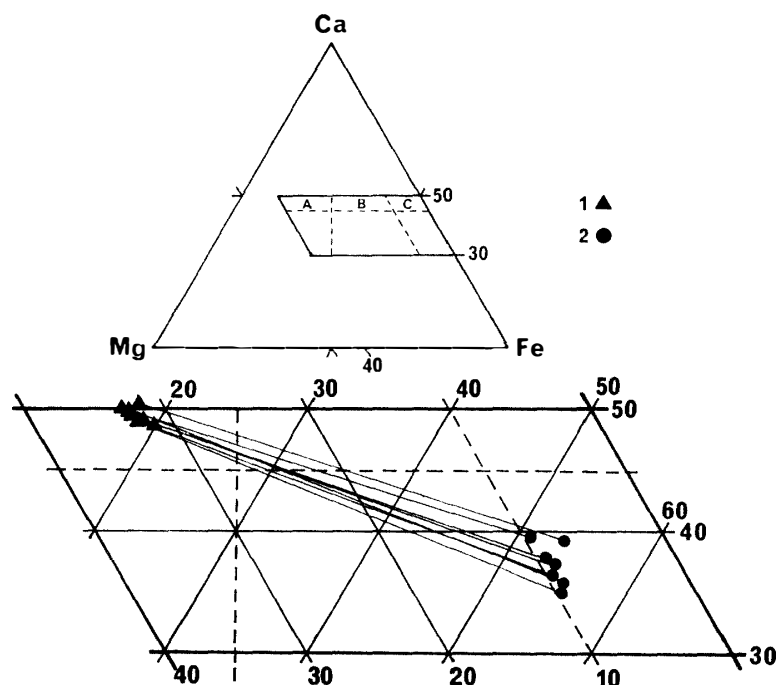** Calculated values from modal composition and constituent mineral chemistry.

Fig. 5. Coexisting garnet and clinopyroxene plotted in terms of Ca, Mg and Fe (atomic) and
connected by tie line. 1: Clinopyroxene. 2: Garnet. A: Salite. B: Ferrosalite.
C: Hedenbergite (Nomenclature of clinopyroxene after POLDERVARRT and HESS,
1955).

quantitative analyses and atomic proportion calculated on the basis of 6 oxygens are
shown in Table 2.

Fig. 5 illustrates the composition of the coexisiting garnet and clinopyroxene in
terms of Ca, Mg and Fe. As the Fe^{3+} contents estimated from the pyroxene stoi-
chiometry are very low, the amounts of ferric iron are probably negligible. Analyzed
clinopyroxenes have a salitic composition (Fig. 5) with low Al_2O_3 contents (Fig. 6)
in spite of the fact that they coexist with garnet. It is considered generally that Al_2O_3
poor pyroxene coexisting with garnet is stable under a very high pressure or low tem-
perature condition.

3.4. Plagioclase

The plagioclase is strongly zoned as shown in Fig. 7, and anorthite component
tends to decrease toward the rim.

4. Physical Condition of Metamorphism

BANNO (1970) showed that the distribution coefficient of Fe (unless designation
provided, Fe means Fe^{2+} in the later section) and Mg between coexisting garnet and
clinopyroxene [$Kd_{Fe-Mg}^{Ga-Cpx} = (Fe/Mg)_{Ga}/(Fe/Mg)_{Cpx}$] is sensitively dependent on tem-
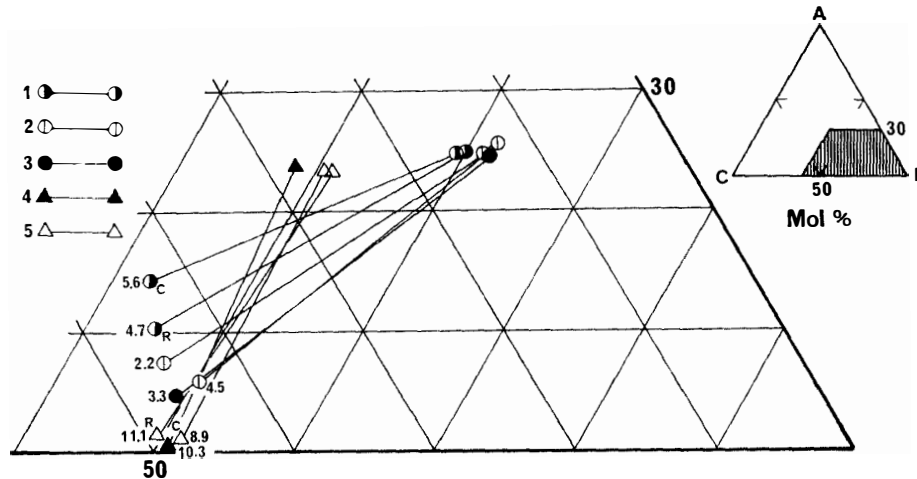perature but virtually independent on pressure and bulk chemistry, so that it can be

Fig. 6.   ACF plot of coexisting garnet and clinopyroxene of different occurrences and connected
by tie line.
1:   HUBREGTES (1973) (granulite facies), C: Core pair, R: Rim pair.
2:   O'HARA (1961) (granulite facies).
3:   Basic granulite from the Kurosegawa Tectonic Zone in southwest Japan (granulite
facies).
4:   Garnet amphibolite from the Kurosegawa Tectonic Zone (amphibolite facies).
5:   This study, C: Core pair, R: Rim pair.

Numbers attached to the symbols indicate Kd_{Fe-Mg}^{Ga-Cpx} values calculated on the basis of
all Fe as FeO.
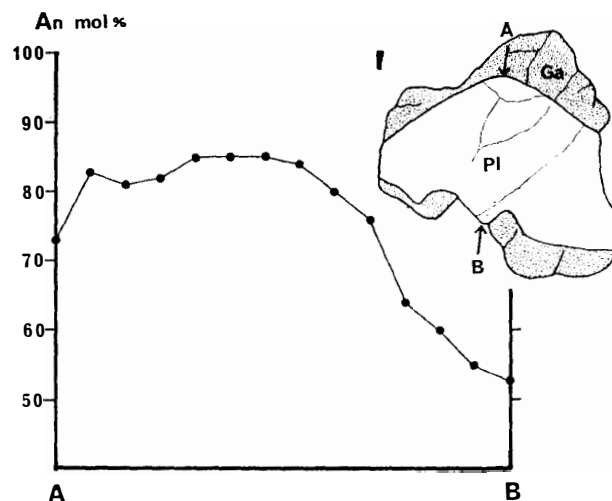
Fig. 7.   Variation of anorthite content in single plagioclase crystal.   A-B: Traverse line.
Ga: Garnet.   Pl: Plagioclase.

used as a useful geothermometer.

RÅHEIM and GREEN (1974) provided experimental data on distribution of Fe and Mg between coexisting garnet and clinopyroxene for eclogite and garnet granulite of tholeiitic composition. Although BANNO (1970) estimated the pressure effect on Kd_{Fe-Mg}^{Ga-Cpx} is small, they found that Kd_{Fe-Mg}^{Ga-Cpx} increase with increasing pressure, and calibrated Kd_{Fe-Mg}^{Ga-Cpx} as a function of temperature and pressure. If the pressure can be independently estimated, their calibration curve can be used as a potential geothermometer.

Recently, MORI and GREEN (1978) examined distribution of Fe and Mg between coexisting ferromagnesian minerals in garnet lherzolite, and they concluded that the Kd_{Fe-Mg}^{Ga-Cpx} is the most sensitive geothermometer.

After stoichiometric recalculation of clinopyroxene and garnet composition (estimation of Fe^{3+} and Fe^{2+} contents), the Kd_{Fe-Mg}^{Ga-Cpx} values were calculated on the adjacent garnet and clinopyroxene rim and on the core of this rock. The Kd_{Fe-Mg}^{Ga-Cpx} values on the rim give a little higher value than of the core. As this is attributed to the retrogressive effect, the minimum Kd_{Fe-Mg}^{Ga-Cpx} value ($=8.1$) on the core can be regarded as an equilibrated Kd_{Fe-Mg}^{Ga-Cpx} value at a near-peak of metamorphism.

The clinopyroxene-garnet rock gives no useful information concerning pressure of metamorphism. But in area-3 of Cape Ryûgû, which was under the same physical condition as area-2 during the metamorphism, staurolite-bearing sillimanite-garnet-biotite gneiss was found (more detailed petrological study on this rock will be published in another paper). As shown in Fig. 8, the distribution coefficient Kd_{Fe-Mg}^{Ga-Cpx}

Fig. 8. Possible P-T condition (shaded area) of the clinopyroxene-garnet rock from Cape Ryûgû determined based on Råheim and Green's geothermometer and "plagioclase-garnet-Al_2SiO_5-quartz geothermometer" (GHENT, 1976) with the stability field of Al-silicate polymorph after HOLDAWAY (1971). ① is a reaction curve for albite + K-feldspar + quartz + H_2O = melt (beginning of anatexis in gneiss) from WINKLER (1976). P-T curve (log Kd = -2.59) determined by "plagi-oclse-garnet-Al_2SiO_5-quartz geother-mometer" is shown by alternating dash and double dots symbols. Basalt-garnet granulite-eclogite phase transi-tional boundaries determined by RINGWOOD and GREEN (1966) and GREEN and RINGWOOD (1967) are shown by dashed lines. Equidistri-bution coefficient Kd_{Fe-Mg}^{Ga-Cpx} lines shown by alternating long dash and dot symbols for the distribution of Fe and Mg between synthetic coexisting garnet and clinopyroxene for tholeiitic basalt composition are from RÅHEIN and GREEN (1974).
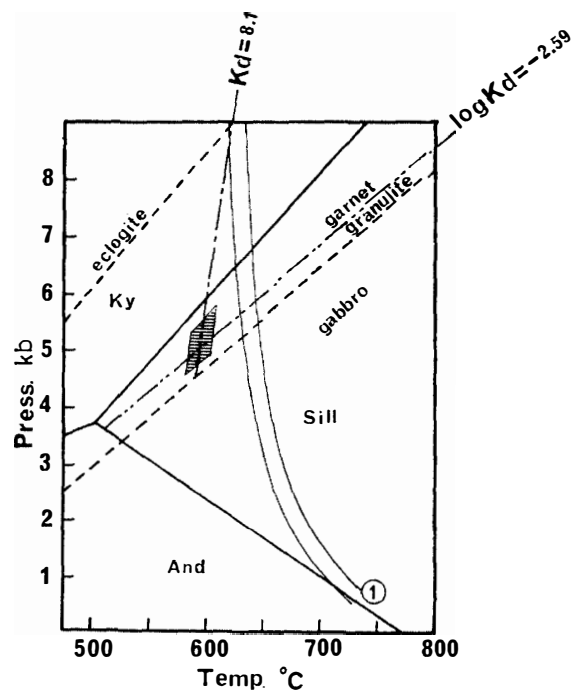
line of the core ($Kd^{Ga-Cpx}_{Fe-Mg} = 8.1$) crosses the sillimanite-kyanite phase transition curve at pressure about 6 kb.   So, we can assume that the pressure prevailing at the peak of metamorphism is less than 6 kb.

On the basis of Råheim and Green's geothermometer, assuming the pressure to be 5 kb, the Kd^{Ga-Cpx}_{Fe-Mg} value of the core gives a temperature about 590°C.

As mentioned above, RÅHEIM and GREEN (1974) used tholeiitic basalt as starting materials to synthesize coexisting garnet and clinopyroxene and showed that the effect on the Kd^{Ga-Cpx}_{Fe-Mg} value of the bulk rock chemistry, especially the Mg/Mg+Fe ratio of the rock, is negligible.   But they also pointed out that the Kd^{Ga-Cpx}_{Fe-Mg} value between coexisting garnet and clinopyroxene crystallized at 30 kb, 1100°C from the Lunar Highland Basalt with very high Al_2O_3 and CaO is higher than the case of the tholeiitic basalt formed under the same condition.   The garnet composition in the Lunar Highland Basalt at 30 kb, 1100°C (44 mol. % grossular component) is very different in grossular content from the garnet in the tholeiitic basalt (19 mol. % grossular component).   This result clearly showed that the Kd^{Ga-Cpx}_{Fe-Mg} value depends on the grossular content of the garnet.

The studied clinopyroxene-garnet rock is richer in CaO as mentioned previously, and grossular+andradite content in the garnet of this rock makes up about 35 mol. %. Consequently, it is possible that the Kd^{Ga-Cpx}_{Fe-Mg} value in this study is apparently larger and indicates a lower equilibrium temperature by the effect of the grossular component in the garnet.

In the later section, the authors will discuss the effect on the Kd^{Ga-Cpx}_{Fe-Mg} of the grossular component in comparison with temperature estimated by the other geothermometer.

As already mentioned, staurolite-bearing sillimanite-garnet-biotite gneiss occurs in area-3 as an intercalation in the biotite gneiss which is one of the most common rock facies in this area.   Chemical analyses were made on garnet, biotite and plagioclase in this rock by means of electron probe microanalyzer.   The value of ln Kd^{Ga-Bi}_{Fe-Mg} (natural logarithm of the apparent distribution coefficient of Fe and Mg between coexisting garnet and biotite) of coexisting garnet and biotite pair in natural rock was crudely calibrated as a function of temperature (THOMPSON, 1976; GOLDMAN and ALBEE, 1977).

FERRY and SPEAR (1978) also calibrated ln Kd^{Ga-Bi}_{Fe-Mg} as a function of temperature and pressure by cation exchange reaction experiments.

As empirical THOMPSON's and GOLDMAN and ALBEE's calibration include the effect of the other elements on the Kd^{Ga-Bi}_{Fe-Mg} value, e. g. Mn and Ca in garnet and Ti in biotite, it is suitable to apply them for natural rock system.   The Kd^{Ga-Bi}_{Fe-Mg} values of this rock calculated from analyzed data and estimated temperature based on the Kd^{Ga-Bi}_{Fe-Mg} geothermometer developed by THOMPSON (1976) and GOLDMAN and ALBEE (1977) are given in Table 3.

Another geothermometer for estimating the equilibrium temperature is "plagio-

Table 3. *Calculated temperature based on the distribution coefficient of Fe and Mg between coexisting garnet and biotite in the staurolite bearing silli-manite-garnet-biotite gneiss from area-3 of Cape Ryûgû.*

Method ln kd_{Fe-Mg}^{Ga-Bi}	Thompson (1976)	Goldman and Albee (1977)
−1.48 (rim)	630° C	570° C
−1.17 (core)	730° C	640° C

clase-garnet-Al_2SiO_5-quartz geothermometer" used by Ghent (1975).

Ghent (1976) demonstrated that the reaction

$$3\ CaAl_2Si_2O_8 = Ca_3Al_2Si_3O_{12} + 2\ Al_2SiO_5 + SiO_2$$
anorthite   grossular   quartz
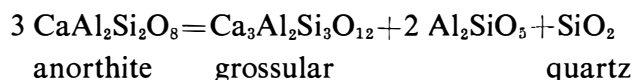
can be used as a potential geothermometer and geobarometer.

The equilibrium of this reaction with sillimanite as Al-silicate polymorph, considering the effect of plagioclase and garnet solid solution and assuming the ideal solution model on both minerals, can be described by the following equation.

$$\frac{-2551.4}{T} + 7.1711 - \frac{0.24842(P-1)}{T} + 3\ \log X_{Gross}^{Ga} - 3\ \log X_{An}^{Pl} = 0. \qquad (1)$$

$T = °K$,

$P = bar$,

$X_{Gross}^{Ga} = $ mol. fraction of grossular component in garnet,

$X_{An}^{Pl} = $ mol. fraction of anorthite component in plagioclase.

The logarithm of the apparent distribution coefficient Kd is defined as log Kd = 3 log X_{Gross}^{Ga} − 3 log X_{An}^{Pl}.

The log Kd value calculated from the analyses of garnet and plagioclase in the staurolite-bearing sillimanite-garnet-biotite gneiss is −2.59. The P–T curve obtained by substitution of this Kd value into eq. (1) is shown in Fig. 8. If we assume the pressure during the metamorphism is 5 kb, the temperature estimated by this geothermometer is about 600°C.

An upper temperature limit is given by the lack of migmatite structure which leads to the conclusion that the condition of partial melting was not reached in Cape Ryûgû area (Fig. 8).

Thus the temperature obtained by the Kd_{Fe-Mg}^{Ga-Cpx} of the clinopyroxene-garnet rock is consistent with the temperature estimated by both Kd_{Fe-Mg}^{Ga-Bi} geothermometer and "plagioclase-garnet-Al_2SiO_5-quartz geothermometer" from cofacial staurolite-bearing sillimanite-garnet-biotite gneiss.

Possibly, this result indicates that the grossular content at least in compositional

range up to 35 mol. % grossular+andradite has no detectable effect on the Kd_{Fe-Mg}^{Ga-Cpx} value.

Therefore, it may be allowed to consider that the temperature estimated from the Kd_{Fe-Mg}^{Ga-Cpx} value obtained in this study, using the calibration of RÅHEIM and GREEN (1974), is the temperature of formation of the clinopyroxene-garnet rock.

5. Conclusion

In Cape Ryûgû, we found the clinopyroxene-garnet rock occuring as a thin layer intercalated in biotite gneiss in area-2. Bulk rock chemical composition as well as field occurrence show that this intercalation could be a metamorphosed sedimentary layer whose composition is richer in CaO.

Chemical analyses of clinopyroxene and garnet were made by means of electron probe microanalyser to elucidate the physical condition of the metamorphism. Application of the Kd_{Fe-Mg}^{Ga-Cpx} geothermometer calibrated by RÅHEIM and GREEN (1974) to this rock indicates a temperature close to 590°C, if the pressure is assumed to be 5 kb.

The other estimates of the temperature of the metamorphism can be made using the Kd_{Fe-Mg}^{Ga-Bi} geothermometer (THOMPSON, 1976; GOLDMAN and ALBEE, 1977) and the "plagioclase-garnet-Al_2SiO_5-quartz geothermometer" (GHENT, 1976) obtained from cofacial staurolite-bearing sillimanite-garnet-biotite gneiss occurring in area-3.

These geothermometers provide nearly the same equilibrium temperature as estimated by the Kd_{Fe-Mg}^{Ga-Cpx} geothermometer, so it is probably safe to conclude that the investigated clinopyroxene-garnet rock crystallized at about 600°C.

Because of the presence of sillimanite as stable Al_2SiO_5 polymorph in this area, if the peak of temperature during the metamorphism was about 600°C, the highest pressure must have been not over 6 kb.

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