Mem. Natl Inst. Polar Res., Spec. Issue, **43**, 101-115, 1986

AMPHIBOLITE-FACIES MINERAL ASSEMBLAGES IN THE BELGICA MOUNTAINS, EAST ANTARCTICA

Masao ASAMI[1], Hideyasu KOJIMA[2], Keizo YANAI[2] and Tamio NISHIDA[3]

[1]*Department of Geological Sciences, College of Liberal Arts, Okayama University, 1-1, Tsushima Naka 2-chome, Okayama 700*

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

[3]*Institute of Earth Science, Faculty of Education, Saga University, Honjo-machi, Saga 840*

Abstract: As the first petrological study of metamorphism in the Belgica Mountains, East Antarctica, mineral assemblages of the metamorphics of various compositions are examined and the metamorphic conditions are preliminarily estimated. The amphibolite-facies metamorphism is indicated by the mineral assemblages. Besides the occurrence of clinohumite and chondrodite in dolomitic marble, the following features are characteristic of the assemblages: the absence of garnet in metabasites and the presence of the calcite-quartz and Ca-garnet-quartz associations and no wollastonite in calcareous rocks. The garnet-biotite thermometry gives the metamorphic temperatures of 680-700°C. The five-phase assemblage forsterite-tremolite-dolomite-calcite-spinel in dolomitic marble is noted for a fluid pressure estimate in this rock. Total fluid pressures around 5 kb at 680-700°C are obtained from the experimental equilibrium relations concerning the five-phase assemblage (P. METZ: Contrib. Mineral. Petrol., **58**, 137, 1976; J. M. RICE: Contrib. Mineral. Petrol., **59**, 237, 1977; H.-R. KÄSE and P. METZ: Contrib. Mineral. Petrol., **73**, 151, 1980). If $P_{solid}=P_{fluid}$ is assumed, the metamorphism would be of relatively low pressure just like that in the Yamato Mountains which are situated about 200 km northeast of the Belgica Mountains.

1. Introduction

The East Antarctic shield around Syowa Station has been studied from geological, petrological and geochronological points of view by Japanese geoscientists since the first Japanese Antarctic Research Expedition (JARE-1). Recent petrological studies made it clear that the amphibolite- to granulite-facies progressive metamorphism in the Prince Olav Coast-Lützow-Holm Bay region was of medium-pressure type (*e.g.* HIROI *et al.*, 1983a, b), while the granulite-facies metamorphism in the Yamato Mountains was characterized by lower solid pressure (*e.g.* ASAMI and SHIRAISHI, 1985). In addition, the chronological data suggest that the main regional metamorphism in the both areas may have taken place about 700 Ma ago, followed by the 400-500 Ma event which probably represents its cooling or granitic intrusion (YANAI *et al.*, 1983; SHIBATA *et al.*, 1985; ASAMI and SHIRAISHI, 1985).

The Belgica Mountains are situated about 200 km southwest of the Yamato Mountains and have geologically been investigated by KOJIMA *et al.* (1981, 1983). According to them, the mountains are composed mainly of high-grade gneiss of various compositions and of 400-500 Ma K-Ar ages. However, compared with the above two areas, metamorphism in this area has not yet been well understood petrologically. In this paper, we present mineral assemblages of the gneiss and briefly discuss metamorphic conditions in the Belgica Mountains on the basis of mineral parageneses of pelitic and calcareous rocks.

2. Geological Outline

The Belgica Mountains (72°18′S–72°43′S latitude and 35°57′E–31°20′E longitude) lie about midway between the Yamato Mountains and the Sør Rondane Mountains, East Dronning Moud Land (Fig. 1). A geological investigation of the Mountains was made by Japanese geologists of JARE-20 in 1979 after the first visit in 1958 and revisit in 1967 by the Belgian party (VAN AUTENBOER and LOY, 1972). The geological and some chronological results were given by KOJIMA *et al.* (1981 and 1983). Those are summarized in the following and the geological map (Fig. 2).

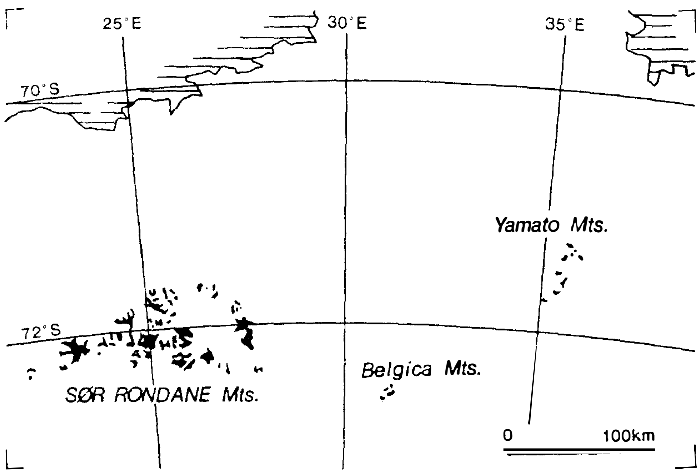

Fig. 1. Location map of the Belgica Mountains.

The mountains consist of three massifs with the highest peak, Mt. Victor, of 2600 m in altitude and several nunataks. The crystalline basement rocks in this area are assigned to the Belgica Group which is divided into the Belgica upper formation and the Belgica lower formation. The Belgica Group is composed of (1) granitic gneiss, (2) marble and skarn, (3) amphibolite, (4) hornblende-biotite gneiss, (5) augen gneiss, (6) clinopyroxene gneiss, (7) garnet-biotite gneiss, and (8) dyke rocks (metabasite, syenite, granodiorite-diorite and pink granite). Granitic gneiss is a main constituent of the Belgica lower formation and hornblende-biotite gneiss occupies a large part of the Belgica upper formation. Marble, skarn and amphibolite are distributed throughout this region, with small amounts of other gneisses. The Belgica Group rocks are slightly to moderately deformed with gentle to open fold structures. Whole rock K-Ar measurements of three gneisses and three dyke rocks were made, with the results ranging from 382 to 472 Ma. The values may correspond to the younger ages (400–500 Ma) known in the Lützow-Holm Bay region and the Yamato Mountains (SHIBATA *et al.*, 1985).

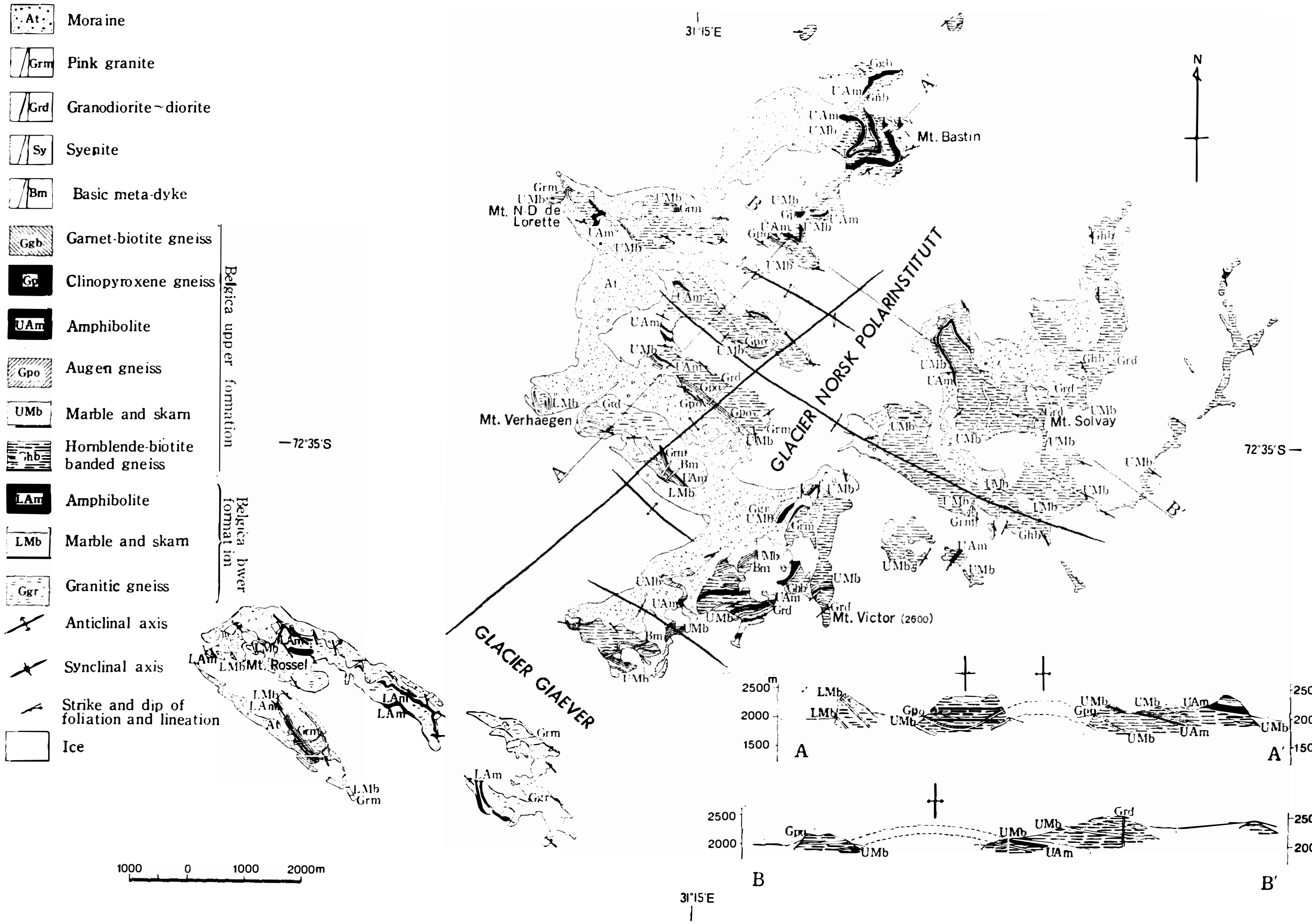

Fig. 2. Geological map of the Belgica Mountains (KOJIMA *et al., 1981*).

3. Mineral Assemblage

The metamorphic rocks in the Belgica Mountains can be grouped into the following four kinds by rock compositions which are presumed by their mineral assemblages and mineral contents: basic rocks, calcareous rocks, pelitic-psammitic rocks and granitic rocks. About one hundred and fifty thin sections of the metamorphic rocks were examined. Mineral assemblages of the four rock groups are listed in Table 1.

Table 1. Mineral assemblages of the metamorphic rocks from the Belgica Mountains.

Basic rocks	
B 1.	Cp+Hb+Bi+Kf+Pl+Qu
B 2.	Hb+Bi+Kf+Pl+Qu
B 3.	Cp+Bi+Kf+Pl+Qu
B 4.	Hb+Bi+Pl+Qu
B 5.	Cp+Hb+Bi+Kf+Pl
B 6.	Cp+Bi+Kf+Pl
B 7.	Hb+Bi+Kf+Pl
B 8.	Cp+Hb+Bi+Pl
B 9.	Hb+Bi+Pl
B 10.	Cum+Bi
Calcareous rocks	
C 1.	Ga+Cp+Hb+Sc+Cc+Kf+Qu+Opq
C 2.	Ga+Sc+Cc+Pl+Qu+Opq
C 3.	Cp+Hb+Kf+Pl+Qu+Sph+Opq
C 4.	Cp+Cc+Pl+Qu+Sph
C 5.	Cp+Sc+Cc+Qu+Sph
C 6.	Hb+Sc+Cc+Kf+Pl+Qu+Sph
C 7.	Sc+Cc+Qu+Sph
C 8.	Hu+Fo+Sp+Tr+Ph+Do+Cc
C 9.	Hu+Fo+Sp+Ph+Do+Cc
C 10.	Cho+Sp+Ph+Do+Cc
C 11.	Fo+Sp+Ph+Do+Cc
C 12.	Fo+Do+Cc±Ph
C 13.	Tr+Ph+Sc+Cc+Kf+Pl+Opq
C 14.	Cp+Sc+Kf+Pl+Sph±Ph
C 15.	Cp+Ph+Sc+Pl+Sph
C 16.	Cp+Hb+Sc+Cc+Pl+Sph+Opq±Bi
C 17.	Cp+Ac+Sc+Cc+Pl+Opq
C 18.	Cp+Ac+Bi+Sc+Sph
C 19.	Ga+Cp+Sc+Cc+Sph
C 20.	Ga+Cp+Hb+Pl+Opq
C 21.	Sc+Kf+Pl+Sph+Opq
Pelitic-psammitic rocks	
P 1.	Ga+Bi+Kf+Pl+Qu+Il+Grp
P 2.	Bi+Kf+Pl+Qu
Granitic rocks	
G 1.	Bi+Pl+Qu±Kf

All the rocks contain apatite and the rocks except calcareous ones carry opaque mineral, sphene and zircon as additional accessories.

Abbreviations: Ac—actinolitic amphibole, Bi—biotite, Cc—calcite, Cho—chondrodite, Cp—clinopyroxene, Cum—cummingtonite, Do—dolomite, Fo—forsterite, Ga—garnet, Grp—graphite, Hb—hornblende, Hu—clinohumite, Il—ilmenite, Kf—K-feldspar, Opq—opaque mineral, Ph—phlogopite, Pl—plagioclase, Qu—quartz, Sc—scapolite, Sp—spinel, Sph—sphene, Tr—tremolite.

Some of such basic rocks as biotite-hornblende gneiss and amphibolite carry actinolite by which hornblende and clinopyroxene are partially rimmed. In some dolomite marbles, forsterite, clinohumite, tremolite and spinel are partially altered to serpentine and/or chlorite along the rim and cracks. One Ca-garnet-plagioclase rock contains epidote which often occurs along the garnet-plagioclase boundary. Such minerals that may be secondary in origin are eliminated from the mineral assemblages in Table 1.

The mineral assemblages B1 and B2 in Table 1 are very commonly recognized in the basic rocks. The pelitic-psammitic rocks are rare in occurrence, and their mineral assemblages are lacking in variety. Compared with the basic and the pelitic-psammitic rocks, the calcareous ones show a wide variety of mineral assemblages due to the

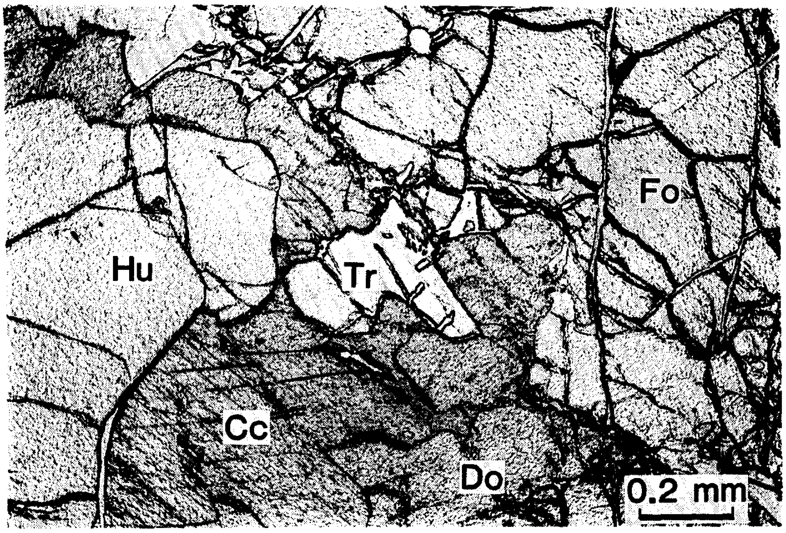

Fig. 3. Photomicrograph showing clinohumite (Hu) associated with forsterite (Fo), tremolite (Tr), dolomite (Do) and calcite (Cc) in dolomitic marble (K79121607). One nicol.

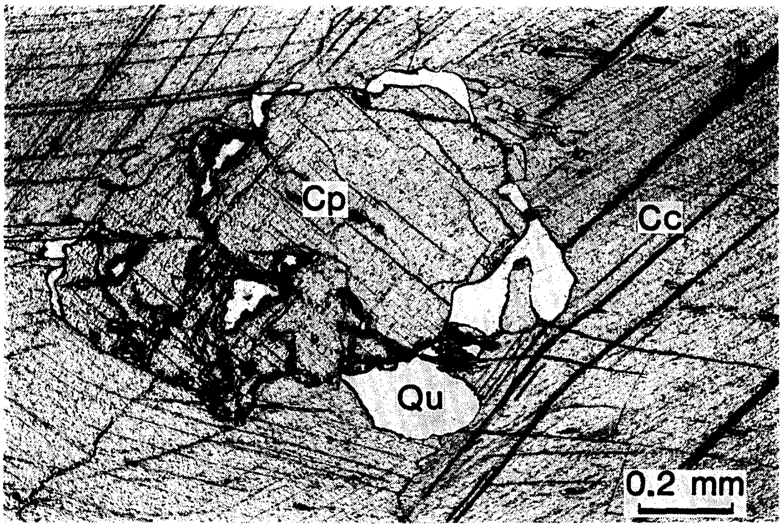

Fig. 4. Photomicrograph showing the association calcite (Cc)-quartz (Qu) in calcite marble (A79121609). Clinopyroxene (Cp) also coexists. One nicol.

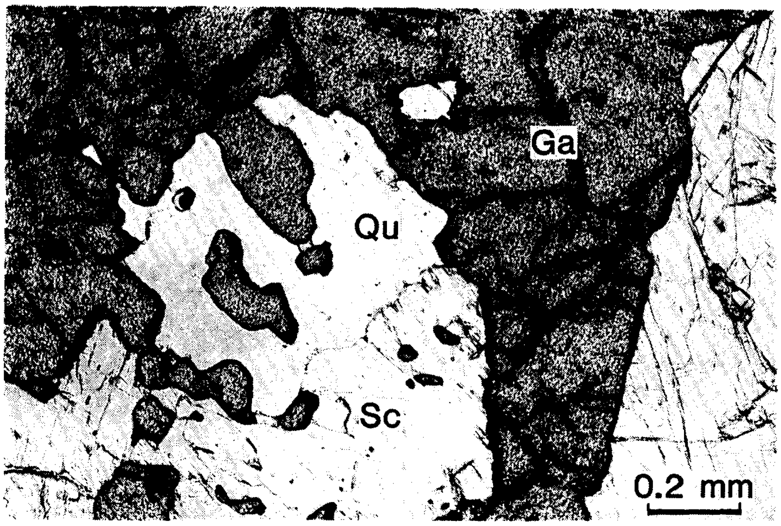

Fig. 5. Photomicrograph showing the association Ca-garnet (Ga)-quartz (Qu) in calc-silicate rock (A79121907). Scapolite (Sc) is also present as one of the essential constituents. One nicol.

occurrence of dolomitic rocks in addition to calcite marble and skarn. No orthopyroxene is found in the metamorphic rocks from the Belgica Mountains. The mineral assemblages in Table 1 indicate that the metamorphic rocks in this area belong to the amphibolite facies.

In calcite-dolomite marble, clinohumite often occurs together with forsterite and spinel (C8 and C9) (Fig. 3), and chondrodite is rarely found in association with spinel (C10). Although dolomitic rocks, some of which contain forsterite and spinel, have also been found in other areas around Syowa Station such as Skallen (YOSHIDA *et al.*, 1976) and Skallevikhalsen (MATSUMOTO, 1982; MATSUEDA *et al.*, 1983), humite-group minerals have not yet been reported from the areas. Metamorphic rocks in the above two areas are of granulite facies unlike the Belgica Mountains. In central Queen Maud Land, however, humite-group minerals are known to occur in some granulite-facies calcareous rocks (GREW, 1984).

Besides the clinohumite and chondrodite occurrence, the following features of mineral assemblages are characteristic of the metamorphics in the Belgica Mountains,

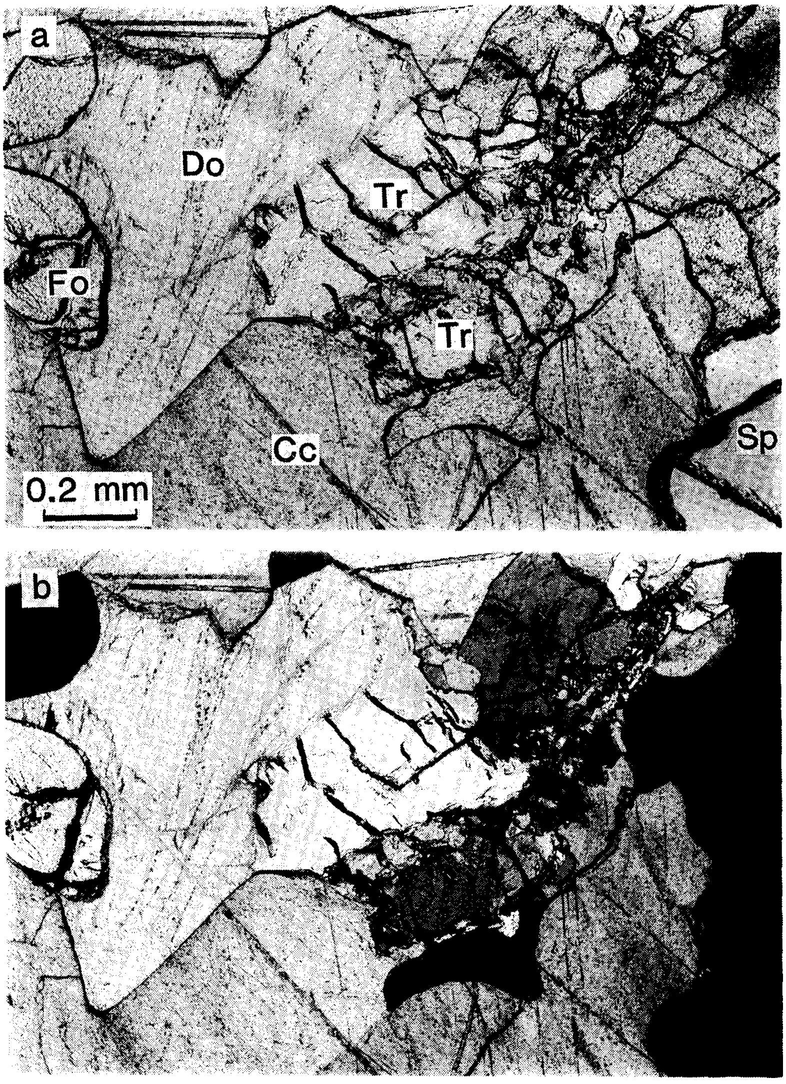

Fig. 6. Photomicrographs showing the five-mineral assemblage forsterite (Fo)-tremolite (Tr)-dolomite (Do)-calcite (Cc)-spinel (Sp) in dolomitic marble (K79121607). (a) one nicol and (b) crossed nicol.

compared with the amphibolite-facies rocks from the other areas around Syowa Station. Garnet is absent in basic rocks of the Belgica Mountains and those of the Yamato Mountains (ASAMI and SHIRAISHI, 1983), while garnet-bearing metabasites are commonly found in the Prince Olav Coast region (YANAI and ISHIKAWA, 1978; NAKAI *et al.*, 1980; SHIRAISHI *et al.*, 1984). However, the presence of the calcite-quartz and Ca-garnet-quartz associations (Figs. 4 and 5) and the absence of wollastonite in the calcareous rocks are common in the Belgica Mountains and the Prince Olav Coast region (SUZUKI and MORIWAKI, 1979; SUZUKI, 1984).

As a rare case, tremolite is found in association with forsterite, spinel, dolomite and calcite in the marble (C8) (Fig. 6). This association which is considered to be petrogenetically important is noted later.

4. Mineralogy

Four rock specimens were mineralogically studied: two garnet-biotite gneisses, one calcite-dolomite marble and one calc-silicate rock. Mineral analyses were made using EPMA of JEOL JXA-733 under such conditions as acceleration voltage of 15 kV, beam currents of about 0.013 μA and a beam diameter of 3 μ. Generally several grains of each mineral species per specimen and two or more points per grain were analyzed. Atomic proportions of Fe^{3+} and Fe^{2+} in Ca-garnet were calculated according to ASAMI and SHIRAISHI (1985).

4.1. *Garnet-biotite gneiss (A79121604 and A79121606)*

This rock consists of quartz, plagioclase, K-feldspar, garnet, biotite, ilmenite, graphite, allanite, apatite and zircon. Garnet forms subhedral porphyroblasts in which round quartz grains are sometimes included. Biotite is much pleochroic: X = pale brownish yellow and Y = Z = dark brown. No tartan twinning and perthite texture can be observed in K-feldspar under the microscope.

Representative analyses of minerals in the two specimens are given in Table 2. Compositional variations of garnet, biotite, feldspars and ilmenite are generally inconspicuous within a single grain and among grains. Garnet is of ferruginous composition. An example of compositional profiles of a garnet porphyroblast in Specimen A79121604 is shown in Fig. 7. The garnet porphyroblast is nearly homogeneous in composition from one edge through the core to the other edge, except the edge showing a slight outward increase of X_{Fe}(= Fe/Fe + Mg) at the contact with biotite. Such a local increase of X_{Fe} suggests an retrograde effect on garnet composition. The other garnet in the same specimen shows similar and uniform compositions (*e.g.* X_{Fe} = 0.954–0.959), with the same local increase of X_{Fe}(0.971) at an edge contacting with biotite. In this specimen, biotite has X_{Fe} = 0.875–0.897 and TiO_2 contents of 4.37–5.19 wt% regardless of contacting with garnet or not, plagioclase is $An_{29.1-31.5}$ and K-feldspar $Or_{95.4-96.3}$. The other specimen (A79121606) contains garnet of X_{Fe} = 0.925–0.935, biotite of X_{Fe} = 0.762–0.791 and 4.81–5.83 wt% TiO_2, and plagioclase of $An_{25.3-27.6}$.

4.2. *Calcite-dolomite marble (K79121607)*

Constituents of this marble are dolomite, calcite, forsterite, clinohumite, phlogopite,

Table 2. Representative mineral analyses for garnet-biotite gneiss by EPMA.

	A79121604							A79121606		
	Ga(I)	Ga(E)	Bi(M)	Bi(C)	Kf	Pl	Il	Ga(I)	Bi(M)	Pl
SiO_2	36.79	36.92	32.26	32.15	63.56	60.28	0.00	37.47	34.22	62.14
TiO_2	0.03	0.02	5.23	4.79	0.00	0.05	50.63	0.01	4.81	0.15
Al_2O_3	19.61	20.30	14.01	14.06	18.16	24.02	0.00	20.33	13.82	23.76
Cr_2O_3	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.20	0.09	0.00
FeO*	35.16	34.85	30.15	31.89	0.02	0.15	48.18	29.02	28.74	0.07
MnO	0.99	1.22	0.09	0.07	0.03	0.00	0.20	3.95	0.32	0.00
MgO	0.68	0.55	2.09	2.31	0.00	0.02	0.02	1.24	4.47	0.00
CaO	6.04	5.83	0.03	0.06	0.05	6.47	0.00	6.81	0.14	5.47
Na_2O	0.04	0.00	0.01	0.06	0.39	8.11	0.00	0.05	0.00	7.90
K_2O	0.00	0.00	8.85	7.99	15.75	0.36	0.00	0.00	8.96	0.36
Total	99.34	99.69	93.10	93.38	97.97	99.46	99.03	99.08	95.57	99.85
O	24	24	22	22	32	32	6	24	22	32
Si	6.045	6.027	5.394	5.368	11.981	10.820	—	6.078	5.493	11.027
Al	3.798	3.906	2.761	2.767	4.035	5.082	—	3.887	2.615	4.970
Ti	0.004	0.002	0.658	0.602	—	0.007	1.959	0.001	0.581	0.020
Cr	—	—	0.003	—	0.001	—	—	0.026	0.011	—
Fe^{2+}	4.832	4.758	4.266	4.453	0.003	0.023	2.073	3.937	3.858	0.010
Mn	0.138	0.169	0.013	0.010	0.005	—	0.009	0.543	0.044	—
Mg	0.167	0.134	0.521	0.575	—	0.005	0.002	0.300	1.069	—
Ca	1.063	1.020	0.005	0.011	0.010	1.244	—	1.184	0.024	1.040
Na	0.013	—	0.003	0.019	0.143	2.823	—	0.016	—	2.718
K	—	—	1.888	1.702	3.788	0.082	—	—	1.835	0.082
X_{Fe}	0.967	0.973	0.891	0.886				0.929	0.783	
Alm	77.9	78.2						66.0		
Pyr	2.7	2.2						5.0		
Sps	2.2	2.8						9.1		
Grs	17.1	16.8						19.9		
Or					96.1					
An						30.0				27.1

* Total iron as FeO. X_{Fe}=Fe/(Fe+Mg). Ga(I): garnet interior, Ga(E): garnet edge, Bi(M): matrix biotite, Bi(C): biotite contacting with garnet, Kf: K-feldspar, Pl: plagioclase, Il: ilmenite.

tremolite, spinel, apatite and zircon. Some crystals of forsterite, clinohumite and spinel are partially altered to serpentine and chlorite. Rarely tremolite is also partially altered to chlorite. Clinohumite has pleochroism of X=light golden yellow and Y=Z= very pale yellow, and sometimes shows twinning of lamellar type. Microscopically no exsolution lamella can be seen in both calcite and dolomite, but calcite is slightly more cloudy than dolomite.

Representative analyses of forsterite, clinohumite, tremolite, phlogopite, spinel, dolomite and calcite are listed in Table 3. The analyzed minerals except for the two carbonates have almost homogeneous compositions within a grain and among grains: $Fo_{98.1-98.4}$ for forsterite, X_{Mg}=0.984–0.988 for clinohumite, X_{Mg}=0.988–0.993 for tremolite, X_{Mg}=0.989–0.992 for phlogopite and X_{Mg}=0.944–0.960 for spinel. Spinel is actually lacking in Cr_2O_3 and MnO and very poor in ZnO (less than 1 wt%). The

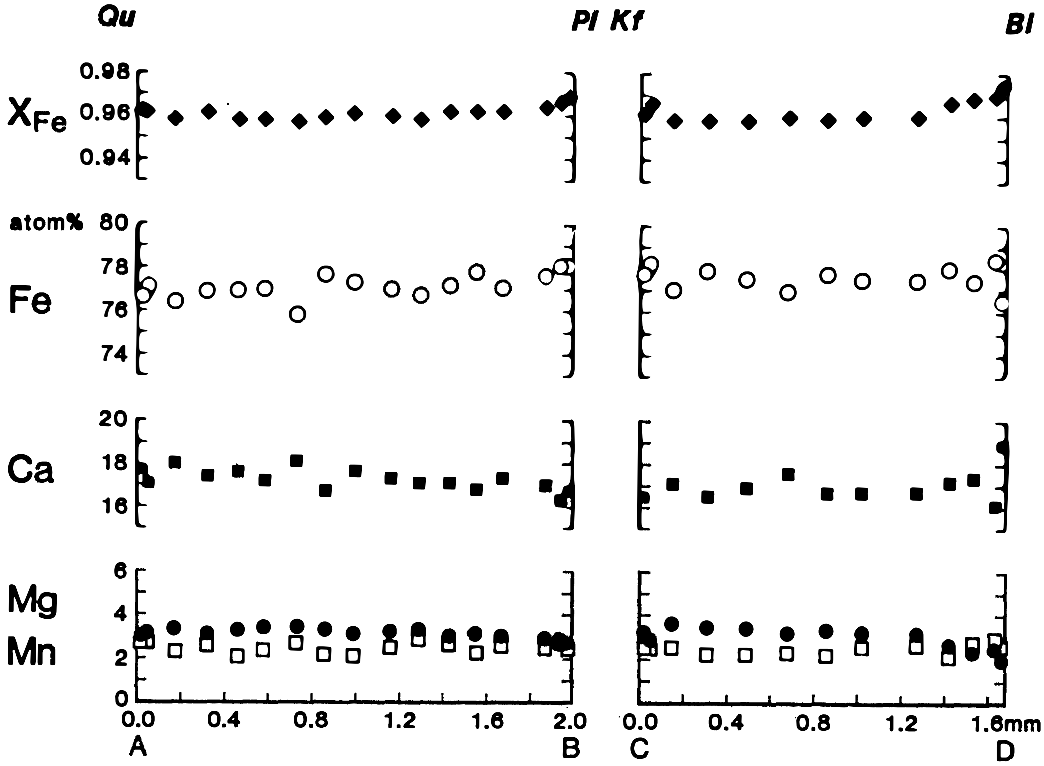

Fig. 7. Compositional profiles of a garnet porphyroblast in garnet-biotite gneiss (A79121604). Those are along two lines, both of which traverse the central part of the garnet. Edges A, B, C and D are in contact with quartz, plagioclase, K-feldspar and biotite, respectively.

Fe_2O_3 content of spinel may be negligible, because the sum of numbers of Fe, Mg and Zn ions is very close to 8 on the basis of 32 oxygens. The $MgCO_3$ content of calcite varies from 4.35 to 6.12 mol% and that of dolomite from 47.31 to 49.92 among grains.

4.3. *Calc-silicate rock* (*A79121907*)

This rock is composed of scapolite, clinopyroxene, garnet, hornblende, K-feldspar, quartz, calcite, epidote, apatite and pyrite. Clinopyroxene is weakly pleochroic with pale green Z-axial color. Garnet is a pale brownish red variety under the microscope. Hornblende shows strong pleochroism: X = light brownish yellow, Y = brownish green and Z = blueish green. K-feldspar exhibits tartan twinning and feeble perthite texture of string type.

Representative compositions of garnet, clinopyroxene, hornblende and scapolite are presented in Table 4. Clinopyroxene is ferrosalite in composition. The X_{Fe} value of each clinopyroxene grain tends to decrease at the edge contacting with garnet and hornblende (0.517–0.577), while it is nearly uniform throughout the interior (0.666–0.700). Garnet is rich in iron but the andradite content varies from 67.7 to 77.5 mol% within one grain. The sum of the oxide components in every garnet analysis is much less than 100 wt%, suggesting a possibility that it is a hydrous variety. Hornblende is of pargasitic composition with X_{Fe} = 0.828–0.865. The meionite content of scapolite varies in mol% from 42.3 to 48.8 among grains.

Table 3. Representative mineral analyses for dolomitic marble (K79121607) by EPMA.

	Fo	Hu	Tr	Ph	Sp	Do	Cc
SiO_2	41.29	37.69	56.01	39.74	0.00	0.00	0.00
TiO_2	0.04	0.95	0.07	0.31	0.07	0.02	0.04
Al_2O_3	0.01	0.05	2.75	16.52	70.47	0.00	0.00
Cr_2O_3	0.00	0.00	0.05	0.03	0.05	0.00	0.00
FeO*	1.99	1.42	0.34	0.49	2.20	0.28	0.10
MnO	0.05	0.06	0.00	0.00	0.02	0.00	0.02
MgO	56.96	57.08	23.77	26.91	26.53	20.25	2.43
ZnO	0.00	0.00	0.00	0.00	0.24	0.00	0.00
CaO	0.02	0.01	14.01	0.04	0.02	31.38	51.87
Na_2O	0.00	0.00	0.48	0.50	0.01	0.00	0.01
K_2O	0.00	0.02	0.27	9.68	0.00	0 02	0.01
Total	100.36	97.28	97.75	94.22	99.61	51.95	54.48
O	4	17	23	22	32	2	2
Si	0.976	3.925	7.650	5.590	—	—	—
Al	—	0.006	0.443	2.739	15.977	—	—
Ti	0.001	0.074	0.007	0.033	0.010	—	0.001
Cr	—	—	0.005	0.003	0.008	—	—
Fe^{2+}	0.039	0.124	0.039	0.058	0.354	0.007	0.003
Mn	0.001	0.005	—	—	0.003	—	0.001
Mg	2.006	8.860	4.838	5.641	7.605	0.942	0.122
Zn	—	—	—	—	0.034	—	—
Ca	0.001	0.001	2.050	0.006	0.004	1.049	1.872
Na	—	—	0.127	0.136	0.004	—	0.001
K	—	0.003	0.047	1.737	—	0.001	—
X_{Mg}	0.981	0.986	0.992	0.990	0.956		
X_{MgCO_3}						0.473	0.061

* Total iron as FeO. X_{Mg}=Mg/(Mg+Fe). $X_{MgCO_3}=MgCO_3/(MgCO_3+CaCO_3)$. Fo: forsterite, Hu: clinohumite, Tr: tremolite, Ph: phlogopite, Sp: spinel, Do: dolomite, Cc: calcite.

5. Metamorphic Conditions

The garnet-biotite Fe-Mg-exchange geothermometer and dolomite-calcite solvus geothermometer are virtually independent of pressure (THOMPSON, 1976; GOLDSMITH and NEWTON, 1969). The garnet-biotite thermometer of THOMPSON (1976) and the dolomite-calcite thermometers of SHEPPARD and SCHWARCZ (1970) and RICE (1977) are applied to estimate temperatures of the amphibolite-facies metamorphism in the Belgica Mountains. Temperatures were calculated from the mineral analyses of the two garnet-biotite gneisses and one calcite-dolomite marble described above. The results are presented in Table 5. The dolomite-calcite thermometry gives much lower temperatures than the garnet-biotite one. In high-grade marble, temperatures obtained from the two-carbonate thermometer tend to be lower than actual metamorphic temperatures, this being mainly due to exsolution of dolomite in calcite (*e.g.* MATSUEDA *et al.*, 1983). Although no dolomite exsolution lamella in calcite can microscopically be recognized in the marble, the varying $MgCO_3$ contents among the carbonate grains suggest that incomplete reexchange of the $MgCO_3$ component might have taken place between dolo-

Table 4. Representative mineral analyses for calc-silicate rock (A79121907) by EPMA.

	Ga	Cp	Hb	Sc
SiO_2	35.11	49.40	37.80	51.89
TiO_2	0.33	0.00	0.14	0.05
Al_2O_3	5.05	0.71	10.57	24.04
Cr_2O_3	0.00	0.02	0.03	0.00
Fe_2O_3**	24.02			
FeO*		20.03	28.63	0.04
MnO	0.68	0.87	0.33	0.05
MgO	0.01	5.44	2.76	0.00
CaO	31.01	22.19	10.59	11.26
Na_2O	0.01	0.41	1.38	7.42
K_2O	0.00	0.00	2.01	0.49
Total	96.22	99.07	94.24	95.24
O	24	6	23	25
Si	6.016	1.978	6.353	7.814
Al	1.020	0.034	2.094	4.267
Ti	0.043	—	0.018	0.006
Cr	—	0.001	0.004	—
Fe^{3+}	2.938			
Fe^{2+}	0.159	0.671	4.025	0.005
Mn	0.099	0.030	0.047	0.006
Mg	0.003	0.325	0.691	—
Ca	5.693	0.952	1.907	1.817
Na	0.003	0.032	0.450	2.167
K	—	—	0.431	0.094
X_{Fe}		0.674	0.853	
	$Grs_{21.2}$ $And_{74.5}$ $Uvr_{0.0}$ $Alm_{2.6}$ $Pyr_{0.0}$ $Sps_{1.6}$	$Wo_{48.9}$ $En_{16.7}$ $Fs_{34.4}$		$Me_{45.6}$

* Total iron as FeO. ** Total iron as Fe_2O_3.
Ga: garnet, Cp: clinopyroxene, Hb: hornblende, Sc: scapolite.

Table 5. Temperatures estimated on the basis of the garnet-biotite and dolomite-calcite thermometers.

	$(Mg/Fe)^{Ga}$	$(Mg/Fe)^{Bi}$	$K_D^{Bi\text{-}Ga}$	$100X_{Cc}^{MgCO_3}$	T_T (°C)	T_S (°C)	T_R (°C)
A79121604	(I) 0.0346	(M) 0.122	3.53		701		
	(E) 0.0282	(C) 0.129	4.57		620		
A79121606	(I) 0.0762	(M) 0.281	3.69		686		
K79121607				6.12		590	568
				5.27		553	542
				4.86		533	528
				4.61		519	520
				4.35		505	511

I: garnet interior, E: garnet edge, M: matrix biotite, C: biotite contacting with garnet.
T_T: after THOMPSON (1976), T_S: after SHEPPARD and SCHWARCZ (1970), T_R: after RICE (1977).

mite and calcite during a later lower-temperature stage. In the garnet-biotite gneiss (A79121604), the garnet edge-contacting biotite pair gives a lower temperature than the garnet interior-matrix biotite pair (Table 5). As stated previously, this fact suggests a local retrograde metamorphic effect on the compositions of the contacting two minerals. Thus it is considered that 680–700°C obtained from the garnet interior-matrix biotite pair are close to temperature conditions of the amphibolite-facies metamorphism in the Belgica Mountains.

The mineral assemblage in the calcite-dolomite marble (K79121607) described is noted in order to infer metamorphic fluid pressures at the time when this rock was formed. The rock-forming minerals of this marble, forsterite, tremolite, dolomite and calcite, are included in the five component system CaO-MgO-SiO_2-CO_2-H_2O. Clinohumite may be largely stabilized by the presence of fluorine (*e.g.* RICE, 1980), so that it does not exactly belong to this system. The above four-mineral phase assemblage in this system is represented by the reaction:

$$\text{tremolite} + \text{dolomite} = \text{forsterite} + \text{calcite} + CO_2 + H_2O. \qquad (1)$$

METZ (1976) and KÄSE and METZ (1980) experimentally studied this reaction under 1, 3 and 5 kb total fluid pressures and located it on the isobaric T-X_{CO_2} sections. The reaction (1) forms univariant curves on the isobaric sections and the curves show actually isothermal character in the X_{CO_2} range higher than 0.5. As a result, under such higher X_{CO_2} conditions the reaction makes up a very narrow divariant field on the total P_{fluid}-T section. This divariant field approximately coincides with the univariant curve (invariant points on the T-X_{CO_2} section) representing the five-phase assemblage with diopside as an additional phase. The invariant points on the T-X_{CO_2} sections were also determined by KÄSE and METZ (1980) as the intersections of the reaction (1) with the reaction:

$$\text{diopside} + \text{dolomite} = \text{forsterite} + \text{calcite} + CO_2. \qquad (2)$$

These relations are illustrated in Fig. 8.

The marble now concerned also contains spinel as an Al_2O_3-bearing phase. According to RICE (1977), the five-phase assemblage forsterite-tremolite-dolomite-calcite-spinel is stable only in high X_{CO_2} part of the unvariant curve of the reaction (1) on the T-X_{CO_2} section: for example, in the range from about 0.8 to 0.9 at 1 kb. Therefore, total fluid pressures under which the marble was formed may be estimated from Fig. 8. By giving 680–700°C as metamorphic temperatures, total fluid pressures around 5 kb are obtained. Solid pressures of the metamorphism may be equal to or higher than the total fluid pressures. If P_{solid} = total P_{fluid} during the amphibolite-facies metamorphism in this area, the metamorphism would be of relatively low pressure just like that in the Yamato Mountains (ASAMI and SHIRAISHI, 1985).

The calcite-quartz association is commonly present but no wollastonite is found in the calcareous rocks from the Belgica Mountains. The experimental results of wollastonite-quartz stability indicate that this paragenetic relation is realized under conditions of total P_{fluid} higher than 1.2 kb and X_{CO_2} higher than 0.5 at 680–700°C (HARKER and TUTTLE, 1956; GREENWOOD, 1967; WINKLER, 1979). The calcite-quartz association as well as the mineral assemblage in the calcite-dolomite marble noted above suggests

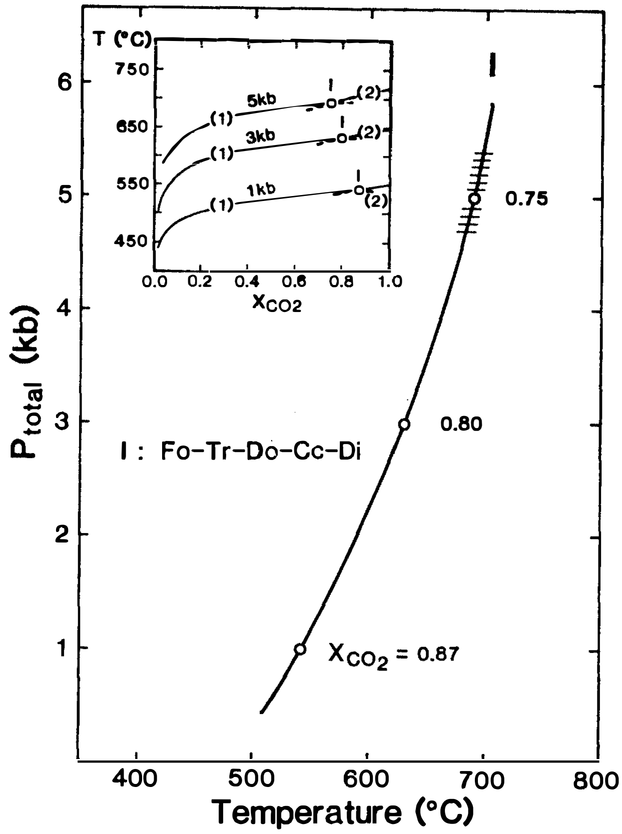

Fig. 8. P-T diagram showing experimentally determined stability relations of the five-phase assemblage forsterite-tremolite-dolomite-calcite-diopside (METZ, 1976; KÄSE and METZ, 1980). This assemblage is of the invariant point (I) at which the reactions (1) and (2) intersect with each other on the T-X_{CO_2} section: (1) tremolite+dolomite= forsterite+calcite+CO_2+H_2O and (2) diopside+dolomite=forsterite+calcite CO_2 (see inset). The shaded portion is estimated conditions of the metamorphism in the Belgica Mountains.

that X_{CO_2} values of fluids in the calcareous rocks were generally high during the metamorphism in this area.

As a matter of course, accuracy of the pressure estimate mentioned above depends largely on that of temperature estimate. Because the garnets used for the thermometry contain considerable amounts of CaO (Table 2), it is inferred that the estimated temperatures are not so accurate as the original values ($\pm$50°C) in THOMPSON's thermometer. Thus the obtained temperatures and pressures are regarded as preliminary ones.

Acknowledgments

The authors wish to express their sincere thanks to Prof. T. NUREKI for his critical reading of the manuscript. Thanks are also extended to Dr. K. SHIRAISHI of National Institute of Polar Research and Dr. Y. MOTOYOSHI of Hokkaido University for their help during microprobe analyses.

References

ASAMI, M. and SHIRAISHI, K. (1983): Mineral parageneses of basic to intermediate metamorphic rocks in the Yamato Mountains, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **28**, 198–214.

ASAMI, M. and SHIRAISHI, K. (1985): Retrograde metamorphism in the Yamato Mountains, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **37**, 147–163.

GOLDSMITH, J. R. and NEWTON, R. C. (1969): P-T-X relations in the system $CaCO_3$-$MgCO_3$ at high temperatures and pressures. Am. J. Sci., SCHAIRER Vol., **267-A**, 160–190.

GREENWOOD, H. J. (1967): Wollastonite stability in H_2O-CO_2 mixtures and occurrence in a contact-metamorphic aureole near Salmo, British Columbia, Canada. Am. Mineral., **52**, 1669–1680.

GREW, E. G. (1984): A review of Antarctic granulite-facies rocks. Tectonophysics, **105**, 177–191.

HARKER, R. I. and TUTTLE, O. F. (1956): Experimental data on the P_{CO_2}-T curve for the reaction; calcite+quartz$\rightleftarrows$wollastonite+carbon dioxide. Am. J. Sci., **254**, 239–256.

HIROI, Y., SHIRAISHI, K., NAKAI, Y., KANO, T. and YOSHIKURA, S. (1983a): Geology and petrology of Prince Olav Coast, East Antarctica. Antarctic Earth Science, ed. by R. L. OLIVER *et al.* Canberra, Aust. Acad. Sci., 32–35.

HIROI, Y., SHIRAISHI, K., YANAI, K. and KIZAKI, K. (1983b): Aluminum silicates in the Prince Olav and Sôya Coasts, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **28**, 115–131.

KÄSE, H.-R. and METZ, P. (1980): Experimental investigation of the metamorphism of siliceous dolomites. IV. Equilibrium data for the reaction; 1 diopside+3 dolomite=2 forsterite+4 calcite $2CO_2$. Contrib. Mineral. Petrol., **73**, 151–159.

KOJIMA, H., YANAI, K. and NISHIDA, T. (1981): Geological map of Belgica Mountains, Antarctica. Antarct. Geol. Map Ser., Sheet 29 (with explanatory text 7 p., 2 pl.). Tokyo, Natl Inst. Polar Res.

KOJIMA, H., YANAI, K. and NISHIDA, T. (1983): Geology and petrology of the Belgica Mountains (abstract). Antarctic Earth Science, ed. by R. L. OLIVER *et al.* Canberra, Aust. Acad. Sci., 54.

MATSUEDA, H., MOTOYOSHI, Y. and MATSUMOTO, Y. (1983): Mg-Al skarn of the Skallevikhalsen on the east coast of Lützow-Holm Bay, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **28**, 166–176.

MATSUMOTO, Y. (1982): Several spinels from the Skallevikhalsen region, east coast of Lützow-Holmbukta, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **21**, 112–119.

METZ, P. (1976): Experimental investigation of the metamorphism of siliceous dolomites. III. Equilibrium data for the reaction; 1 tremolite+11 dolomite=8 forsterite+13 calcite+9 CO_2+1 H_2O for the total pressures of 3,000 and 5,000 bars. Contrib. Mineral. Petrol., **58**, 137–148.

NAKAI, Y., KANO, T. and YOSHIKURA, S. (1980): Geological map of Cape Ryûgû, Antarctica. Antarct. Geol. Map Ser., Sheet 15 (with explanatory text 9 p., 2 pl.). Tokyo, Natl Inst. Polar Res.

RICE, J. M. (1977): Contact metamorphism of impure dolomitic limestone in the Boulder aureole, Montana. Contrib. Mineral. Petrol., **59**, 237–259.

RICE, J. M. (1980): Phase equilibria involving humite minerals in impure dolomitic limestones. Part I. Calculated stability of clinohumite. Contrib. Mineral. Petrol., **71**, 219–235.

SHEPPARD, S. M. F. and SCHWARCZ, H. P. (1970): Fractionation of carbon and oxygen isotope and magnesium between coexisting metamorphic calcite and dolomite. Contrib. Mineral. Petrol., **26**, 161–198.

SHIBATA, K., YANAI, K. and SHIRAISHI, K. (1985): Rb-Sr mineral isochron ages of metamorphic rocks around Syowa Station and from the Yamato Mountains, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **37**, 164–171.

SHIRAISHI, K., HIROI, Y. and ONUKI, H. (1984): 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. Mem. Natl Inst. Polar Res., Spec. Issue, **33**, 126–144.

SUZUKI, M. (1984): Reexamination of metapelites in the Cape Omega area, westernmost part of Prince Olav Coast, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **33**, 145–154.

SUZUKI, M. and MORIWAKI, K. (1979): Geological map of Cape Omega, Antarctica. Antarct. Geol.

Map Ser., Sheet 21 (with explanatory text 5 p., 2 pl.). Tokyo, Natl Inst. Polar Res.

THOMPSON, A. B. (1976): Mineral reactions in pelitic rocks; II. Calculation of some P-T-X(Fe-Mg) phase relations. Am. J. Sci., **276**, 425–454.

VAN AUTENBOER, T. and LOY, W. (1972): Recent geological investigations in the Sør-Rondane Mountains, Belgicafjella and Sverdrupfjella, Dronning Maud Land. Antarctic Geology and Geophysics, ed. by R. J. ADIE. Oslo, Universitetsforlaget, 563–571.

WINKLER, H. G. F. (1979): Petrogenesis of Metamorphic Rocks (fifth edition). New York, Springer, 348 p.

YANAI, K. and ISHIKAWA, T. (1978): Geological map of Cape Hinode, Antarctica. Antarct. Geol. Map Ser., Sheet 11 (with explanatory text 6 p.). Tokyo, Natl Inst. Polar Res.

YANAI, K., SHIBATA, K. and SHIRAISHI, K. (1983): Syowa Kiti fukin san henseigan no Rb-Sr nendai (Rb-Sr ages of metamorphic rocks from Syowa Station). Dai-4-kai Nankyoku Chigaku Shinpojiumu Puroguram·Kôen Yôshi (Program·Abstr. 4th Symp. Antarct. Geosci.), Tokyo, Natl Inst. Polar Res., 1.

YOSHIDA, M., YOSHIDA, Y., ANDO, H., ISHIKAWA, T. and TATSUMI, T. (1976): Geological map of Skallen, Antarctica. Antarct. Geol. Map Ser., Sheet 9 (with explanatory text 16 p., 2 pl.).

(Received April 3, 1986; Revised manuscript received June 2, 1986)