

ORTHOPYROXENE-BEARING ROCKS FROM THE TENMONDAI
AND NAGA-IWA ROCKS IN THE PRINCE OLAV COAST,
EAST ANTARCTICA:
FIRST APPEARANCE OF ORTHOPYROXENE IN
PROGRESSIVE METAMORPHIC SEQUENCE

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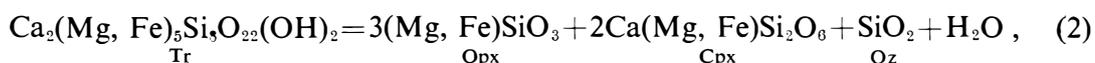
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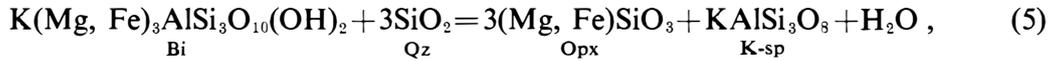
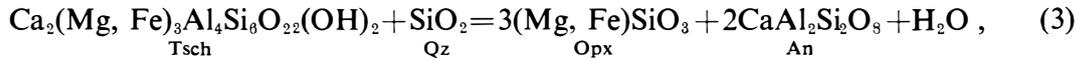
Abstract: Orthopyroxene first appears in the Tenmondai and Naga-iwa Rocks in the progressive metamorphic sequence of the kyanite-sillimanite type from northeast to southwest along the Prince Olav and Sôya Coasts, East Antarctica. Field occurrence and detailed petrography of three orthopyroxene-bearing rocks from the bedrock exposures are presented in this paper. The mineral compositions as well as mineral textures suggest that the rocks are close to chemical equilibrium, that orthopyroxene was first produced in such manner (order) as is predicted experimentally and theoretically, and that the chemical compositions of the calcic amphiboles coexisting with orthopyroxene can be indicators of metamorphic grade.

1. Introduction

The first appearance of orthopyroxene in a progressive metamorphic sequence is usually considered to mark the beginning of the granulite facies, though the detail differs from textbook to textbook (MIYASHIRO, 1965, 1973; WINKLER, 1979; TURNER, 1981). Orthopyroxene is produced by various reactions as follows;



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and so on. The equilibrium temperatures of these reactions vary with the Fe^{2+}/Mg ratios of the minerals, as well as with P_{total} , $P_{\text{H}_2\text{O}}$, and P_{O_2} . Therefore, the amphibolite-granulite facies transition is usually gradual.

HIROI *et al.* (1983a, b) showed progressive metamorphism of the kyanite-sillimanite type in the Proterozoic high-grade metamorphic rocks exposed along the Prince Olav and Sôya Coasts, East Antarctica (68–69.5°S, 39–45°E). Metamorphic grade increases from northeast to southwest, and the coasts are divided into three areas of different metamorphic facies; amphibolite, transitional, and granulite (Fig. 1). In the transitional area orthopyroxene occurs only sporadically and aluminous anthophyllite (gedrite) is still stable.

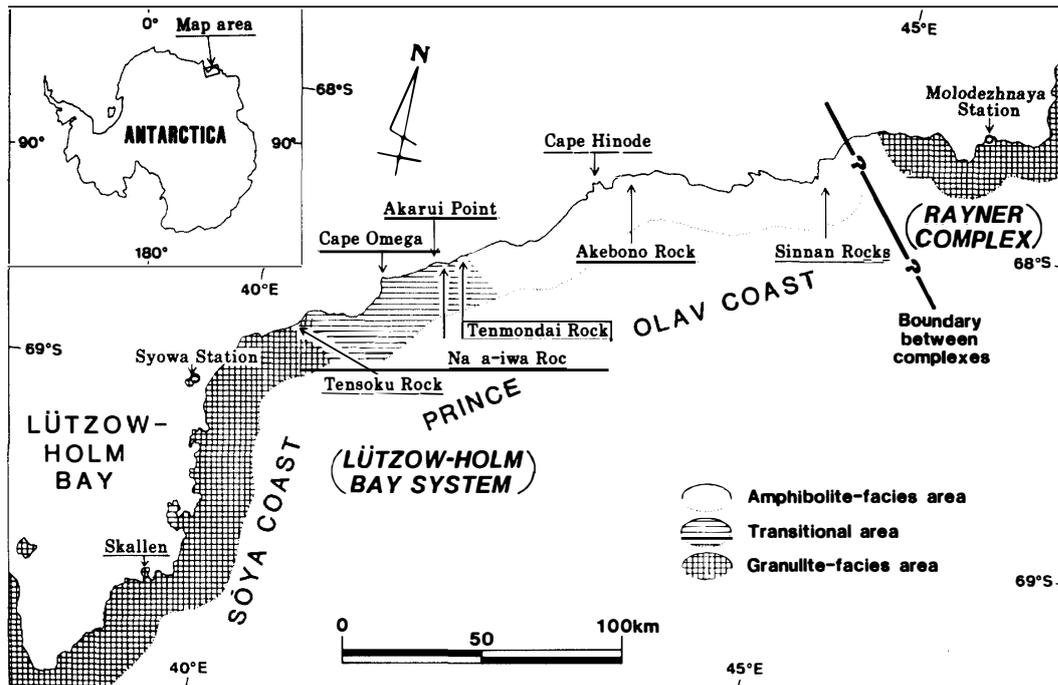


Fig. 1. Map of the Prince Olav and Sôya Coasts, showing geologic units, boundary, and metamorphic facies.

This paper aims to present petrography of the rocks in which orthopyroxene first appears in the progressive sequence, and to discuss the phase relations and compositional changes of minerals.

2. Geologic Outline

The high-grade metamorphic rocks in the Prince Olav and Sôya Coasts were

once termed the Lützow-Holm Bay system (TATSUMI and KIZAKI, 1969). Later they were divided into two distinct geologic units, which are, from east to west, the Okuiwa group (Insel complex) and the Ongul group, based on metamorphic and deformational characteristics (RAVICH and KAMENEV, 1975; RAVICH and GURIKUROV, 1978; YOSHIDA, 1978, 1979a; YOSHIDA *et al.*, 1982, 1983; GURIKUROV, 1982). The "amphibolite-facies" Okuiwa group (Insel complex) was considered by YOSHIDA (1978, 1979a) and YOSHIDA *et al.* (1982, 1983) to be younger than the granulite-facies Ongul group. However, recent geologic studies of the Okuiwa group (Insel complex) have revealed that the lithologic and deformational features of the group are in common to those of the Ongul group (HIROI *et al.*, 1983a; SHIRAIISHI *et al.*, 1983). Both groups consist largely of well-layered pelitic and intermediate rocks and partly of migmatitic rocks, and were folded, at least, twice; the earlier isoclinal folds with axial planes trending N-S to NW-SE and the later open to close folds with axial planes of an NE-SW trend. The pelitic rocks are biotite, garnet-biotite, and sillimanite-biotite gneisses, and the intermediate rocks include biotite-hornblende gneiss and charnockitic gneiss. The migmatitic rocks are granitic to granodioritic in composition, and are of anatectic origin (HIROI *et al.*, 1983b). Recent petrologic studies, in addition, have revealed that the metamorphic features such as the facies series of the groups are in common, as shown below. Therefore, the high-grade metamorphic rocks in the coasts are collectively called as the Lützow-Holm Bay system again (Fig. 1) (HIROI *et al.*, 1983a). The Lützow-Holm Bay system was extensively intruded by the Early Paleozoic granite and pegmatite. Detailed geology of the bedrock exposures along the coasts can be found in the Antarctic Geological Map Series issued by the National Institute of Polar Research, Tokyo, Japan.

The K-Ar and Rb-Sr ages of total rocks or mineral separates concentrate at about 500 Ma, indicating the heating event coeval with the Early Paleozoic granite and pegmatite activity (YANAI and UEDA, 1974), which is known over a large portion of East Antarctica (GREW, 1982). A few Rb-Sr total rock or mineral ages, however, range from 1000 to 1200 Ma (MAEGOYA *et al.*, 1968; SHIRAHATA, 1983), dating the regional metamorphism of the Lützow-Holm Bay system. GREW (1978) reported a similar Rb-Sr whole rock age (987 Ma) on charnockitic gneiss of the Rayner complex exposed at Molodezhnaya Station (see location in Fig. 1). YANAI *et al.* (1983) recently have suggested that rocks of the Lützow-Holm Bay system have a low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, which indicates that the system did not have a long pre-metamorphic history. This is in marked contrast with a suggested age of 1900 Ma by SHIRAHATA (1983) for pyroxene gneiss of the Lützow-Holm Bay system and with the long poly-metamorphic history of the Rayner complex (GREW, 1978).

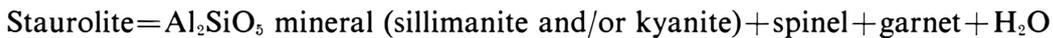
3. Petrologic Outline

The Prince Olav and Sôya Coasts are divided into three areas of different metamorphic grade, as mentioned above (Fig. 1). The eastern part of the Prince Olav Coast is the amphibolite-facies area where calcium-poor amphiboles (anthophyllite, gedrite, and cummingtonite) occur (RAVICH and KAMENEV, 1975; HIROI *et al.*, 1983a, b), and its western part is a transitional area from the amphibolite to the granulite facies.

In the transitional area orthopyroxene occurs only sporadically (HIROI *et al.*, 1983a, b; SUZUKI, 1983), and gedrite is still stable (this paper). The Sôya Coast to the west is the granulite-facies area characterized by the common occurrence of orthopyroxene in various kinds of rocks (BANNO *et al.*, 1964; KIZAKI, 1964; SUWA, 1968; YOSHIDA, 1978, 1979a, b; YOSHIDA and AIKAWA, 1983; YOSHIDA *et al.*, 1982; SUZUKI, 1982, 1983).

The sillimanite+K-feldspar association is commonly found throughout the coasts (HIROI *et al.*, 1983a, b). Even the corundum + muscovite+K-feldspar association is found in a silica-deficient rock from the amphibolite-facies area (HIROI *et al.*, 1983a, b). Metastable kyanite occurs in most of sillimanite-bearing rocks regardless of metamorphic grade, indicating the regional metamorphism was of the kyanite-sillimanite type (HIROI *et al.*, 1983a, b). On the other hand, andalusite rarely occurs in kyanite-sillimanite-bearing rocks cut extensively by the Early Paleozoic granite and pegmatite, suggesting the thermal metamorphism by the granite and pegmatite under the condition differing from the preceding regional metamorphism (HIROI *et al.*, 1983a, b).

Within the amphibolite-facies area the following staurolite dehydration reaction is inferred to have taken place (HIROI *et al.*, 1983a, b).



The reaction product is found not only in the transitional area but also in the granulite-facies area, showing the common prograde recrystallization history of the high-grade metamorphic rocks along the coasts (HIROI *et al.*, 1983a).

4. Field Occurrence and Chemical Compositions of Orthopyroxene-Bearing Rocks

In the progressive metamorphic sequence along the Prince Olav and Sôya Coasts, orthopyroxene first appears in the Tenmondai and Naga-iwa Rocks in the western part of the Prince Olav Coast (Fig. 1). These bedrock exposures are located at the eastern and western flanks of the outlet of the Higasi-naga-iwa Glacier (Fig. 2), and are underlain mainly by well-layered pelitic and intermediate gneisses and granodioritic migmatite. Basic rocks of subordinate amount occur as thin layers or blocks within the well-layered gneisses and migmatite. Migmatite shows various structures like agmatite, scholenite, diktyonite, nebulite, etc. The compositional layering of well-layered gneisses as well as mineral foliations strikes NW-SE and dips steeply toward SW or NE, showing tight folds. Small discordant masses (mostly dikes) of reddish brown granite and pegmatite, probably Early Paleozoic in age, intrude the gneissic and migmatitic complex. One and two specimens of orthopyroxene-bearing rocks were collected from the Tenmondai and Naga-iwa Rocks, respectively (Fig. 2). Mineral assemblages of the specimens as well as of a gedrite-bearing rock are listed in Table 1. T-10 from the Tenmondai Rock is free from quartz, while the others contain various amount of quartz.

T-10 occurs as a paleozome within granodioritic migmatite (Fig. 3a). It is characterized in hand specimen by pale greenish brown plagioclase associated with brown orthopyroxene, dark green hornblende and black biotite. The migmatite is

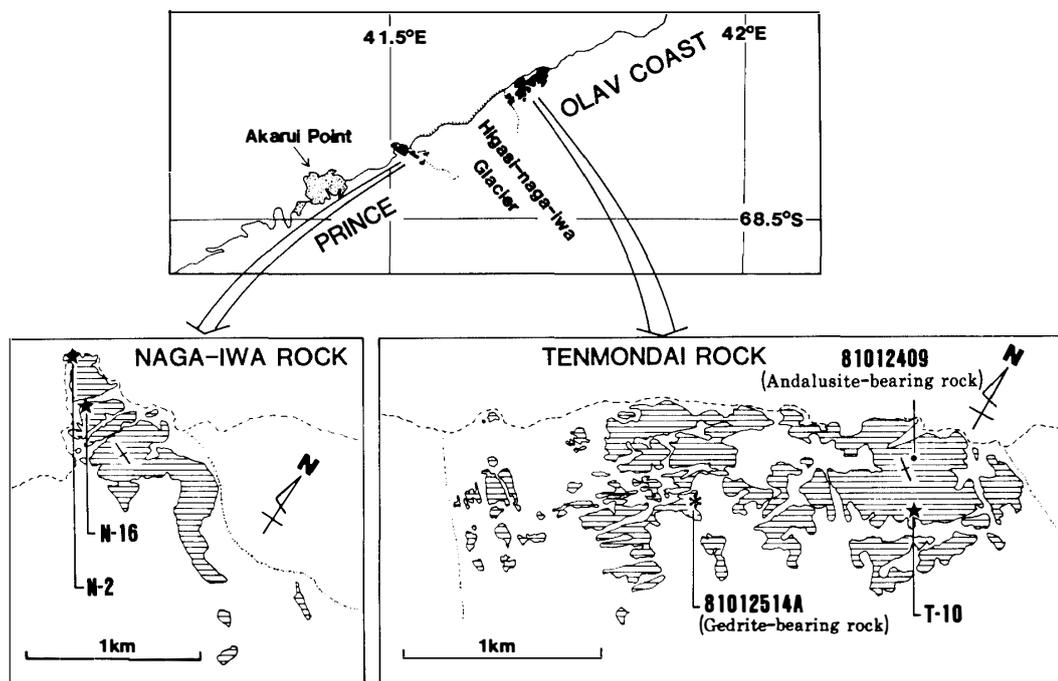


Fig. 2. Map showing localities of specimens described.

intruded by reddish brown granitic dikes and veins. Andalusite-bearing kyanite-sillimanite-garnet-biotite gneiss (Sp. No. 81012409), which is extensively cut by the granite, occurs near the locality of T-10 (Fig. 2). Andalusite is a product of the thermal metamorphism by the granite, while kyanite and sillimanite are the products of the preceding regional metamorphism (HIROI *et al.*, 1983a). In this bedrock exposure, the Tenmondai Rock, an orthopyroxene-free and gedrite-bearing rock occurs as well-layered gneiss with garnet-biotite gneiss (Fig. 2; Sp. No. 81012514A).

Naga-iwa Rock specimen N-2 occurs as a concordant lensoid body, 30×100 cm in size, in garnet-biotite gneiss (Fig. 3b). Its mode of occurrence in the field is similar to that of metabasites including pyroxenites in the granulite-facies Sōya Coast. Its bulk chemical composition listed in Table 2 is also similar to that of pyroxenites in the granulite-facies area, though the origin of such rocks has not been clarified. The rock is characterized by the low Al_2O_3 content and the high $\text{MgO}/(\text{MgO} + \text{FeO})$ ratio in composition, and by pale brown orthopyroxene, green amphibole, light green clinopyroxene and black biotite in handspecimen.

The other Naga-iwa Rock specimen (N-16) occurs as well-layered gneiss with garnet-biotite gneiss. The rock shows a gradual compositional change from garnet-bearing and hornblende-free part to garnet-free and hornblende-rich part. The bulk rock composition listed in Table 2 is that of the garnet-hornblende-bearing part. It is characterized by the high Al_2O_3 content and the low $\text{MgO}/(\text{MgO} + \text{FeO})$ ratio in composition, and by pale greenish brown plagioclase associated with brown orthopyroxene, red garnet, dark green hornblende, and black biotite in handspecimen.

Table 1. Mineral assemblages of rocks described and mineral abbreviations.

Locality	Specimen No.	Mineral														
		Opx	Cpx	Ho	Tr	Ged	Cum	Gar	Bi	Pl	K-sp	Qz	Il	Mt	Others	
Tenmondai Rock	T-10	+		+					+	+			+	+	Ap, Py, Zi	
	81012514A					+		+	+	+		+		+	Ap, Py, Zi	
Naga-iwa Rock	N-2	+	+		+		*		+	+	+	+			Ap, Chr, Ms*, Pent, Po	
	N-16	+		+				+	+	+		+	+	+	Ap, Py, Zi	
Mineral abbreviations																
Ab	— albite				Gar	— garnet				Pent	— pentlandite					
An	— anorthite				Ged	— gedrite				Pl	— plagioclase					
Anth	— anthophyllite				Gl	— glaucophane				Po	— pyrrhotite					
Ap	— apatite				Ho	— hornblende				Py	— pyrite					
Bi	— biotite				Il	— ilmenite				Qz	— quartz					
Ca-amph	— calcic amphibole				K-sp	— K-feldspar				Ta	— talc					
Chr	— chromite				Ms	— magnesite				Tr	— tremolite					
Cpx	— clinopyroxene				Mt	— magnetite				Tsch	— tschermakite					
Cum	— cummingtonite				Opx	— orthopyroxene				Zi	— zircon					
Ed	— edenite				Par	— pargasite										

* Retrogressive.

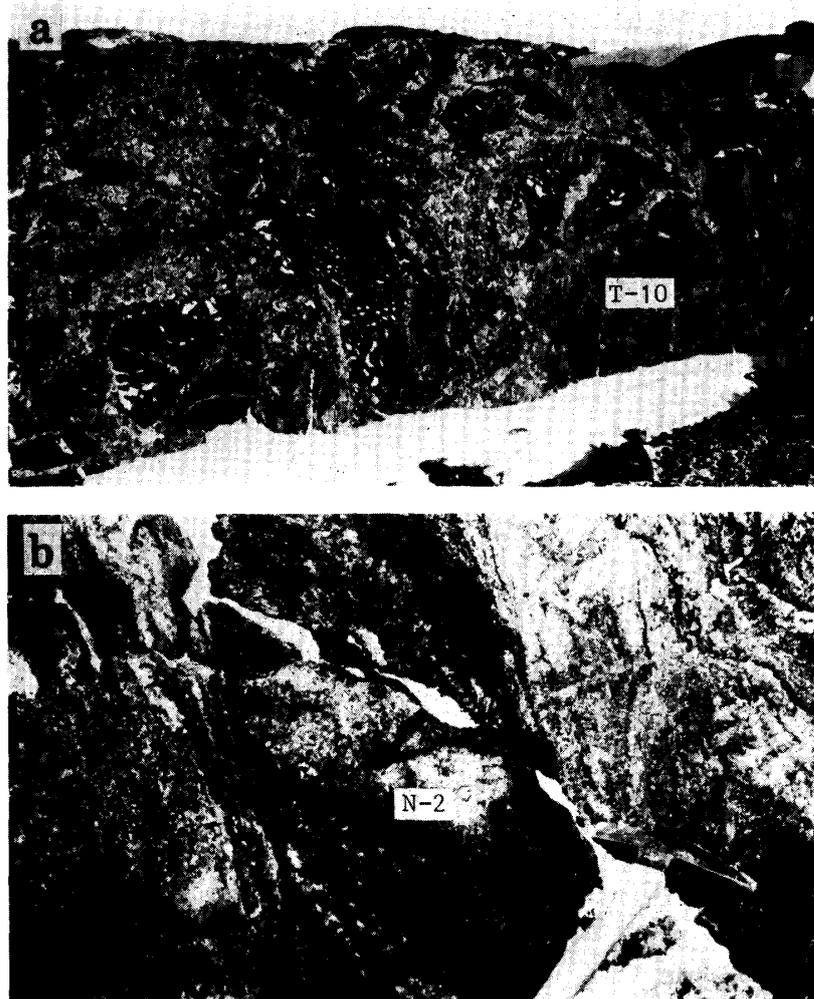


Fig. 3. Photographs showing field occurrence of orthopyroxene-bearing rocks. a. T-10 at the Tenmondai Rock. b. N-2 at the Naga-iwa Rock.

Table 2. Bulk chemical compositions of orthopyroxene-bearing rocks from the Naga-iwa Rock.

Specimen No.	N-2	N-16
SiO ₂	51.34	58.25
TiO ₂	0.31	1.13
Al ₂ O ₃	4.79	17.63
Fe ₂ O ₃	2.31	1.40
FeO	7.81	6.58
MnO	0.26	0.29
MgO	19.98	2.03
CaO	9.42	5.06
Na ₂ O	0.63	4.57
K ₂ O	0.70	1.11
H ₂ O (+)	1.88	0.95
H ₂ O (-)	0.21	0.19
P ₂ O ₅	tr.	0.51
Total	99.64	99.70
Mole MgO/(MgO+FeO)	0.820	0.354

Analyst; H. ONUKI.

5. Mineral Chemistry and Texture

Electron microprobe analysis of minerals was performed using JEOL JXA-733 under such conditions as an acceleration voltage of 15 kV, beam currents of 0.012–0.015 μA , and a beam diameter of 3 μm . Generally, several grains of each mineral per specimen and two or more points per grain were analyzed. Representative analyses of minerals in each specimen are listed in Tables 3, 4, and 5.

5.1. Orthopyroxene

Orthopyroxene usually occurs as anhedral grains in direct contact with most of minerals present (Figs. 4b, 5, and 6). In N-16 it sometimes includes hornblende (Fig. 6). Orthopyroxene in quartz-free T-10 is richest in Al.

5.2. Clinopyroxene

Clinopyroxene occurs only in N-2, though it is common in basic metamorphic rocks in the Prince Olav and Sôya Coasts. It is a poikilitic porphyroblast including orthopyroxene, calcic amphibole, and small amounts of plagioclase, K-feldspar and

Table 3. Representative microprobe analyses of minerals in T-10.

Mineral	Opx	Ho	Ho*	Bi	Pl(1)	Pl(2)	Pl(3)	Il	Mt
SiO ₂	51.16	42.36	48.75	37.11	58.41	58.73	55.64	—	—
TiO ₂	0.08	1.81	0.19	3.54	0.03	0.02	—	48.35	0.02
Al ₂ O ₃	2.85	13.44	8.08	16.39	26.72	26.78	28.06	—	0.14
Cr ₂ O ₃	—	0.18	0.09	0.17	0.09	0.03	—	0.12	1.32
FeO**	22.38	13.78	12.25	12.88	0.29	0.12	0.16	50.23	89.64
MnO	0.73	0.14	0.26	0.10	—	0.04	0.02	0.45	0.01
MgO	22.49	12.35	15.20	16.35	0.01	—	0.02	0.14	—
CaO	0.30	11.15	11.32	—	7.98	8.32	10.54	—	0.07
Na ₂ O	0.02	2.07	1.14	0.39	7.34	7.46	6.36	—	—
K ₂ O	0.01	0.69	0.39	9.09	0.22	0.18	0.18	0.02	—
NiO	—	0.06	—	0.04	—	—	0.03	0.05	—
Total	100.03	98.03	97.67	96.06	101.09	101.68	101.01	99.36	91.20
O	6	23	23	22	32	32	32		
Si	1.910	6.250	7.062	5.437	10.370	10.369	9.966		
Ti	0.002	0.200	0.021	0.390	0.004	0.002	—		
Al	0.126	2.337	1.380	2.830	5.590	5.572	5.924		
Cr	—	0.021	0.010	0.020	0.012	0.004	—		
Fe	0.699	1.701	1.483	1.578	0.043	0.017	0.023		
Mn	0.023	0.018	0.032	0.012	—	0.006	0.003		
Mg	1.252	2.716	3.283	3.571	0.003	0.001	0.005		
Ca	0.012	1.762	1.756	—	1.517	1.574	2.032		
Na	0.002	0.591	0.320	0.110	2.527	2.554	2.210		
K	0.001	0.130	0.073	1.698	0.050	0.040	0.042		
Ni	—	0.007	—	0.005	—	—	0.004		
X _{Mg} ***	0.642	0.615	0.689	0.694					

* Rim, retrogressive. ** Total Fe. *** Mole MgO/(MgO+FeO). Analyst; K. SHIRAIHI. Pl(1): core, Pl(2) and Pl(3): rims.

Table 4. Representative microprobe analyses of minerals in N-2.

Mineral	Opx	Cpx	Tr	Cum*	Bi	Pl	K-sp	Chr	Pent	Ms*
SiO ₂	55.53	53.98	52.41	57.47	40.23	57.10	64.82	—	0.36	—
TiO ₂	0.03	—	0.07	—	0.53	0.02	—	0.05	—	—
Al ₂ O ₃	0.55	1.00	5.08	0.34	15.04	26.50	18.58	8.29	—	0.01
Cr ₂ O ₃	0.32	1.01	1.52	0.04	1.54	—	—	56.91	—	0.08
FeO**	13.11	3.87	4.89	11.56	4.89	0.12	—	30.66	29.28	16.68
MnO	0.55	0.26	0.22	0.47	0.12	—	—	0.70	0.01	0.88
MgO	29.59	16.20	19.79	26.50	22.90	—	—	3.24	0.05	31.98
CaO	0.46	23.47	12.31	0.85	0.05	9.02	0.03	—	0.02	0.24
Na ₂ O	—	0.54	0.85	0.05	0.30	6.42	1.52	0.12	0.09	0.03
K ₂ O	—	0.03	0.20	—	9.40	0.30	14.65	—	—	—
NiO	0.13	0.03	0.20	0.24	0.44	—	—	0.07	38.56	—
Total	100.14	100.39	97.83	97.52	95.39	99.48	99.60	100.04	68.28	49.90
O	6	6	23	23	22	32	32	8		
Si	1.976	1.972	7.352	7.948	5.724	10.309	11.967	—		
Ti	0.001	—	0.007	—	0.057	0.002	—	0.003		
Al	0.023	0.043	0.840	0.055	2.522	5.638	4.043	0.688		
Cr	0.009	0.029	0.168	0.005	0.173	—	—	3.173		
Fe	0.390	0.118	0.574	1.337	0.582	0.019	—	1.808		
Mn	0.016	0.008	0.027	0.055	0.014	—	—	0.040		
Mg	1.570	0.882	4.138	5.463	4.856	—	—	0.341		
Ca	0.018	0.919	1.849	0.125	—	1.744	0.006	—		
Na	—	0.038	0.232	0.014	0.082	2.246	0.542	0.016		
K	—	0.002	0.088	—	1.705	0.069	3.451	—		
Ni	0.004	0.001	0.023	0.027	0.050	—	—	0.004		
X _{Mg} ***	0.801	0.882	0.878	0.803	0.893					0.774

* Retrogressive. ** Total Fe. *** Mole MgO/(MgO+FeO). Analyst; Y. HIROI.

quartz (Fig. 5). It contains Cr₂O₃ up to about 1 weight percent.

5.3. Calcic amphibole

Calcic amphibole is tremolite in N-2, while it is common hornblende in T-10 and N-16, reflecting the difference in host rock composition. As is shown in Fig. 7, hornblendes in T-10 and N-16 are more pargasitic than the amphibolite-facies ones, and are less pargasitic than the granulite-facies one. Calcic amphiboles are sometimes fringed with thin more-tremolitic rims. The rims are considered to be of retrograde origin.

5.4. Biotite

Biotite occurs in all specimens. It is phlogopitic in N-2, reflecting the host rock composition. The Ti content is as high as about 5 weight percent TiO₂ in N-16.

5.5. Plagioclase

Plagioclase occurs in every specimen, but it is present only in a small amount in N-2. It shows chemical heterogeneity in T-10 within a grain and among grains; the core is constantly An=36, the rim varies from An=36 to An=46. On the other

Table 5. Representative microprobe analyses of minerals in N-16.

Mineral	Opx	Ho	Gar	Bi(1)	Bi(2)	Pl*	Pl**	Il	Mt
SiO ₂	50.62	42.10	37.06	36.18	36.00	60.64	59.54	—	0.05
TiO ₂	0.08	2.15	0.06	5.13	5.05	0.01	0.01	48.36	0.20
Al ₂ O ₃	0.91	10.81	21.04	15.36	14.49	24.70	25.32	0.14	0.31
Cr ₂ O ₃	—	0.11	0.02	0.04	0.04	—	0.12	—	0.11
FeO***	29.87	18.55	26.10	17.35	20.16	0.20	0.31	46.85	93.04
MnO	1.81	0.21	4.77	0.28	0.11	—	0.05	3.31	0.18
MgO	16.37	9.39	4.38	11.73	10.41	—	0.01	0.43	0.04
CaO	0.66	11.19	5.51	—	0.01	6.44	7.21	—	—
Na ₂ O	—	1.60	0.09	0.06	—	8.08	7.83	0.06	—
K ₂ O	0.01	1.33	—	9.42	10.15	0.44	0.51	—	—
NiO	—	0.03	0.14	—	—	—	—	0.07	—
Total	100.33	97.44	99.17	95.55	96.42	100.51	100.91	99.22	93.93
O	6	23	12	22	22	32	32		
Si	1.965	6.422	2.966	5.467	5.492	10.772	10.587		
Ti	0.002	0.246	0.004	0.583	0.579	0.002	0.002		
Al	0.042	1.943	1.985	2.736	2.605	5.170	5.307		
Cr	—	0.013	0.001	0.004	0.005	—	0.017		
Fe	0.969	2.366	1.747	2.193	2.572	0.029	0.046		
Mn	0.059	0.027	0.323	0.036	0.014	—	0.007		
Mg	0.947	2.136	0.523	2.642	2.368	—	0.002		
Ca	0.027	1.829	0.473	—	0.001	1.226	1.373		
Na	—	0.473	0.014	0.017	—	2.784	2.700		
K	—	0.258	—	1.815	1.975	0.099	0.116		
Ni	—	0.004	0.009	—	—	—	—		
X _{Mg} ****	0.494	0.474	0.230	0.546	0.479				

* Core. ** Rim. *** Total Fe. **** Mole MgO/(MgO+FeO). Analyst; K. SHIRAIISHI.
Bi(1): in hornblende-free part, Bi(2): in hornblende-bearing part.

hand, it is fairly homogeneous in N-2 and N-16. Plagioclase in N-16 often includes garnet.

5.6. Garnet

Garnet occurs only in N-16. It is usually included in plagioclase but it sometimes is in direct contact with other minerals. It is fairly homogeneous in chemical composition.

5.7. Other minerals

K-feldspar in N-2 is orthoclase, and contains albite component up to 13.5 percent.

Opaque minerals are ilmenite, magnetite, and pyrite in T-10 and N-16. They are chromite, pentlandite, and pyrrhotite in N-2.

Small amounts of secondary cummingtonite and magnesite are also present in N-2.

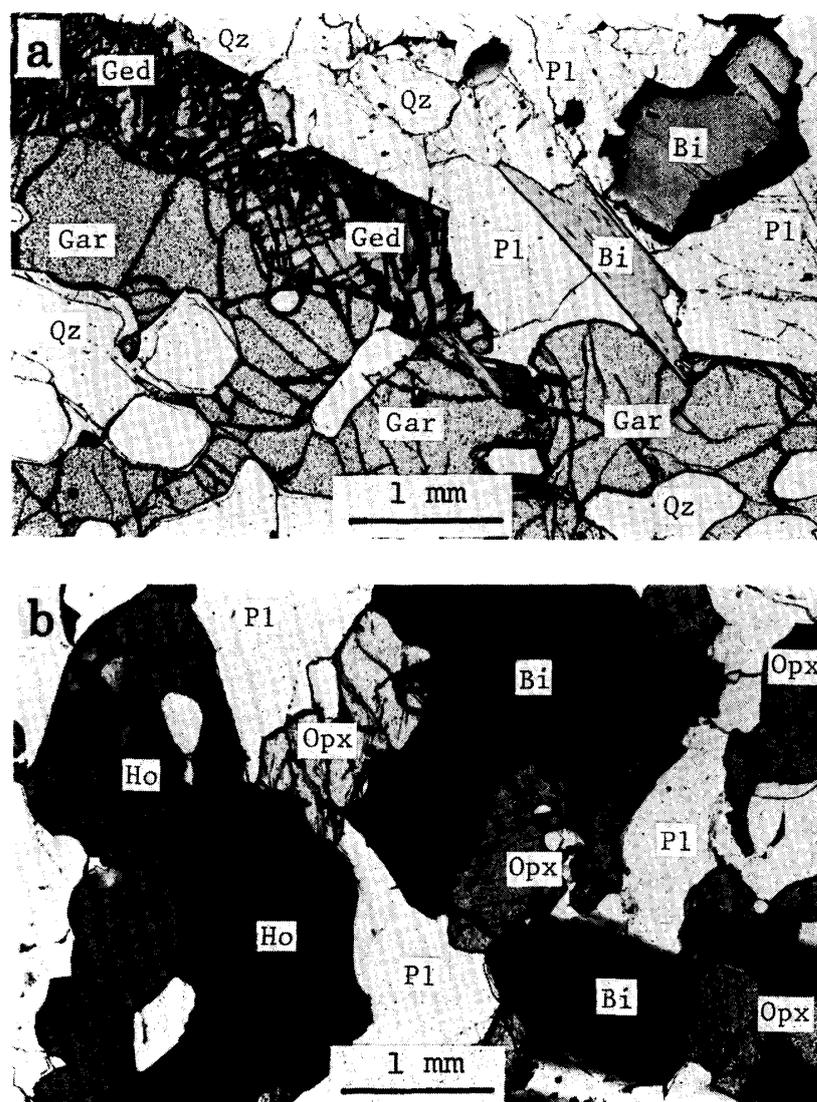


Fig. 4. Photomicrographs showing textures of gedrite- and orthopyroxene-bearing rocks from the Tenmondai Rock. a. Gedrite in gedrite-garnet-biotite gneiss (Sp. No. 81012514A). b. Orthopyroxene in orthopyroxene-hornblende-biotite-plagioclase gneiss (T-10). One nicol.

6. Discussion

6.1. Mineral equilibria

Basic to intermediate metamorphic rocks containing pyroxenes, amphiboles, garnet, biotite, plagioclase, Ti-Fe phase and quartz are generally composed of twelve oxides; SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , Cr_2O_3 , FeO , MnO , MgO , CaO , Na_2O , K_2O and H_2O . The twelve-component system may be simplified to six-component subsystem SiO_2 - Al_2O_3 -(Mg, Fe)O-CaO- Na_2O - H_2O , when we deal with the stability relations among pyroxenes, amphiboles, garnet, plagioclase, and quartz. For quartz-bearing rocks*, the subsystem is presented as an Al_2O_3 -(Mg, Fe)O-CaO- Na_2O tetra-

* For K-feldspar-quartz-bearing rocks such as N-2, K_2O may also be considered to be an excess component, and biotite can be plotted in the $(\text{Al}_2\text{O}_3$ - $\text{K}_2\text{O})$ -(Mg, Fe)O-CaO- Na_2O tetrahedron.

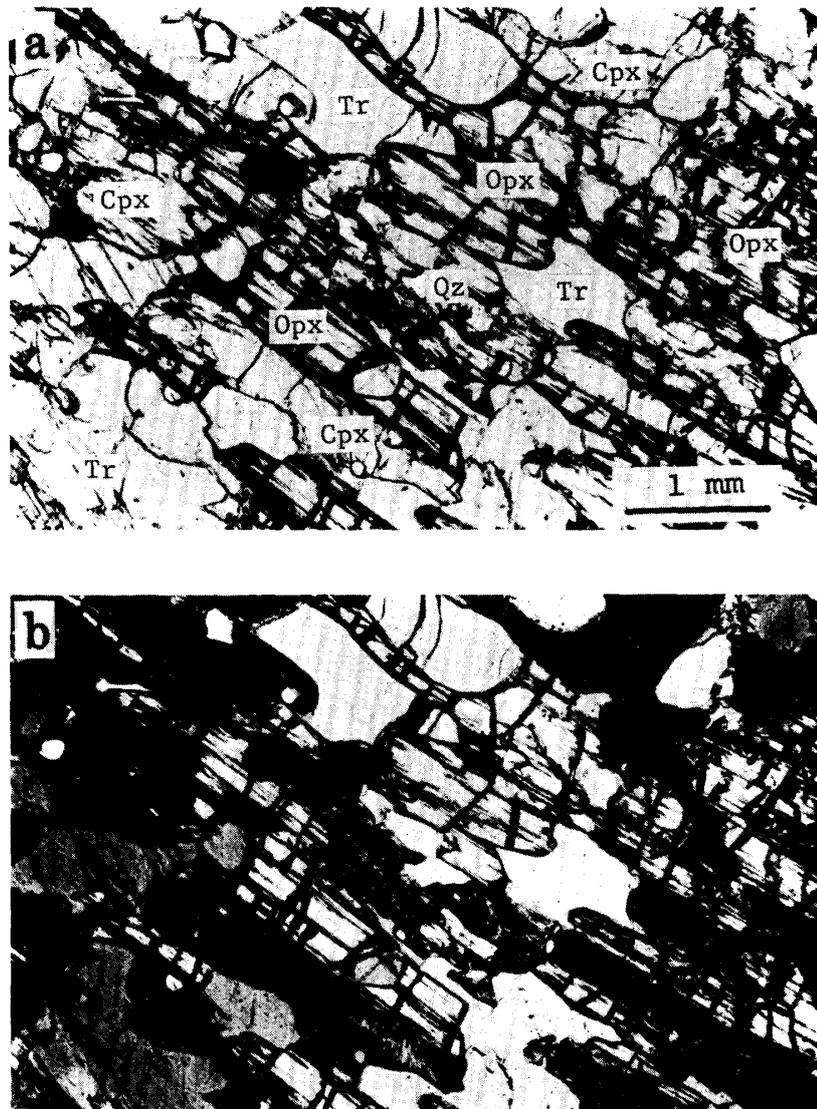


Fig. 5. Photomicrographs showing textures of orthopyroxene, clinopyroxene, tremolite and quartz in N-2 from the Naga-iwa Rock. a. One nicol. b. Nicols crossed.

hedron. Figure 8 is such a tetrahedron, showing chemical relations among minerals, especially calcic amphibole. As is apparent in the figure, the Na content of calcic amphibole may be closely related to the albite content of coexisting plagioclase. The more calcic plagioclase will coexist with the more tremolitic amphibole and the more albitic plagioclase will coexist with more edenitic (and pargasitic) amphibole. This is just the case of the present study. Chemographic relations of coexisting orthopyroxene, calcic amphibole, and clinopyroxene or garnet are shown in Figs. 9a and 9b. Note T-10 is free from quartz. Compatible relations of mineral assemblages are found, showing the difference in host rock chemical compositions such as the Al_2O_3 content and the $MgO/(MgO+FeO)$ ratio. Thus, chemographic relations of coexisting minerals in the different mineral assemblages suggest chemical equilibrium of the specimens under the given metamorphic conditions.

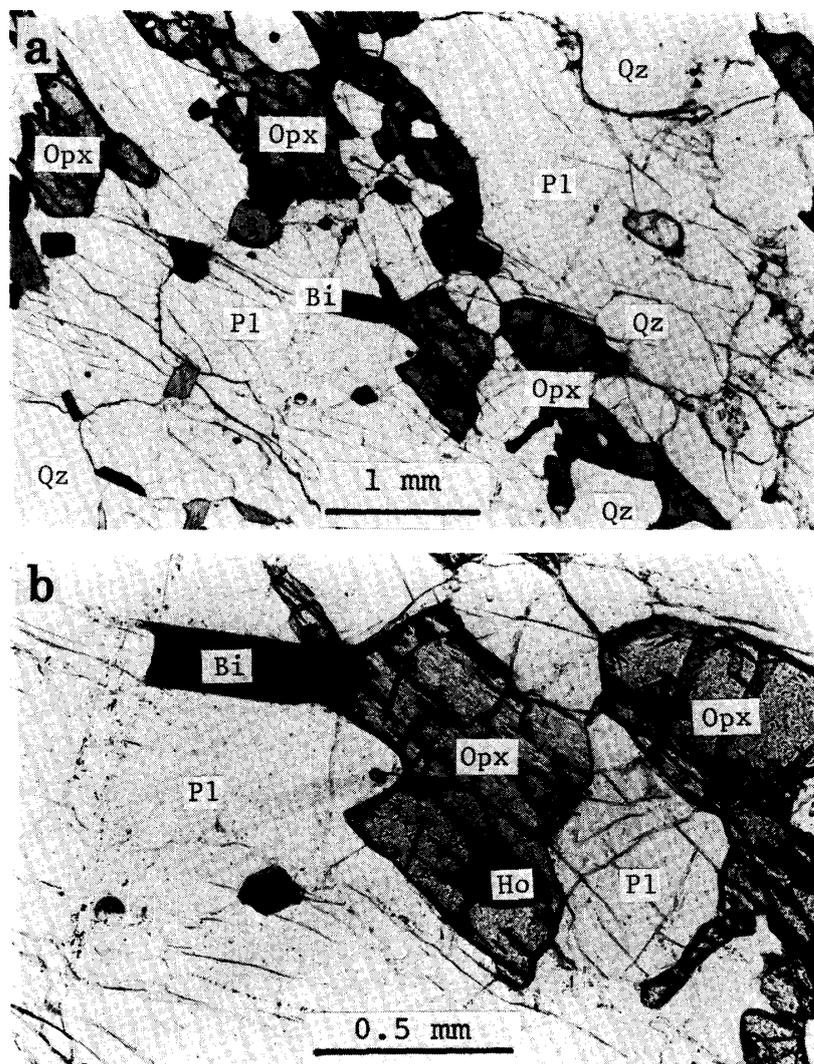


Fig. 6. Photomicrographs showing textures of orthopyroxene in orthopyroxene-hornblende-garnet-biotite-plagioclase-quartz gneiss (N-16) from the Naga-iwa Rock. a. One nicol. b. Enlarged photomicrograph of lower central part of a. Note orthopyroxene includes hornblende.

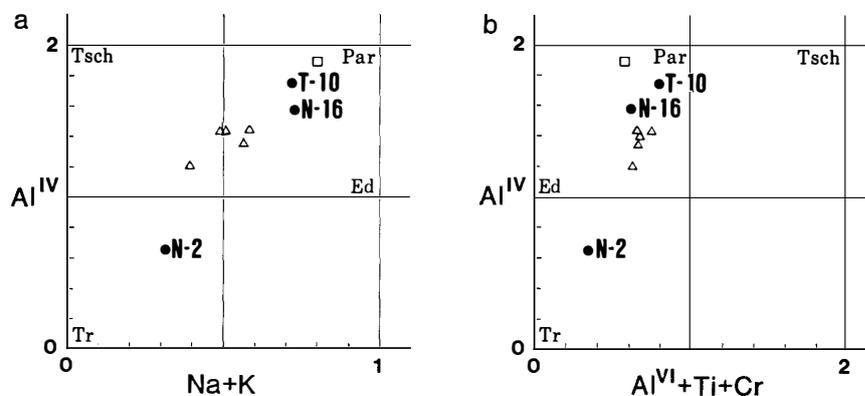


Fig. 7. Diagrams showing chemical compositions of calcic amphiboles in T-10, N-2 and N-16. Triangle: Amphibolite facies (Cape Hinode; KANISAWA and YANAI, 1982). Square: Granulite facies (Skallen; SUZUKI, 1983). a. Al^{IV} vs. $(Na+K)$. b. Al^{IV} vs. $(Al^{VI}+Ti+Cr)$.

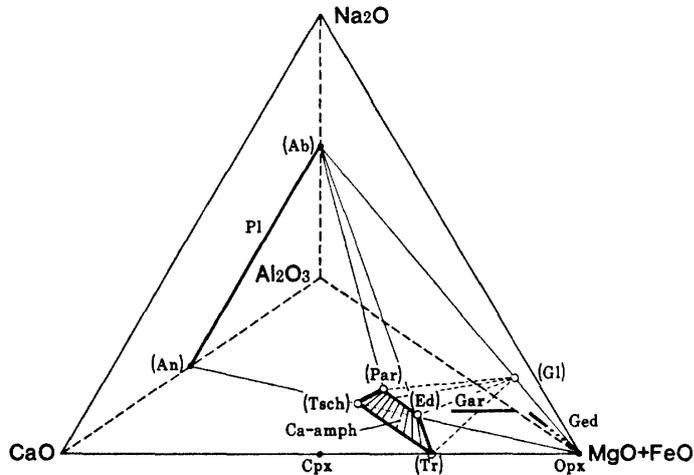


Fig. 8. Tetrahedron $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{CaO}-(\text{MgO}+\text{FeO})$ showing chemical relations among minerals.

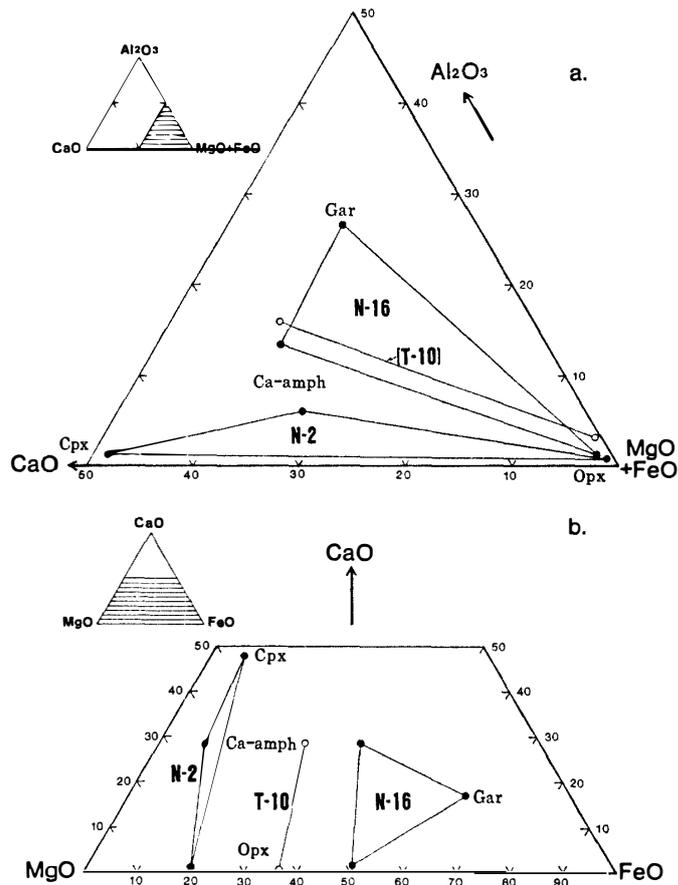


Fig. 9. Chemographic relations among orthopyroxene, calcic amphibole, and clinopyroxene or garnet. Note T-10 is free from quartz. a. $\text{Al}_2\text{O}_3-\text{CaO}-(\text{MgO}+\text{FeO})$ diagram. b. $\text{CaO}-\text{MgO}-\text{FeO}$ diagram.

a type I rock, and orthopyroxene in it may have been produced by reactions (1) and (3). N-2 is extremely poor in Al, though it has a high $MgO/(MgO+FeO)$ ratio. Hence, N-2 is partly of type II, and the orthopyroxene-forming reaction in it may be reaction (2). This is in good agreement with the mineral assemblage and textures. Orthopyroxene-producing reaction(s) in T-10 is not known at present, but the pargasitic (tschermakitic) composition of calcic amphibole in T-10 suggests reaction (3). It is worthy to note that orthopyroxene occurs together with spinel, calcic amphibole, and clinopyroxene or olivine or plagioclase in the ultrabasic rocks from the Akarui Point which is the next bedrock exposure of the Naga-iwa Rock (see location in Figs. 1 and 2) (HIROI *et al.*, 1983b; YANAI *et al.*, 1984). The ultrabasic rocks are, at least partly, of type III, and the orthopyroxene-forming reactions in the rocks may be reactions (8) and (9). Thus, orthopyroxene "first" appears in the progressive metamorphic sequence in the Prince Olav Coast in such manner (order) as is predicted experimentally and theoretically.

6.3. Compositional change of calcic amphibole

Calcic amphibole generally occurs from the greenschist facies up to the lower granulite facies. Its compositional change may be used as an indicator of metamorphic grade, at least, in the case of low degree of freedom. Calcic amphiboles in T-10 and N-16 are more pargasitic than those from the amphibolite-facies area and are less pargasitic than the granulite-facies one, as mentioned above (Fig. 7). T-10 is free from quartz, but N-16 contains quartz. N-2 also contains quartz. The compositional change of calcic amphiboles in the quartz-bearing rocks may be discussed in the $Al_2O_3-(Mg, Fe)O-CaO-Na_2O$ tetrahedron (Fig. 8). In this system, four-phase assemblages such as $Opx+Ho+Gar+Pl$ and $Opx+Cpx+Tr+Pl$ are invariant at given P_{total} , P_{H_2O} , and T . Thus, at the given metamorphic conditions, the mineral assemblages of N-2 and N-16 are invariant, and the chemical compositions of the calcic amphiboles are fixed. Moreover, ordinary basic to intermediate rocks are more Al-rich than N-2 and less Al-rich than N-16, and the compositions of calcic amphiboles

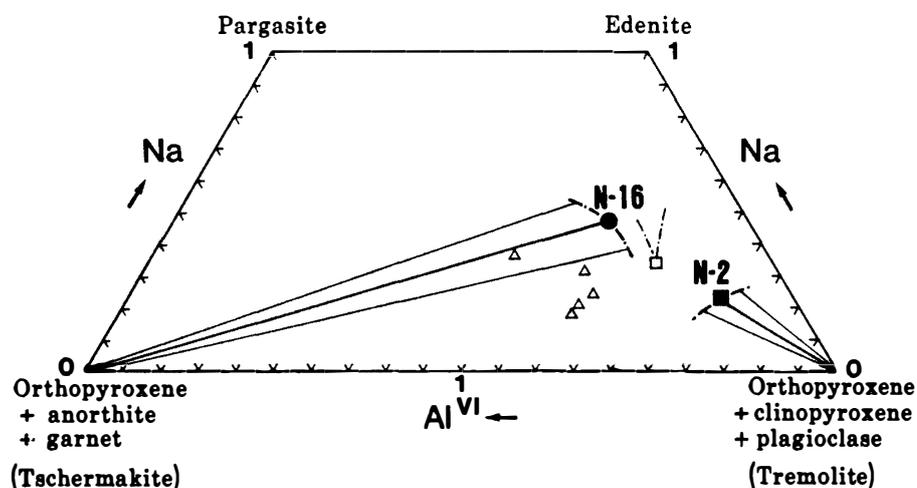


Fig. 10. Diagram showing compositional changes of calcic amphiboles with increasing metamorphic grade.

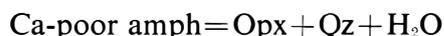
in the specimens are thought to be of the typically Al-poor (tremolitic) and Al-rich (tschermakitic) ones, respectively (Fig. 9a). However, Mg and Fe²⁺ actually do not have the same chemical characteristics. Gernet tends to be present in Fe²⁺-rich rocks (Fig. 9b). Taking this point into account, we must consider that the five-phase assemblage such as Opx + Cpx + Ho + Gar + Pl is invariant at given metamorphic conditions*.

In any case, the chemical compositions of calcic amphiboles in N-2 and N-16 can be indicators of metamorphic grade. Figure 10 is a kind of phase diagram showing such scheme. As the metamorphic grade increases, compositions of calcic amphiboles change by reactions (2) and (3). More comprehensive study of compositional changes of calcic amphibole in the amphibolite-, transitional and granulite-facies areas along the Prince Olav and Sôya Coasts will be presented elsewhere.

7. Conclusion

Orthopyroxene first appears in the Tenmondai and Naga-iwa Rocks in the progressive metamorphic sequence of the kyanite-sillimanite type from northeast to southwest along the Prince Olav Coast, East Antarctica. Textures and chemical compositions of minerals suggest that the rocks are close to chemical equilibrium.

One of the orthopyroxene-bearing rocks is typically rich in Al and Fe²⁺, and the following reactions are inferred to have taken place in the rock.



Another orthopyroxene-bearing rock is extremely poor in Al, and the next reaction is the orthopyroxene-forming reaction in the rock.



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* N-2 contains both K-feldspar and quartz, and K₂O is considered to be an excess component, as mentioned above. Therefore, the mineral assemblage Opx + Cpx + Tr + Bi + Pl in N-2 is still invariant.

- phibole stability. Amphiboles; Petrology and Experimental Phase Relations, ed. by D. R. VEBLER and P. H. RIBBE. Washington, D.C., Mineral. Soc. Am., 229–353 (Review in Mineralogy, Vol. 9B).
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