Proc. NIPR Symp. Antarct. Geosci., 1, 73-97, 1987

PROGRESSIVE METAMORPHISM OF CALC-SILICATE ROCKS FROM THE PRINCE OLAV AND SÔYA COASTS, EAST ANTARCTICA

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Abstract: Metamorphosed calc-silicate rocks occur sporadically as small masses enclosed in other high-grade metasedimentary rocks of the Late Proterozoic Lützow-Holm Complex in the Prince Olav and Sôya Coasts, East Antarctica. Southwestward progressive metamorphism of the calc-silicate rocks is clarified which is in good agreement with the results of previous studies on the pelitic and basic-intermediate rocks. Two isograds are mapped on the basis of the continuous reaction epidote+quartz±calcite=grandite garnet+plagioclase+Fe-oxides± scapolite+H_2O and the discontinuous reaction grossular+quartz=wollastonite +anorthite in the amphibolite-facies and granulite-facies terrains, respectively. The latter is the best-defined isograd among those so far drawn in various rock types of the Lützow-Holm Complex, as it is based on a vapor-absent reaction and the effects of additional components such as Fe_2O_3 and Na_2O on the reaction are estimated to have been negligible in the studied rocks. Pressure of about 7 kb is evaluated by the discontinuous reaction at $T=810\pm20$°C in the granulite-facies terrain. The present study, together with the previously published ones, confirms that the regional metamorphic geotherm of the Lützow-Holm Complex based on the progressive mineral zones was of the medium-pressure type and was distinct from those of the adjacent Rayner and Yamato-Belgica Complexes. The occurrence of grossular with or without quartz in the granulite-facies terrain suggests that the vapor phase was generally poor in both H_2O and CO_2 during the high-grade metamorphism.

1. Introduction

High-grade metamorphic rocks are exposed along the Prince Olav and Sôya Coasts, East Antarctica (between 39-45°E in longitude), which belong to the Late Proterozoic Lützow-Holm Complex (Fig. 1). In the area, southwestward progressive metamorphism of the medium-pressure type from the upper amphibolite facies to the granulite facies has been revealed by the studies on the pelitic and basic-intermediate

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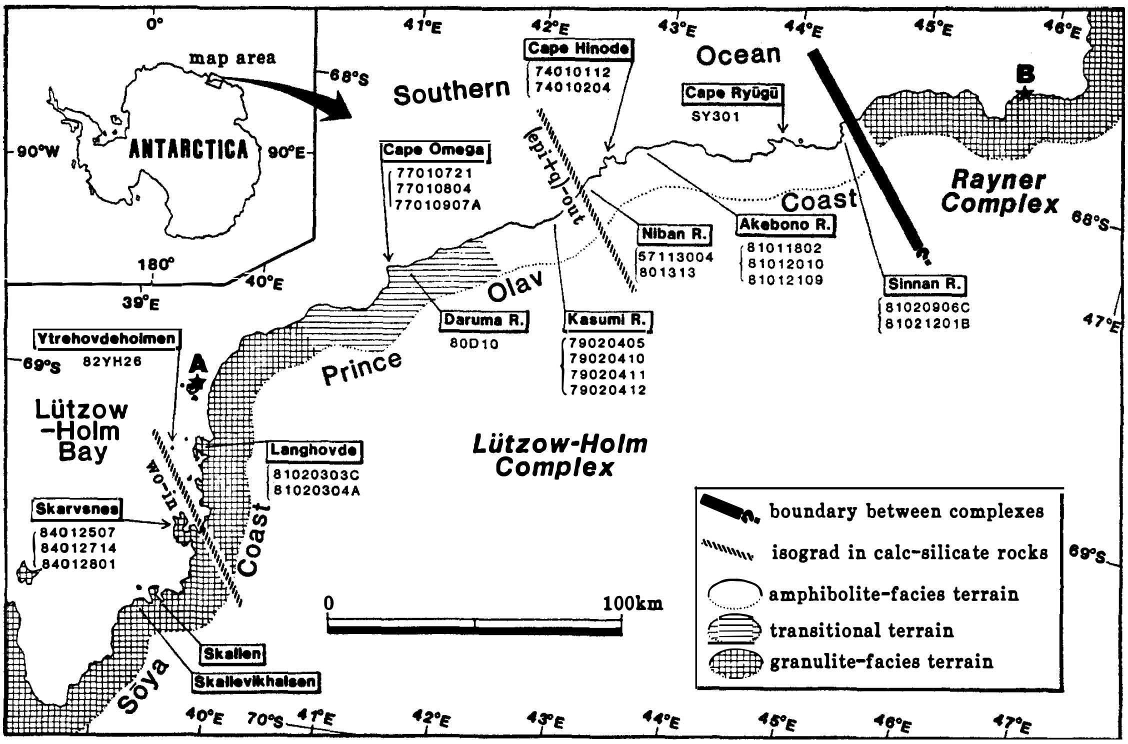


Fig. 1. Map of the Prince Olav and Sôya Coasts, East Antarctica, showing boundary between complexes, metamorphic facies, specimen localities, and isograds in calc-silicate rocks. A; Syowa Station, B; Molodezhnaya Station. See text for details about the isograds.

rocks (HIROI *et al.*, 1983b, c; SHIRAISHI *et al.*, 1984; SUZUKI, 1985). Although small in amount, calc-silicate rocks also occur sporadically in the area and show variations in mineral assemblage (TATSUMI and KIKUCHI, 1959; BANNO *et al.*, 1964a, b; TATSUMI *et al.*, 1964; SUWA, 1968; SUWA and TATSUMI, 1969; YOSHIDA *et al.*, 1976; ISHIKAWA *et al.*, 1977; YOSHIDA, 1977, 1978; KANISAWA *et al.*, 1979; MATSUMOTO *et al.*, 1979; SUZUKI, 1979a, b; SUZUKI and MORIWAKI, 1979; YOSHIKURA *et al.*, 1979; NAKAI *et al.*, 1980; KANISAWA and YANAI, 1982; MATSUMOTO 1982; NISHIDA *et al.*, 1982, 1984; HIROI *et al.*, 1983a, 1986a, b; KIZAKI *et al.*, 1983; MATSUEDA *et al.*, 1983; MOTOYOSHI and SHIRAISHI, 1985). The purpose of this paper is to clarify progressive metamorphism of the calc-silicate rocks based mainly on petrography in order to confirm the thermal structure of the Lützow-Holm Complex and to get new information on the metamorphic conditions. More comprehensive study including mineral chemistry will be presented elsewhere.

2. Geologic and Petrologic Outline

The high-grade metamorphic rocks exposed along the Prince Olav Coast and around Lützow-Holm Bay have been extensively studied by the Japanese geologists for the last 30 years, and a geologic map of each bedrock exposure on a scale of 1 : 25000 or 1 : 5000 has been published by the National Institute of Polar Research, Tokyo. Summarizing the accumulated data, HIROI *et al.* (1984a, b) proposed that the rocks in the region constitute a single geologic unit (Lützow-Holm Complex) which is distinct in age and/or type of regional metamorphism from the adjacent Rayner and Yamato-Belgica Complexes to the east and to the southwest, respectively.

The Lützow-Holm Complex consists largely of well-layered pelitic-psammitic and "intermediate" (between basic and pelitic-psammitic) gneisses with some migmatitic rocks. Lesser amounts of metamorphosed calcareous, basic, and ultrabasic rocks are also present. The pelitic-psammitic rocks show a wide range in bulk chemical composition and are sillimanite-garnet-biotite, sillimanite-cordierite-biotite, Ca-poor amphibole or orthopyroxene-garnet-biotite, garnet-biotite, and biotite gneisses. The intermediate rocks include biotite-hornblende and orthopyroxene-biotite-hornblende gneisses. Orthopyroxene-bearing rocks occur in the higher-grade part of the complex, as will be mentioned later. The migmatitic rocks are granitic to granodioritic in composition and are of anatectic origin (HIROI *et al.*, 1983c). They occur more abundantly in the lower-grade part than in the higher-grade part of the complex.

The Lützow-Holm Complex has been deformed, at least twice; the axial planes of earlier isoclinal folds trend N-S to NW-SE and those of later open to close folds NE-SW (SHIRAISHI, 1986; HIROI and SHIRAISHI, 1986; SHIRAISHI *et al.*, 1987). The Lützow-Holm Complex was extensively intruded by the Early Paleozoic granite and pegmatite.

Many K-Ar and Rb-Sr ages of about 500 Ma obtained from whole rock and mineral separates indicate a heating event coeval with the Early Paleozoic granite and pegmatite activity (YANAI and UEDA, 1974; SHIBATA *et al.*, 1985), which is known over a large portion of East Antarctica (GREW, 1982). The Rb-Sr method on whole rock and mineral separates, however, often indicates older ages (680–1200 Ma), which probably date the earlier regional metamorphism of the complex (MAEGOYA *et al.*, 1968; SHIRAHATA, 1983; SHIBATA *et al.*, 1986). It is significant that the initial $^{87}Sr/^{86}Sr$ ratios of metasedimentary gneisses of the Lützow-Holm Complex are relatively low (0.705–0.706) (SHIBATA *et al.*, 1986). This suggests that most, if not all, metasediments of the complex did not have a long pre-metamorphic history.

The Prince Olav Coast and Lützow-Holm Bay region is divided into three terrains of different metamorphic facies (Fig. 1). The eastern part of the Prince Olav Coast is an amphibolite-facies terrain where calcium-poor amphiboles (anthophyllite and cummingtonite) occur and no orthopyroxene has been found (RAVICH and KAMENEV, 1975; HIROI *et al.*, 1983c). Its western part is a transitional terrain from the amphibolite facies to the granulite facies. In the transitional terrain, orthopyroxene occurs sporadically, confined to rocks with appropriate bulk chemical compositions (HIROI *et al.*, 1983c, 1986b; SHIRAISHI, 1986; SHIRAISHI *et al.*, 1984; SUZUKI, 1984). The region around Lützow-Holm Bay is a granulite-facies terrain characterized by the common occurrence of orthopyroxene in basic-intermediate and some psammitic rocks as well as in ultrabasic rocks (BANNO *et al.*, 1964a, b; KIZAKI, 1964; SUWA, 1968; YOSHIDA, 1978, 1979a, b; YOSHIDA *et al.*, 1982; SUZUKI, 1982, 1983, 1986; KATSUSHIMA, 1985; MOTOYOSHI and SHIRAISHI, 1985; MOTOYOSHI, 1986; HIROI *et al.*, 1986b). The first appearance of orthopyroxene in the transitional terrain may be attributed to the following continuous reactions (SHIRAISHI *et al.*, 1984; SHIRAISHI, 1986; HIROI and SHIRAISHI, 1986; HIROI *et al.*, 1986b):

In basic-intermediate rocks;

anthophyllite or cummingtonite=orthopyroxene+quartz+H_2O,

tremolite=orthopyroxene+clinopyroxene+quartz+H_2O,

tschermakite in hornblende+quartz=orthopyroxene+anorthite+H_2O.

In ultrabasic rocks;

chlorite+plagioclase=orthopyroxene+hornblende+H_2O,

chlorite=olivine+orthopyroxene+spinel+H_2O,

garnet=orthopyroxene+spinel+plagioclase,

anthophyllite+olivine=orthopyroxene+H_2O,

tremolite+olivine=orthopyroxene+clinopyroxene+H_2O,

tschermakite in hornblende+olivine=orthopyroxene+clinopyroxene+spinel +H_2O.

The sillimanite+K-feldspar+quartz assemblage (no primary muscovite) was stable in pelitic gneisses over the entire study area (HIROI *et al.*, 1983b, c; MOTOYOSHI *et al.*, 1985). Moreover, the corundum+K-feldspar+muscovite paragenesis was stable in the amphibolite-facies terrain (HIROI *et al.*, 1983a, b, c). These facts suggest that the muscovite+quartz assemblage was not stable throughout the study area. It is significant that a small amount of metastable kyanite occurs as relict inclusions within garnet and plagioclase grains in many of the sillimanite-bearing gneisses regardless of the metamorphic grade, suggesting that rocks of the Lützow-Holm Complex uniformly experienced prograde recrystallization from the kyanite to the sillimanite stability fields (HIROI *et al.*, 1983b, c; MOTOYOSHI *et al.*, 1985). On the other hand, andalusite locally occurs in rocks cut extensively by the Early Paleozoic granite and pegmatite, suggesting contact metamorphism by the granite and pegmatite under the different conditions from those during the earlier regional metamorphism (HIROI *et al.*, 1983c; HIROI and SHIRAISHI, 1986; SHIRAISHI *et al.*, 1987). HIROI *et al.* (1983b, c) and MOTOYOSHI *et al.* (1985) mapped two isograds in pelitic rocks based on the following two continuous reactions in the amphibolite-facies and granulite-facies terrains, respectively;

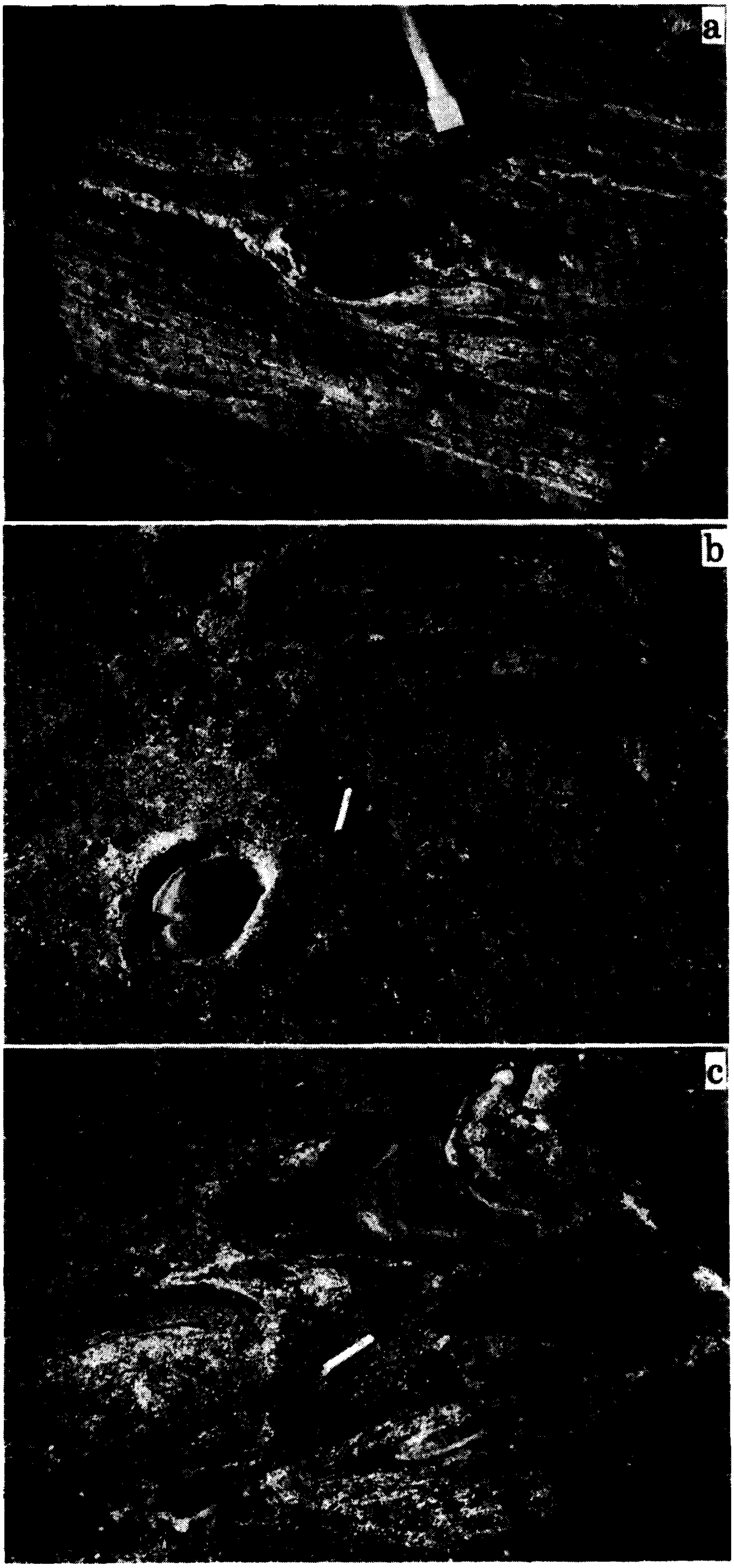
staurolite=aluminum silicate(s)+garnet+hercynite+H_2O,

garnet+sillimanite=hercynite+quartz.

Thus, previously mapped isograds including the boundaries between the metamorphic facies are all based on continuous reactions. However, this, along with the gradual changes in partition coefficient of elements between minerals and in chemical composition of solid solution minerals (SHIRAISHI, 1986; MOTOYOSHI, 1986; HIROI *et al.*, in preparation), indicates the southwestward progressive metamorphism in the Lützow-Holm Complex.

3. Mode of Field Occurrence of Calc-silicate Rocks

Calc-silicate rocks sporadically occur as small rounded to lenticular masses from a few cm up to about 5 m in diameter within pelitic-psammitic and intermediate rocks (Fig. 2). They also occur as thin layers associated with marble layers which are concordantly intercalated with other gneisses. The calc-silicate rocks usually grade into other rocks and are often heterogeneous within a mass. They occasionally show a compositional layering (Figs. 2b and 2c).



a. Small lens-shaped mass of calc-silicate rock in biotite-hornblende gneiss. Akebono Rock, Prince Olav Coast.

b. Small rounded and lens-shaped masses of calc-silicate rock in orthopyroxene-biotite-hornblende gneiss. Skarvsnes, Sôya Coast.

c. Irregularly shaped masses of calc-silicate rock in orthopyroxene-biotite-hornblende gneiss. Skarvsnes, Sôya Coast. Note the compositional layering in the masses.

Fig. 2. Photographs showing mode of field occurrence of calc-silicate rocks.

Table 1. Mineral assemblages of calc-silicate rocks and mineral abbreviations.

Locality	Prince Olav Coast													
	Sinnan Rs.		C.R.	Akebono Rock			Cape Hinode		Niban R.		Kasumi Rock			
Specimen No.	8102 0906C	8102 1201B	SY 301	8101 1802	8101 2010	8101 2109	7401 0112	7401 0204	5711 3004	8013 13	7902 0405	7902 0410	7902 0411	7902 0412
calcite			+					+	+		+	+	+	+
quartz	+	+	+	+	+	+		+	+	+				
wollastonite														
epidote	+	+		+		+	+	+		+	+			+
garnet	+	+	+	+	+	+	+	+	+	+	+			+
plagioclase	+	+	+	+	+	+	+			+	+			+
scapolite	+									+	+			+
K-feldspar														
clino-pyroxene	+	+	+	+	+	+	+	+	+	+	+			+
Ca-amphibole			+		+					+		+	+	
sphene	+	+	+	+	+	+		+		+	+			+
magnetite	+	+	+	+		+	+	+	+		+			+
hematite		+							+					
ilmenite			+		+							+	+	
Fe-sulphide	+											+	+	
apatite	+	+	+	+	+	+	+	+	+	+	+	+	+	+
dolomite												+	+	
olivine												+	+	
clinohumite												+	+	
spinel													+	
biotite												+	+	
chlorite													+	
←—— amphibolite facies ——→														

Mineral abbreviations

andalusite—	and	anorthite—	an	apatite—	ap	biotite—	bi
calcite—	cc	Ca-amphibole—	Ca-amph	chlorite—	chl	clinohumite—	chu
clinopyroxene—	cpx	dolomite—	do	epidote—	epi	Fe-sulphide—	Fe-sul
garnet—	gar	grossular—	gr	hematite—	hm	ilmenite—	il
K-feldspar—	Ksp	kyanite—	ky	magnetite—	mt	meionite—	me
olivine—	ol	plagioclase—	pl	scapolite—	sc	sillimanite—	sil
sphene—	sph	spinel—	sp	wollastonite—	wo	zoisite—	zo

4. Progressive Mineral Changes in Calc-silicate Rocks

Mineral assemblages in calc-silicate rocks from various localities in the study area are presented in Table 1. The following may be pointed out as the progressive mineral changes in the calc-silicate rocks.

(1) Primary epidote occurs in the amphibolite-facies terrain. The epidote+quartz assemblage is found in the more restricted area, that is, in the lowest-grade part of the study area.

(2) Garnet occurs throughout the study area. However, the garnet+quartz

Table 1 (continued).

Locality	Prince Olav Coast				Sôya Coast					
	D.R.	Cape Omega			Langhovde		Ytr.	Skarvsnes		
Specimen No.	80D 10	7701 0721	7701 0804	7701 0907A	8102 0303C	8102 0304A	82YH 26	8401 2507	8401 2714	8401 2801
calcite					+	+	+	(+)*	(+)*	(+)*
quartz				+			+	+	+	+
wollastonite								+	+	+
epidote										
garnet	+	+	+	+		+	+	(+)*	(+)*	(+)*
plagioclase	+	+	+	+	+		+	+	+	+
scapolite	+		+	+	+	+		+	+	+
K-feldspar	+			+						
clinopyroxene	+	+	+	+	+	+	+	+	+	+
Ca-amphibole	+	+			+					
sphene	+	+	+	+				+	+	+
magnetite	+	+	+							
hematite	+									
ilmenite										
Fe-sulphide					+					
apatite	+	+	+	+	+	+	+	+	+	+
dolomite										
olivine										
clinohumite										
spinel										
biotite					+					
chlorite										
	←——transitional——→				←————granulite facies————→					

* (+); present as relic, being included in plagioclase and wollastonite and separated from quartz.

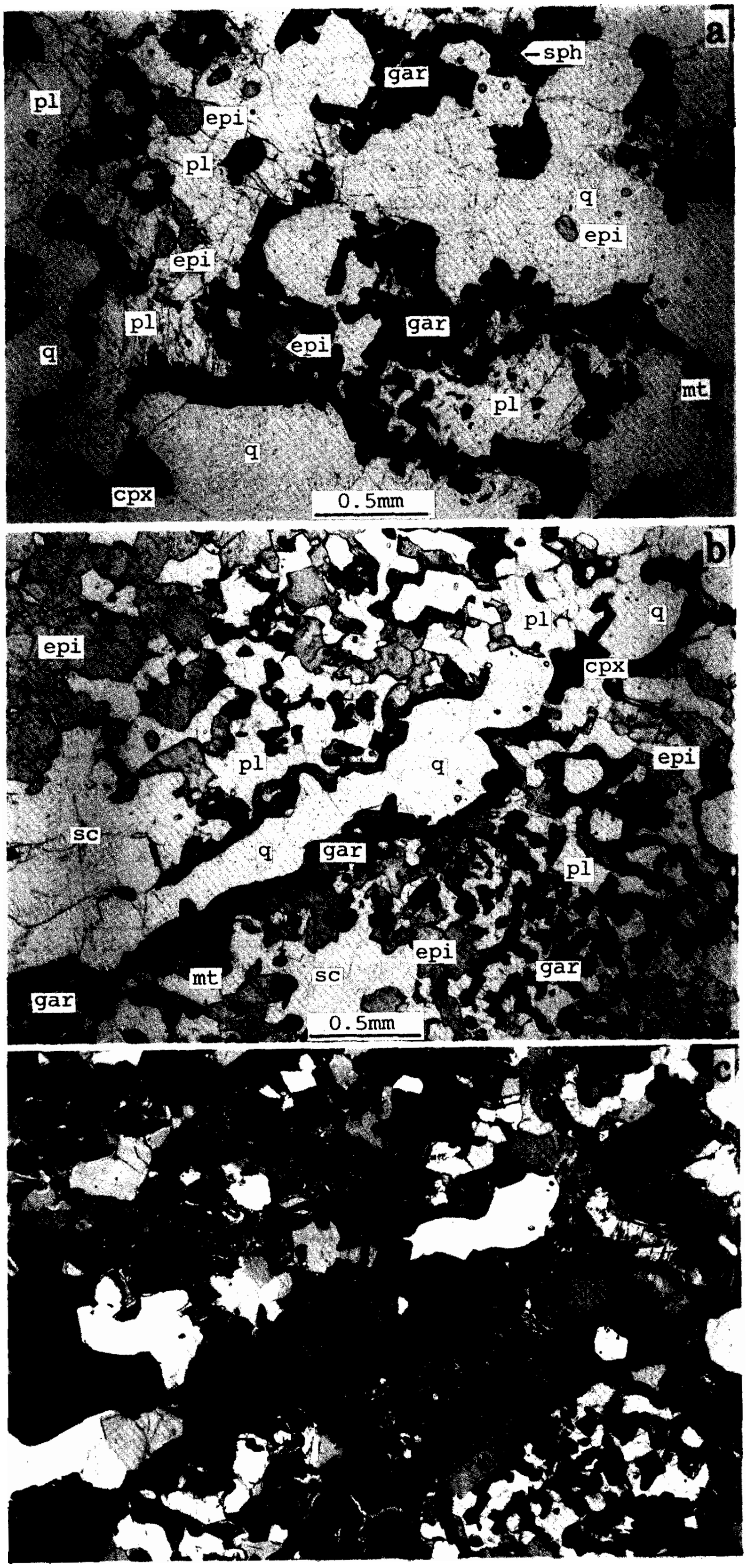
assemblage is not found in the higher-grade part of the granulite-facies terrain.

(3) Wollastonite occurs with calcic plagioclase in the higher-grade part of the granulite-facies terrain, where the stable garnet+quartz assemblage is not found.

(4) The calcite+quartz assemblage is found widely in the study area except for the higher-grade part of the granulite-facies terrain, where wollastonite occurs.

(5) Clinopyroxene, calcic amphiboles, plagioclase, scapolite, and sphene occur throughout the study area.

Two specimens from the Kasumi Rock in the Prince Olav Coast are silica-undersaturated dolomitic marbles. Occurrence of such a kind of rocks has been known in the southern part of the Sôya Coast (*e.g.* Skallen and Skallevikhalsen, see Fig. 1) (BANNO *et al.*, 1964a, b; SUWA, 1968; SUWA and TATSUMI, 1969; YOSHIDA *et al.*, 1976; YOSHIDA 1977, 1978; MATSUMOTO, 1982; MATSUEDA *et al.*, 1983) and in Botnnuten, an isolated nunatak situated to the south of Lützow-Holm Bay (MOTOYOSHI and SHIRAISHI, 1985). Petrologic study of the dolomitic marbles will be presented elsewhere.

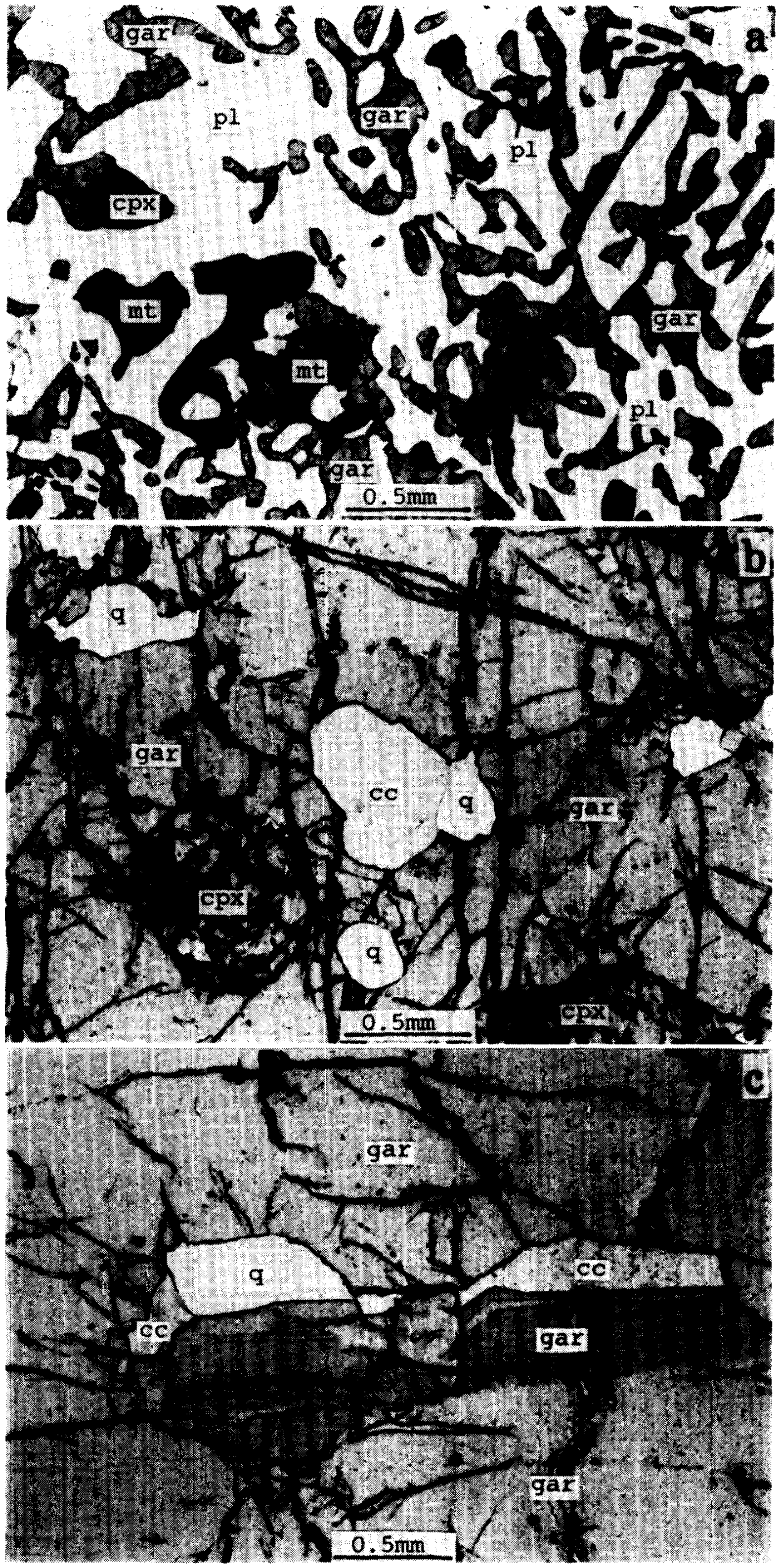


a. *Sp. 81021201B. Epidote showing two modes of occurrence; as inclusions in grandite garnet and sodic plagioclase and as an anhedral grain in direct contact with quartz. Small amounts of dark green clinopyroxene and magnetite are also present. Plane polarized light.*

b. *Sp. 81020906C. Symplectitic intergrowth of grandite garnet, calcic plagioclase, and CO_3-scapolite between epidote and quartz. Small amounts of dark green clinopyroxene and magnetite are also present. Plane polarized light.*

c. *Ditto. Crossed nicols.*

Fig. 3. Photomicrographs showing textures of minerals in calc-silicate rocks from Sinnan Rocks, Prince Olav Coast.

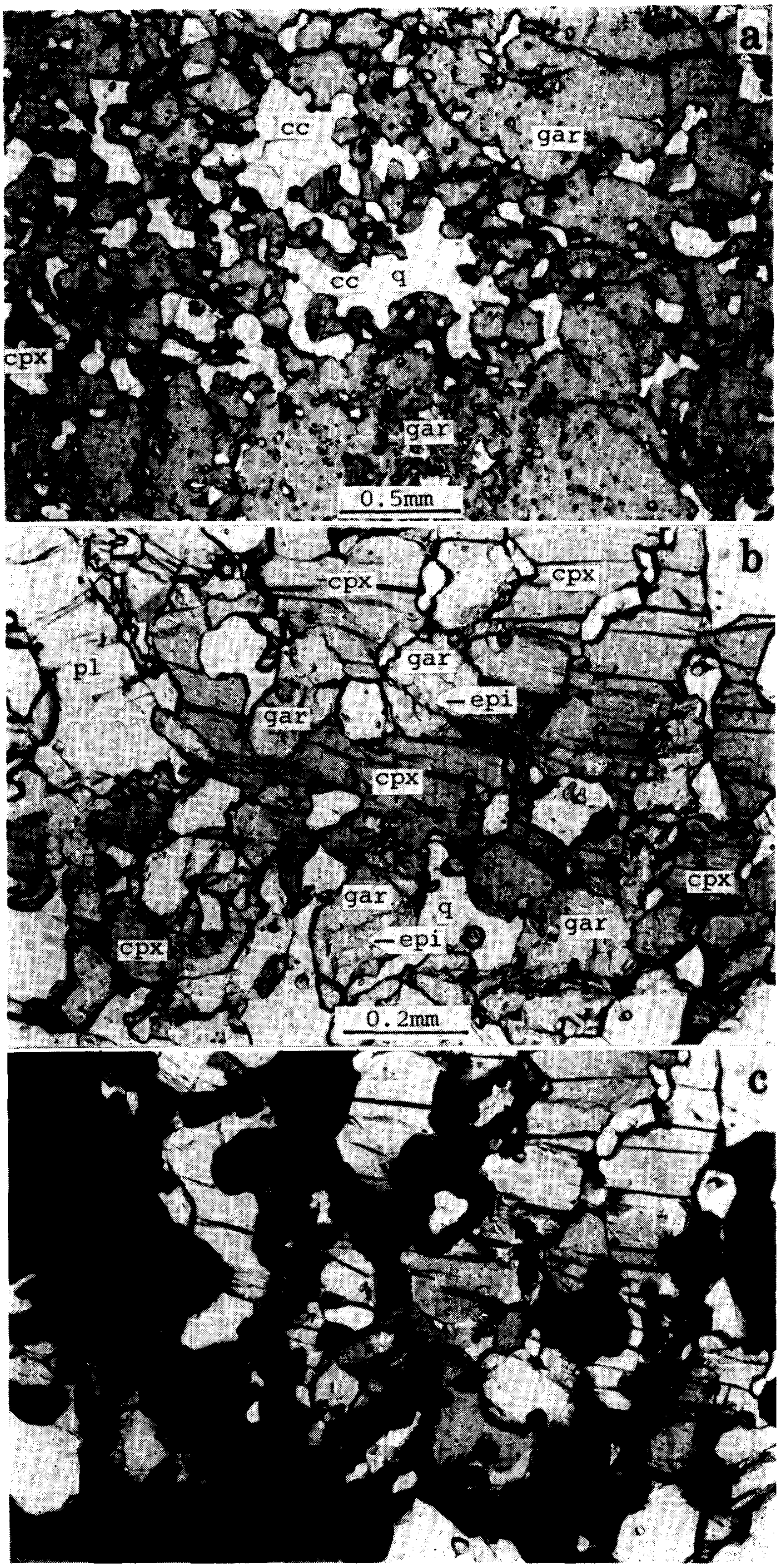


a. Sp. 74010112. Symplectitic intergrowth of grandite garnet and anorthite with small amounts of magnetite and fassaite (*Kanisawa and Yanai, 1982*). *Bulk chemical composition of this rock is close to chemical composition of epidote* (*see Table 2*).

b. Sp. 74010204. Porphryoblastic grandite garnet including pale green clinopyroxene, calcite, and quartz. Epidote is also present somewhere.

c. Sp. 74010204. Grandite garnet showing local heterogeneity.

Fig. 4. Photomicrographs showing textures of minerals in calc-silicate rocks from Cape Hinode, Prince Olav Coast. Plane polarized light.

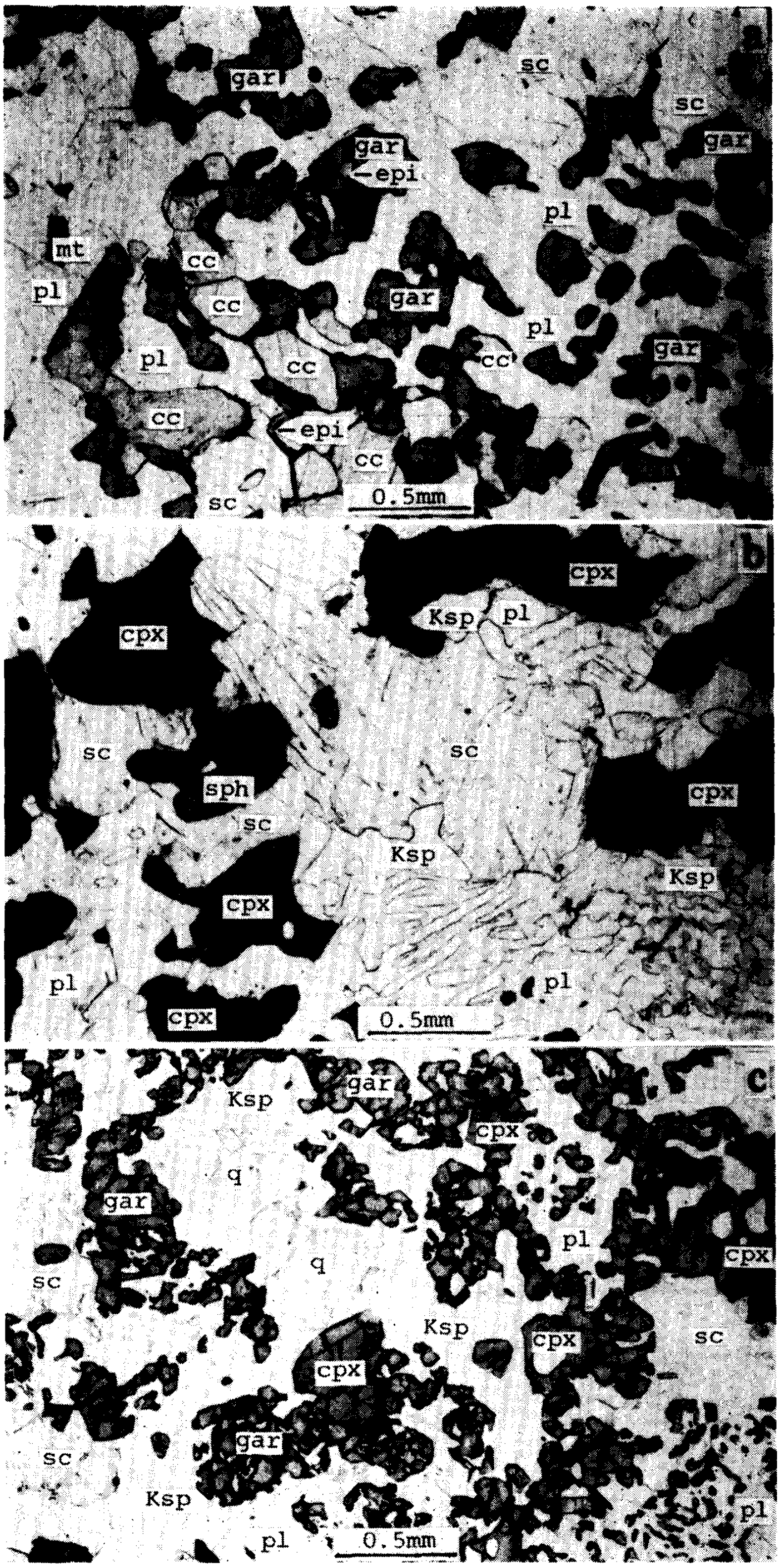


a. Sp. 57113004. Poikilitic grandite garnet containing calcite, quartz, and green clinopyroxene. Epidote is also present somewhere. Plane polarized light.

b. Sp. 801313. Intergrowth of pale green clinopyroxene, Ca-rich pyralspite garnet, calcic plagioclase, and quartz. Note epidote inclusions in garnet. Epidote is occasionally in direct contact with quartz somewhere. Plane polarized light.

c. Ditto. Crossed nicols.

Fig. 5. Photomicrographs showing textures of minerals in calc-silicate rocks from Niban Rock, Prince Olav Coast.

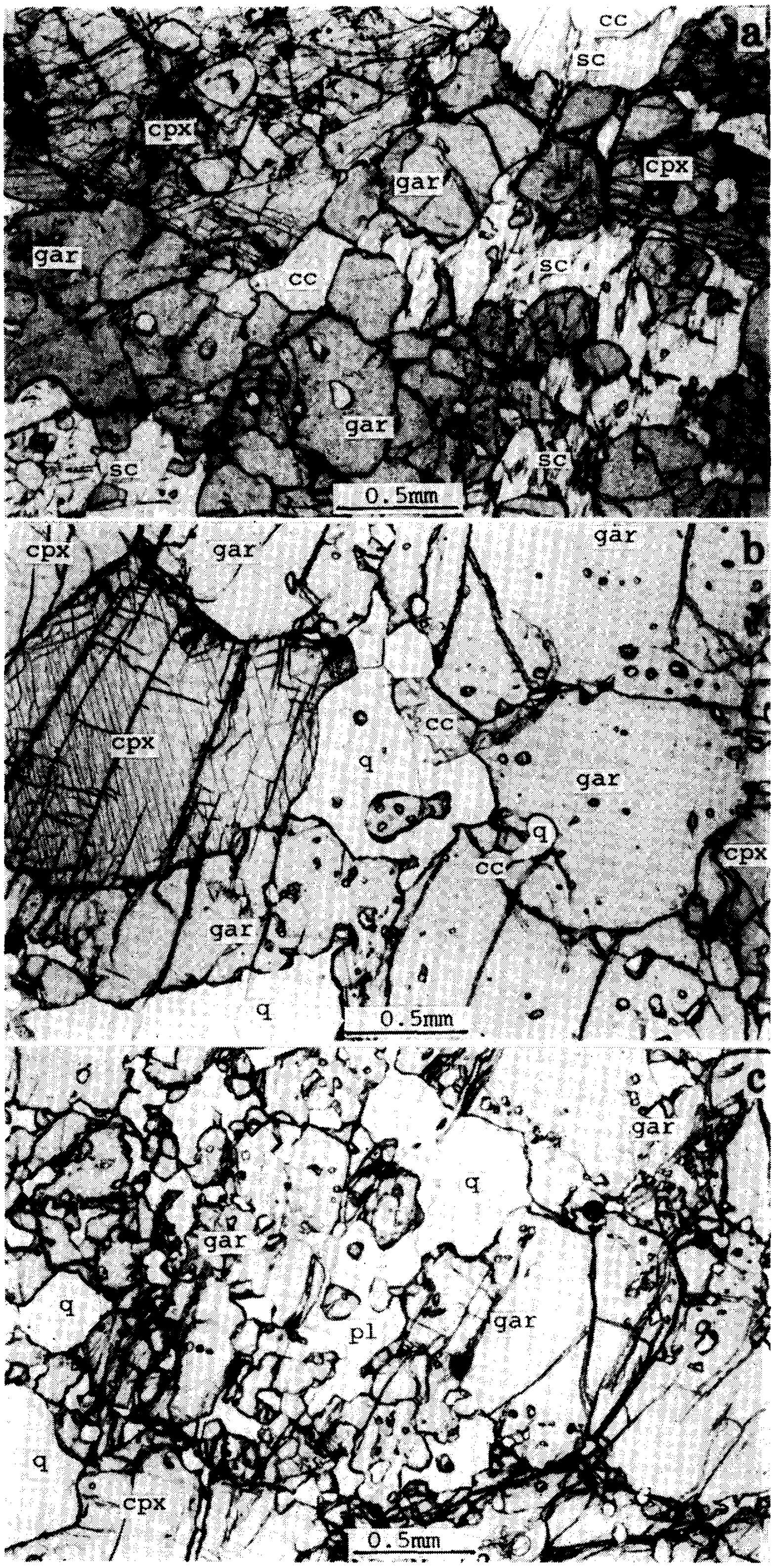


a. *Sp. 79020405. Symplectitic intergrowth of grandite garnet, calcic plagioclase,* CO_3*-scapolite, and calcite. Small amounts of magnetite and epidote are also present. Epidote shows two modes of occurrence; as inclusions in garnet and as films between plagioclase and calcite. Bulk chemical composition of this rock is close to chemical composition of epidote (see Table 2).*

b. *Sp. 80D10. Intimate association of dark green clinopyroxene, calcic plagioclase, scapolite, K-feldspar and sphene.*

c. *Sp. 77010907A. Symplectitic intergrowth of grandite garnet, calcic plagioclase, and scapolite. Fassaitic clinopyroxene, K-feldspar, and quartz are also present (SUZUKI, 1979a, b).*

Fig. 6. Photomicrographs showing textures of minerals in calc-silicate rocks from Kasumi Rock (Sp. 79020405), Daruma Rock (Sp. 80D10), and Cape Omega (Sp. 77010907A), Prince Olav Coast. Plane polarized light.

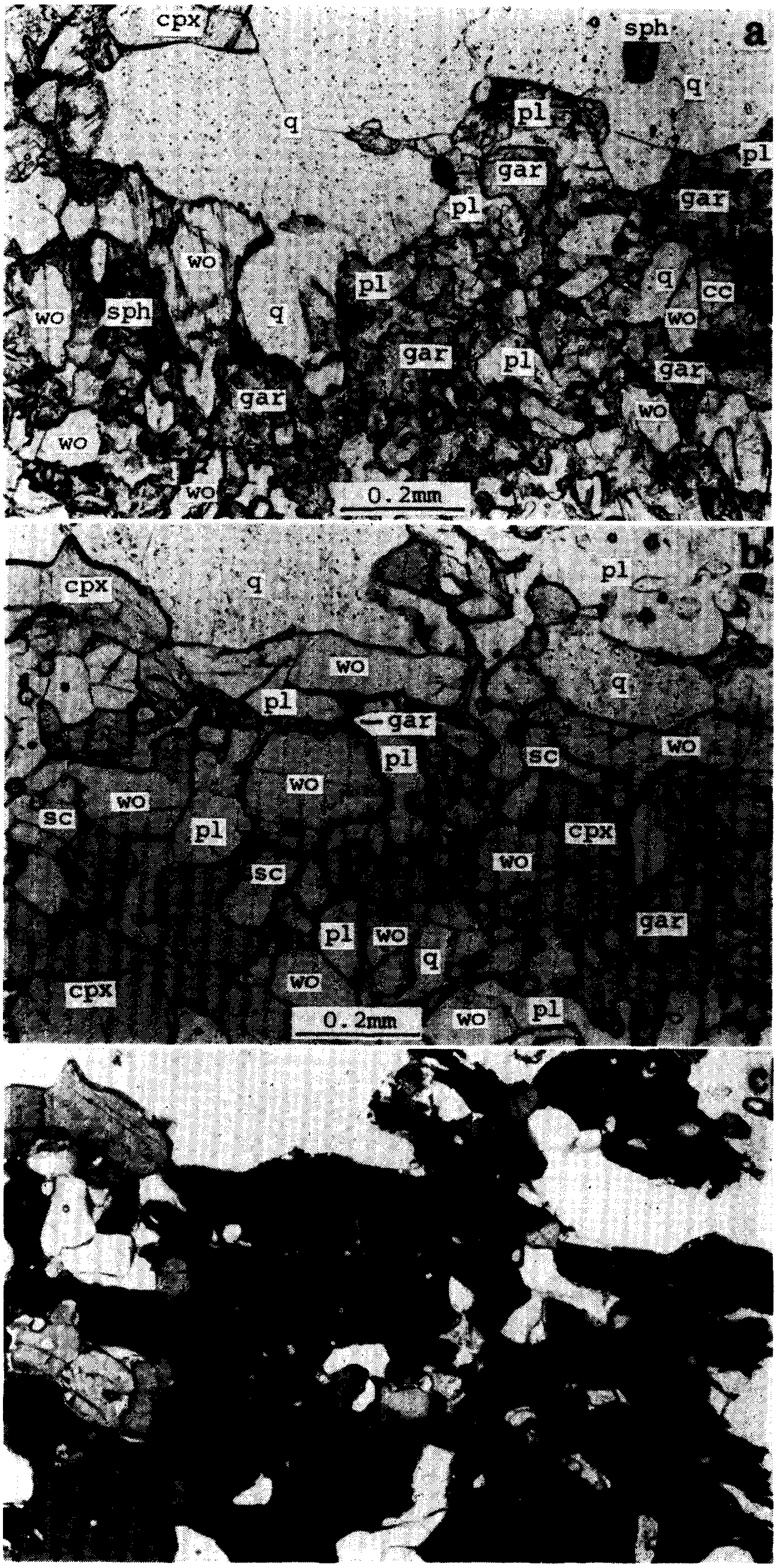


a. Sp. 81020304A. Intimate association of grandite garnet, pale green clinopyroxene, CO_3-scapolite, and calcite.

b. Sp. 82YH26. Porphyroblastic grossular including pale green clinopyroxene, calcite, and quartz. Mineral compositions are listed in Table 3.

c. Sp. 82YH26. Porphyroblastic grossular including pale green clinopyroxene, anorthite, and quartz. Anorthite often contains fine-grained inclusions of quartz and is in direct contact with calcite somewhere.

Fig. 7. Photomicrographs showing textures of minerals in calc-silicate rocks from Langhovde (Sp. 81020304A), Sôya Coast, and Ytrehovdeholmen (Sp. 82YH26). Plane polarized light.



a. Sp. 84012507. Intimate association of wollastonite, anorthite, and quartz. Grossular and calcite are also present, but these minerals are not in direct contact with quartz. Plane polarized light. Mineral compositions are listed in Table 3.

b. Sp. 84012801. Intimate association of wollastonite, anorthite, CO_3-scapolite, pale green clinopyroxene, and quartz. Grossular is also present as anhedral grains totally enclosed by wollastonite and anorthite and as films between wollastonite and anorthite or CO_3-scapolite. Plane polarized light.

c. Ditto. Crossed nicols.

Fig. 8. Photomicrographs showing textures of minerals in calc-silicate rocks from Skarvsnes, Sôya Coast.

5. Mineral Textures

Representative modes of occurrence of minerals under the microscope are shown in Figs. 3–8. Characteristic mineral textures are summarized as follows.

Epidote: Epidote usually occurs as anhedral inclusions in plagioclase and garnet (Figs. 3, 4a, 5b, 5c and 6a). It is sometimes in direct contact with quartz only in rocks from the lowest-grade part of the study area. Secondary epidote is not uncommon, which occurs as euhedral to subhedral grains replacing plagioclase and as anhedral grains between plagioclase and other minerals such as clinopyroxene, garnet, and calcite (*e.g.*, Fig. 6a).

Garnet: Garnet shows four modes of occurrence as follows; (1) as a constituent of symplectitic intergrowths mainly with plagioclase and with minor clinopyroxene and iron oxides (Figs. 3, 4a, 6a and 6c); (2) as massive poikilitic grains including clinopyroxene, epidote, plagioclase, calcite, and quartz (Figs. 4b, 4c, 5 and 8); (3) as anhedral grains mantled by plagioclase and wollastonite (Fig. 8a); and (4) as films between wollastonite and plagioclase or scapolite grains (Figs. 8b and 8c). The third mode of occurrence is seen in wollastonite-bearing rocks from the higher-grade part of the granulite-facies terrain. Garnet showing the last mode of occurrence is also found in the wollastonite-bearing rocks, and may be retrograde in origin. It is noteworthy that garnet is occasionally heterogeneous in composition within a single grain, as is apparent optically (Fig. 4c).

Wollastonite: Wollastonite is in direct contact with garnet, clinopyroxene, plagioclase, quartz, scapolite, and sphene (Fig. 8). It is most intimately interlocked with plagioclase (Figs. 8b and 8c), but it is also found between calcite and quartz grains (Fig. 8a).

Other minerals: Clinopyroxene is in direct contact with every mineral present. It shows variation in chemical composition from specimen to specimen, as is apparent optically. Some are dark green in color and carry very fine-grained Fe-oxide, suggesting that they are fassaites (KANISAWA and YANAI, 1982). Calcic amphiboles are also in direct contact with every mineral. However, some are of retrograde origin, replacing clinopyroxene. Scapolite is in contact with plagioclase or calcite or both in many specimens. Sphene is present in most of the specimens as euhedral to anhedral grains. It occasionally contains ilmenite. Fe-oxide (magnetite$\pm$hematite) commonly occurs in rocks carrying epidote and/or symplectitic intergrowths of garnet and plagioclase.

6. Discussion

6.1. Reaction relations of minerals in calc-silicate rocks

Reactions among minerals including calcite, quartz, wollastonite, grandite garnet, epidote, plagioclase, and scapolite can be analyzed, for the first approximation, in the system CaO-Al_2O_3-SiO_2-H_2O-CO_2 (Fig. 9a). The following univariant reactions in the system may be significant in the study area, which are shown by crossing tie lines in Fig. 9a.

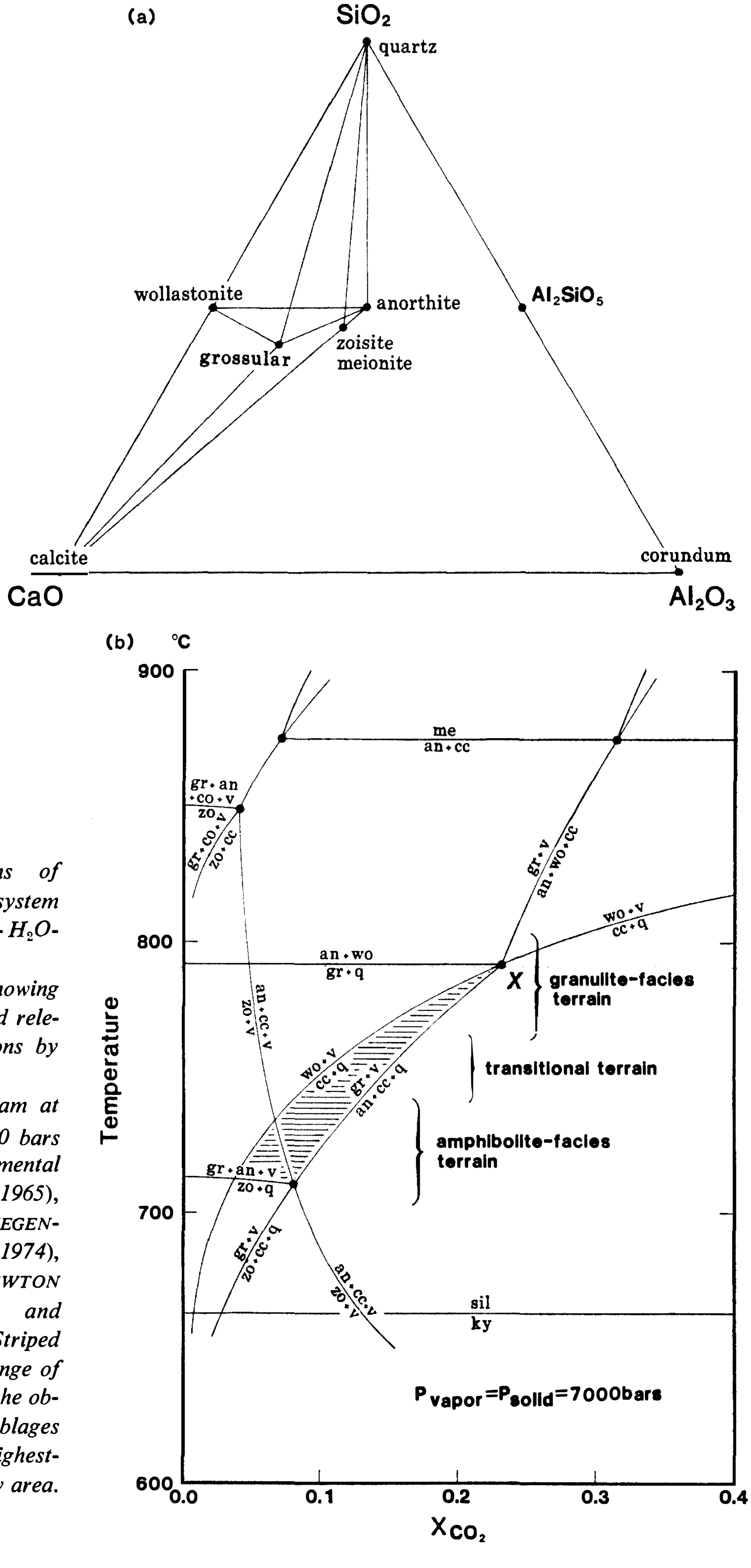


Fig. 9. *Reaction relations of minerals in the system CaO-Al_2O_3-SiO_2-H_2O-CO_2.*

a. *Triangular diagram showing phase compositions and relevant univariant reactions by crossing tie lines.*

b. *Isobaric T-X_{CO_2} diagram at $P_{vaporr} = P_{solid} = 7000$ bars based mainly on experimental data of NEWTON (1965), HOLDAWAY (1971), ZIEGENBEIN and JOHANNES (1974), GOLDSMITH and NEWTON (1977), and ALLEN and FAWCETT (1982). Striped region indicates the range of T-X_{CO_2} conditions for the observed mineral assemblages except for that in the highest-grade part of the study area. See text for details.*

$$4Ca_2Al_3Si_3O_{12}(OH)+SiO_2=Ca_3Al_2Si_3O_{12}+5CaAl_2Si_2O_8+2H_2O \quad (1)$$
zoisite quartz grossular anorthite

$$2Ca_2Al_3Si_3O_{12}(OH)+CO_2=3CaAl_2Si_2O_8+CaCO_3+H_2O \quad (2)$$
zoisite anorthite calcite

$$Ca_3Al_2Si_3O_{12}+CO_2=CaAl_2Si_2O_8+2CaCO_3+SiO_2 \quad (3)$$
grossular anorthite calcite quartz

$$CaCO_3+SiO_2=CaSiO_3+CO_2 \quad (4)$$
calcite quartz wollastonite

$$Ca_3Al_2Si_3O_{12}+SiO_2=CaAl_2Si_2O_8+2CaSiO_3 \quad (5)$$
grossular quartz anorthite wollastonite

$$Ca_3Al_2Si_3O_{12}+CO_2=CaAl_2Si_2O_8+CaSiO_3+CaCO_3 \quad (6)$$
grossular anorthite wollastonite calcite

$$3CaAl_2Si_2O_8+CaCO_3=Ca_4Al_6Si_6O_{24}CO_3 \quad (7)$$
anorthite calcite meionite

In Fig. 9b these reactions along with others are shown on a T-X_{CO_2} diagram at $P_{vapor}=P_{solid}=7$ kb. P_{solid} of 7 kb is an average of the previously estimated values for the Lützow-Holm Complex, as will be mentioned later. In Fig. 9b, the striped region bounded by reactions (1), (3), and (4) indicates the range of T-X_{CO_2} conditions for the observed mineral assemblages except for that in the highest-grade part of the study

Table 2. Bulk chemical compositions of calc-silicate rocks.

Locality	Prince Olav Coast			Sôya C.
	C. Ryûgû	C. Hinode	Kasumi R.	Langhovde
Specimen No.	SY301	74010204	79020405	81020303A*
SiO_2	47.47	38.78	37.04	52.11
TiO_2	0.90	0.26	0.39	0.48
Al_2O_3	7.90	24.44	22.05	2.15
Fe_2O_3	8.63	9.60	3.27	0.80
FeO	5.78	3.31	6.47	6.82
MnO	1.79	0.22	0.15	0.20
MgO	8.08	0.51	0.77	11.83
CaO	17.91	22.10	24.76	22.51
Na_2O	0.61	0.29	0.24	0.54
K_2O	—	0.06	0.12	0.04
$H_2O(+)$	0.22	0.55	3.75**	2.32
$H_2O(-)$	0.05	0.24	0.03	0.19
P_2O_5	0.64	0.11	0.06	—
Total	100.48	100.47	100.10	99.99
Data source	1	2	3	4

1: NAKAI *et al.* (1980). 2: KANISAWA *et al.* (1979). 3: NISHIDA *et al.* (1984). 4: HIROI *et al.* (1986b).

* clinopyroxenite associated with Sp. 81020303C.

** probably CO_2, because of the presence of calcite and CO_3-scapolite.

area, where the grossular+quartz paragenesis was no more stable. Composition and pressure of the vapor phase which existed during the high-grade metamorphism will be discussed later.

The restricted occurrence of epidote, especially when it coexists stably with quartz, in the lowest-grade part of the study area (lower-grade part of the amphibolite-facies terrain) is in good agreement with the topology of univariant reactions in Fig. 9b. Moreover, textural relations of epidote with garnet, plagioclase, and quartz are well-explained by reaction (1). Therefore, we can map the (epidote+quartz)-out isograd based on reaction (1) in the amphibolite-facies terrain, as shown in Fig. 1. In the absence of quartz epidote was stable beyond the isograd, as described above, and the upper stability of epidote may have been defined by reaction (2). On the other hand, it must be noted that epidote-consuming reactions in the natural system seem to be continuous being observed over a range of spatial extent. This is due to the effects of additional components such as Na_2O and Fe_2O_3. The common occurrence of Fe-oxides with epidote and in the symplectitic intergrowths of garnet and plagioclase witnesses the interpretation and is in agreement with the experimental data of LIOU (1973). In this connection, it is noteworthy that the bulk chemical compositions of rocks composed mainly of the symplectitic intergrowth of garnet, plagioclase, and Fe-oxide with or without scapolite (*e.g.*, Sp. 74010204 (KANISAWA *et al.*, 1979) and Sp. 79020405 (NISHIDA *et al.*, 1984), see Table 2) are close to chemical compositions of epidote.

The restricted occurrence of wollastonite in the highest-grade part of the study area (higher-grade part of the granulite-facies terrain) is also in harmony with the topology of the univariant reactions in Fig. 9b. In addition, the textural relations among wollastonite, garnet, plagioclase, calcite, and quartz are well-explained by reactions (4) and (5). Therefore, we can map the wollastonite-in isograd based on reactions (4) or (5) in the granulite-facies terrain as shown in Fig. 1. If reactions (4) and (5) had taken place simultaneously, the T-X_{CO_2} conditions during the high-grade metamorphism on the isograd were close to invariant point X in Fig. 9b. Reaction (5) is useful to estimate P_{solid}-T conditions during metamorphism, because it does not involve a vapor phase. On the other hand, it must be noted that reaction (5) is affected by additional components such as Na_2O and Fe_2O_3, the effects of which on the reaction will be discussed and estimated in the next section. In this connection, it is noteworthy that CO_3-scapolite commonly occurs throughout the study area. This apparently conflicts with the position of reaction (7) in Fig. 9b. However, in the presence of Na_2O reaction (7) becomes continuous toward the low-temperature side, as experimentally shown by ELLIS (1978). The continuous reaction between CO_3-scapolite, plagioclase, and calcite is a potential geothermometer (OTERDOOM and GUNTER, 1983; HIROI *et al.*, in preparation).

The observed paragenetic changes and related textures of minerals in the calc-silicate rocks in the Lützow-Holm Complex indicate the southwestward increase in metamorphic temperature. This is in good agreement with the previously published petrologic studies on the pelitic and basic-intermediate rocks mentioned above.

Table 3. Representative microprobe analyses of minerals in calc-silicate rocks from granulite-facies terrain.

Specimen	82YH26			84012507						84012714					
Mineral	gar	pl	cpx	wo	gar	pl	sc	cpx	sph	wo	gar	pl	sc	cpx	sph
SiO_2	38.68	43.61	51.35	50.89	38.58	43.20	40.99	50.36	29.37	50.97	39.07	43.65	42.17	50.56	30.02
TiO_2	0.15	tr	—	—	—	—	—	—	35.00	—	—	—	—	—	36.26
Al_2O_3	20.18	35.69	0.92	0.07	19.93	35.73	30.07	0.53	2.59	tr	20.44	36.20	29.08	0.94	2.72
Cr_2O_3	0.07	—	tr	—	—	—	—	—	0.13	—	—	—	—	—	tr
FeO*	5.67	0.05	12.97	0.44	5.59	tr	0.17	16.72	0.85	0.49	5.83	tr	0.41	16.74	0.28
MnO	0.79	—	0.47	0.55	1.33	tr	tr	1.36	0.05	0.45	1.24	—	—	1.21	0.10
MgO	0.18	—	9.55	tr	0.08	—	0.05	7.11	tr	0.11	0.15	tr	tr	6.76	tr
CaO	32.80	19.23	24.52	47.38	33.11	19.75	21.50	23.32	27.34	47.31	32.72	19.59	21.06	23.42	27.89
Na_2O	—	0.64	0.18	tr	—	0.35	1.29	tr	tr	—	—	0.37	1.32	0.08	—
K_2O	—	tr	tr	—	—	tr	0.12	tr	tr	—	—	—	0.20	—	—
Total	98.52	99.22	99.96	99.33	98.62	99.03	94.19	99.40	95.33	99.33	99.45	99.81	94.24	99.71	97.27
O	12	8	6	6	12	8	(Si+Al =12)	6	10	6	12	8	(Si+Al =12)	6	10
Si	2.991	2.034	1.971	1.988	2.983	2.020	6.436	1.983	2.015	1.991	2.994	2.047	6.620	1.982	2.007
Al	1.839	1.962	0.042	0.003	1.816	1.969	5.564	0.025	0.209	0.001	1.846	1.976	5.380	0.044	0.213
Ti	0.009	0.001	—	—	—	—	—	—	1.806	—	—	—	—	—	1.823
Cr	0.004	—	0.001	—	—	—	—	—	0.007	—	—	—	—	—	—
Fe*		0.002	0.416	0.014		0.001	0.023	0.550	0.014	0.016		0.002	0.054	0.549	0.017
Fe^{3+}**	0.158				0.220						0.168				
Fe^{2+}**	0.209				0.142						0.206				
Mn	0.052	—	0.015	0.018	0.087	0.001	0.002	0.045	0.003	0.015	0.080	—	—	0.040	0.007
Mg	0.020	—	0.546	0.001	0.009	—	0.011	0.417	0.004	0.007	0.017	0.001	0.009	0.395	0.003
Ca	2.717	0.956	1.009	1.983	2.742	0.989	3.616	0.984	2.010	1.979	2.688	0.973	3.542	0.984	1.997
Na	—	0.058	0.013	0.003	—	0.032	0.391	0.002	0.003	—	—	0.033	0.402	0.006	—
K	—	0.001	0.001	—	—	0.001	0.024	0.001	0.001	—	—	—	0.041	—	—
Total	7.999	5.014	4.014	4.010	7.999	5.013	16.067	4.007	6.072	4.009	7.999	5.031	16.048	4.000	6.067
$X_{grossular}$	0.825				0.812						0.816				
$X_{anorthite}$		0.942				0.968						0.967			

* total Fe as FeO and Fe^{2+}.

** calculated assuming perfect stoichiometry.

6.2. Effects of additional components on reaction grossular+quartz=anorthite+wollastonite

Reaction (5) is one of the most significant reactions in the study area to estimate P_{solid}-T conditions during regional metamorphism, as mentioned above. The end-member univariant reaction has been extensively investigated by mineral synthesis experiments (NEWTON, 1966; BOETTCHER, 1970; HUCKENHOLZ, 1974; HUCKENHOLZ *et al.*, 1975; WINDOM and BOETTCHER, 1976). The effects of Na_2O and Fe_2O_3 on the reaction have also been evaluated experimentally by WINDOM and BOETTCHER (1976) and HUCKENHOLZ *et al.* (1981). These studies show that the presence of Na_2O in plagioclase and that of Fe_2O_3 in garnet have opposite effects on the *P-T* conditions of the reaction and therefore the effects of these additional components on the reaction often cancel out. To estimate the effects of additional components on reaction (5) in the study area, microprobe analysis of specimens 82YH26, 84012507, and 84012714 from the granulite-facies terrain was carried out. The results are listed in Table 3. In these specimens, garnet contains a grossular molecule more than 80% (the rest are andradite, spessartine, and almandine molecules) and plagioclase contains an anorthite molecule more than 94%. Wollastonite and quartz are almost pure. According to the experimental data of WINDOM and BOETTCHER (1976), addition of 6 mole percent albite shifts the curve of reaction (5) to the low-temperature side within 10°C. On the other hand, the univariant curve of the reaction with 80 mole% grossular and 20 mole% andradite is located at about 10°C high-temperature side to that of reaction (5) (HUCKENHOLZ *et al.*, 1981). Because MnO and FeO enter mainly garnet, effects of these components may be similar to that of Fe_2O_3. The effects of MnO and FeO on reaction (5) are assumed to be the same magnitude as that of Fe_2O_3. Summantion of the opposite effects of the similar magnitude makes it possible to conclude that the *P-T* conditions of the observed reaction in the study area were close to those of the endmember univariant reaction (5).

6.3. P-T conditions during regional metamorphism

The effects of additional components on reaction (5) are estimated to have been negligible in the study area, as discussed above. Thus, the isograd based on discontinuous reaction (5) is best-defined among those so far mapped in the study area, and important to estimate P_{solid}-T conditions during the granulite-facies metamorphism. There are many useful geothermometers for rocks in the study area, but reliable geobarometers are not so abundant. Consequently, we use the isograd based on reaction (5) to estimate solid pressure here. Temperature of about 810 ± 20°C has been estimated for the rocks near the isograd (YOSHIDA and AIKAWA, 1983; KATSUSHIMA, 1985; MOTOYOSHI, 1986; SUZUKI, 1986), thereby pressure of 6.5–7.5 kb is calculated (Fig. 10). This agrees fairly well with the pressure estimates of KATSUSHIMA (1985), MOTOYOSHI (1986), and SUZUKI (1986) using garnet-plagioclase-sillimanite-quartz, garnet-pyroxenes-plagioclase-quartz and other geobarometers.

P-T conditions for rocks in the amphibolite-facies terrain were estimated to be 700 ± 20°C and 6–7 kb by HIROI *et al.* (1983c). Recalculated temperature for Sp. SY301 from the amphibolite-facies terrain (YOSHIKURA *et al.*, 1979) using ELLIS and GREEN's (1979) garnet-clinopyroxene thermometer is about 700°C and agrees with the

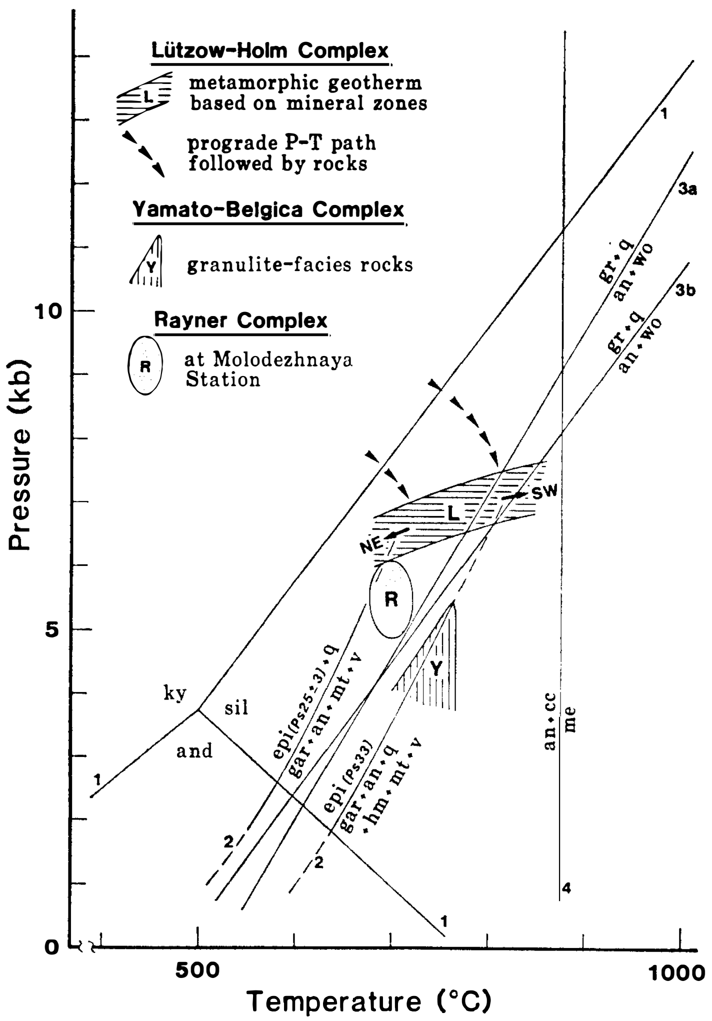


Fig. 10. P-T diagram showing metamorphic geotherm of Lützow-Holm Complex and P-T conditions for granulite-facies rocks of adjacent Yamato-Belgica and Rayner Complexes for comparison. P-T paths followed by rocks of the Lützow-Holm Complex are also shown after HIROI *et al. (1984a, b, 1986b),* HIROI *and* SHIRAISHI *(1986), and* SHIRAISHI *et al. (1987).*
1; HOLDAWAY *(1971), 2;* LIOU *(1973), 3a;* NEWTON *(1966),* BOETTCHER *(1970), and* WINDOM *and* BOETTCHER *(1976), 3b;* HUCKENHOLZ *(1974) and* HUCKENHOLZ *et al. (1975, 1981), 4;* GOLDSMITH *and* NEWTON *(1977). See text for details.*

above temperature estimate. These data suggest that there is a pressure gradient in addition to the temperature gradient in the study area, and the regional metamorphic geotherm of the Lützow-Holm Complex based on the progressive mineral zones was of the medium-pressure type (Fig. 10). However, it must be noted that the metamorphic geotherm was not always identical with the prograde *P-T* paths followed by rocks (see Fig. 10).

Reaction (5) is also useful for direct comparison of the *P-T* conditions of the granulite-facies rocks of the Lützow-Holm Complex with those of the Yamato-Belgica Complex. In the Yamato-Belgica Complex, occurrence of granulite-facies calc-silicate rocks has been known, which contain the wollastonite+anorthite assemblage (SHIRAISHI *et al.*, 1983; ASAMI and SHIRAISHI, 1985). As shown in Fig. 10, these two complexes belonged to the distinct facies series. Likewise, the *P-T* conditions during the granulite-facies metamorphism of the Rayner Complex at Molodezhnaya Station (GREW, 1981) were different from those of the Lützow-Holm Complex (Fig. 10).

6.4. *Vapor phase composition*

The striped region in Fig. 9b indicates the range of T-X_{CO_2} conditions for the observed mineral assemblages in the calc-silicate rocks except for that in the highest-grade part of the study area, as mentioned above. The mineral assemblage in the highest-grade part of the study area may have been stable near the univariant curve of reaction (6). Therefore, it is suggested that X_{CO_2} progressively increased from the amphibolite-facies terrain to the granulite-facies terrain and that the vapor phase generally had a high ratio of H_2O to CO_2 throughout the study area if $P_{vepor}=P_{solid}$ and the vapor phase was composed mainly of H_2O and CO_2. The latter point apparently disagrees with the estimated P_{H_2O} (=0.5 P_{solid} in the amphibolite-facies terrain) by HIROI *et al.* (1983c) based on the formation of granitic migmatite by partial melting of country gneisses and the corundum+K-feldspar paragenesis from muscovite. It is also in disagreement with the following field and petrographic features, which suggest that $P_{H_2O}<P_{solid}$. (1) No partial melting of calc-silicate rocks took place in the study area (*cf.* experimental data of HUCKENHOLZ *et al.* (1975)). (2) Fe-rich epidote coexisting with hematite and magnetite shows a breakdown texture in the amphibolite-facies rocks, as described above (*cf.* experimentally determined upper stability limit of Fe-rich epidote by LIOU (1973) in Fig. 10). In this connection, it is significant that calc-silicate rocks are too small in size and too poor in amount to have had a sufficient buffer ability controlling the composition of the vapor phase in and out of the masses of calc-silicate rocks. Therefore, it may be concluded that both H_2O and CO_2 were generally poor in the vapor phase during the high-grade metamorphism. It is not clear, however, whether this means $P_{solid}>P_{vapor}$ or due to the enrichment of other components such as CH_4, F, and Cl in the vapor phase.

7. Conclusion

Calc-silicate rocks occur sporadically in the study area usually as small masses enclosed in other metasedimentary gneisses. Southwestward progressive metamorphism of the rocks is clarified which is in good agreement with the results of previous studies on the pelitic and basic-intermediate rocks. Two isograds based on the following continuous and discontinuous reactions are mapped in the amphibolite-facies and granulite-facies terrains, respectively.

$$\text{Epidote}+\text{quartz}\pm\text{calcite}=\text{garnet}+\text{plagioclase}+\text{Fe-oxide(s)}\pm\text{scapolite}+H_2O\ .$$

$$\text{Grossular}+\text{quartz}=\text{anorthite}+\text{wollastonite}\ .$$

The second isograd is best-defined among those so far mapped in various rock types of the Lützow-Holm Complex, because its reaction is vapor-absent. Moreover, mineral chemistry shows that the effects of additional components on the reaction were negligible in the studied rocks. Pressure of about 7 kb is estimated by the discontinuous reaction at $T=810\pm20°C$ in the granulite-facies terrain. This, in conjunction with the previously published data on other rock types, confirms that the regional metamorphic geotherm of the Lützow-Holm Complex based on the progressive mineral zones was of the medium-pressure type and was distinct from those of the adjacent Yamato-Belgica and Rayner Complexes. The occurrence of grossular with or without quartz in the granulite-facies terrain suggests that the vapor phase was generally poor in both H_2O and CO_2 during the high-grade metamorphism.

Acknowledgments

We would like to express our sincere thanks to many geologists who carried out geologic survey in the Prince Olav and Sôya Coasts for their field information and specimens.

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(Received March 25, 1987; Revised manuscript received April 28, 1987)