

PETROGRAPHY AND GEOTHERMOMETRY-GEOBAROMETRY OF BOTNNUTEN, EAST ANTARCTICA

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Abstract: Botnnuten is an isolated nunatak situated between Lützow-Holm Bay and the Yamato Mountains, East Antarctica. It is composed of well-layered pelitic and basic gneisses with subordinate amounts of calc-silicate rock. The petrographical examinations revealed that the assemblages of sillimanite+K-feldspar+biotite in the pelitic gneiss, and garnet+clinopyroxene+orthopyroxene+plagioclase+quartz in the basic gneiss are observed to have coexisted stably. Sillimanite+spinel assemblage included in porphyroblastic garnet is totally interpreted to be a breakdown product after staurolite during the prograde recrystallization.

The present phase relations and geothermo-barometries yielded the metamorphic conditions of Botnnuten rocks to be 750–800°C at 5–6 kbars.

On the basis of the petrographical features with respect to the occurrence of aluminous silicate minerals and the recrystallization history inferred from the textural relationships, and the *P-T* conditions mentioned above, it is concluded that Botnnuten is a low-pressure portion of the Lützow-Holm Complex.

1. Introduction

Botnnuten is an isolated nunatak which is located at 70°24'S in latitude and at 38°01'E in longitude about 170 km SSW of Syowa Station (Fig. 1).

The region around Botnnuten including Lützow-Holm Bay and the Yamato-Belgica Mountains is underlain chiefly by complexes of Precambrian high-grade metamorphic rocks associated with various kinds of plutonic rocks. Recently, HIROI *et al.* (1984a) have distinguished two major geological units in this region, namely the Lützow-Holm Complex and the Yamato-Belgica Complex, based on the geochemical features of source rocks, conditions of metamorphism and plutonism. According to them, the former is composed of metasedimentary and metabasic rocks with sporadic distribution of ultrabasic rocks. Metapelitic rocks occasionally include aluminous silicates such as garnet, staurolite, sapphirine and Al₂SiO₅ minerals. The metamorphism is characterized by kyanite-sillimanite type grading up progressively from northeast to southwest. On the other hand, the latter lacks ultrabasic rocks, whereas plutonic activities of syenite and granite are widely recognized. The above-mentioned aluminous silicate minerals are scarcely present in the rocks from the Yamato-Belgica Complex. The metamorphism is a low-pressure type indicated by the occurrence of wollastonite+anorthite instead of grossular+quartz. Since Botnnuten lies between these complexes, its petrographical data are indispensable in order to consider whether Botnnuten

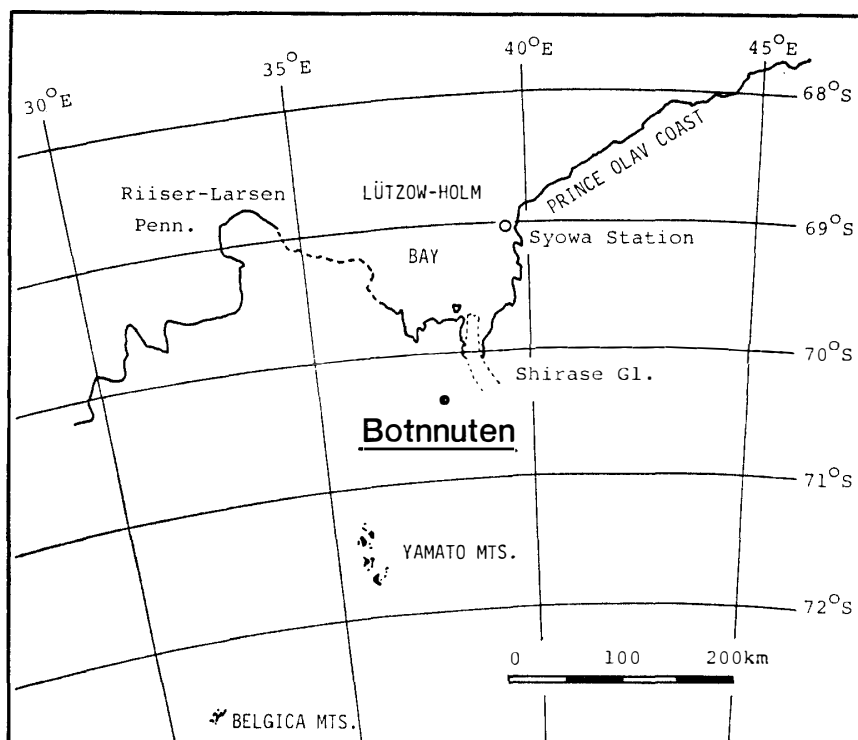


Fig. 1. Locality map of Botnnuten and the surrounding areas.

belongs to the Lützow-Holm Complex or to the Yamato-Belgica Complex.

This paper re-investigates the rocks from Botnnuten collected by three members of the wintering team of the 1st Japanese Antarctic Research Expedition, S. NAKANO, T. KIKUCHI and T. KITAMURA in 1957, and discusses the conditions of metamorphism with respect to the metamorphic evolution of Botnnuten.

2. Geology and Petrography

Botnnuten crops out at a height of about 1460 m above sea level and the altitude from the continental ice level is approximately 300–400 m. As shown in Fig. 2, it is composed of well-layered metamorphic rocks striking N10–40°W and dipping 10°E–NE (TATSUMI and KIKUCHI, 1959).

We investigated microscopically the rocks, specimen No. 57102719–57102732, and classified them into three major groups, namely pelitic gneiss, basic gneiss and calc-silicate rock. The pelitic gneiss and the basic gneiss are further divided into three and two types respectively based on the mineral assemblages as summarized in Table 1. The following are their petrographical characteristics.

2.1. Pelitic gneiss

The pelitic gneiss comprises biotite gneiss, garnet-biotite gneiss and garnet-sillimanite-biotite gneiss. The main constituent minerals are biotite, plagioclase and quartz with or without K-feldspar. Fe-Ti oxide and other opaque minerals are rarely observed. Muscovite is scarcely present in the gneiss.

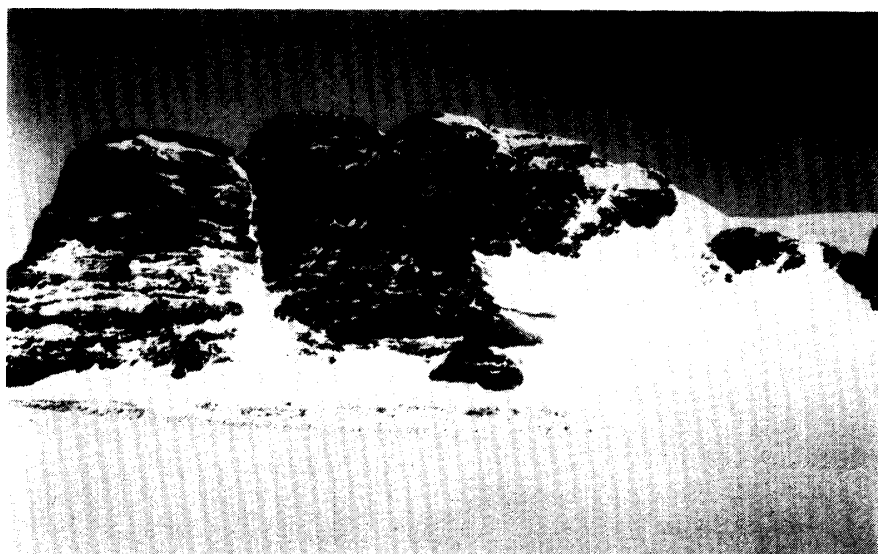


Fig. 2. North face of Botnnuten. It is composed of well-layered gneisses dipping gently to the north. Photo by K. SHIRAIISHI in 1983.

Table 1. Mineral assemblages in the rocks from Botnnuten.

Rock type	Specimen No.	Gar	Cpx	Opx	Hb	Bt	Pl	Kf	Qz	Sill	Sp	Mt	Il	Others	
Pelitic gneiss															
Bt gneiss	57102717					+	+	+	+					Op, Zr	
	57102718					+	+	+	+					Op, Ap, Zr	
	57102720					+	+		+					Ap, Zr	
Gar-Bt gneiss	57102731	+				+	+	+	+		-			Op, Zr	
Gar-Sill-Bt gneiss	57102721	+				+	+		+		- (-)			Op, Zr	
	57102723	+				+	+	+	+		+	(-)	+	Pi, Zr, Xe(?)	
	57102724	+				+	+	+	+	+				Op, Zr	
Basic gneiss															
Hb-Px gneiss	57102719		+	+	+	-	+						+	Ap, Zr, Po, Ch	
	57102722		+	+	+		+		+			+	+	Py	
	57102727		+	+	-	-	+					+	+	Zr, Po, Ch	
	57102729			+	+		+	+	+					Op, Ap, Cal	
Gar-Hb-Px gneiss	57102726	+	+	+	+		+		+			+	+	Ap, Zr, Po	
	57102732	+	+	+	+		+		+			+	+	Ap, Zr, Py	
Calc-silicate rock															
	57102730a	Fo, Phl, Dol, Cal													
	57102730b	Di, Scap, Sph, Kf, Qz, Ap													

Abbreviations: Ap-apatite Bt-biotite Cal-calcite Ch-chalcopyrite
 Cpx-clinopyroxene Di-diopside Dol-dolomite Fo-forsterite
 Gar-garnet Hb-hornblende Il-ilmenite Kf-K-feldspar
 Mt-magnetite Op-unidentified opaque phase Opx-orthopyroxene
 Phl-phlogopite Pi-pinite (probably after cordierite) Pl-plagioclase
 Px-pyroxene Py-pyrite Qz-quartz Scap-scapolite
 Sill-sillimanite Sp-spinel Sph-sphene Xe-xenotime
 Zr-zircon.
 + common, - rare, () as inclusion.

Garnet occurs in 57102731, 57102721, 57102723 and 57102724 (Figs. 3A, 3B, 3C, 3D and 3E). The latter three also carry sillimanite (Figs. 3C, 3D and 3F). In 57102721 and 57102723, green spinel is present, being associated with garnet and sillimanite (Figs. 3C and 3E).

The garnet in garnet-sillimanite-biotite gneiss often includes quartz, biotite, sillimanite and spinel. These inclusions are expected to provide us valuable infor-

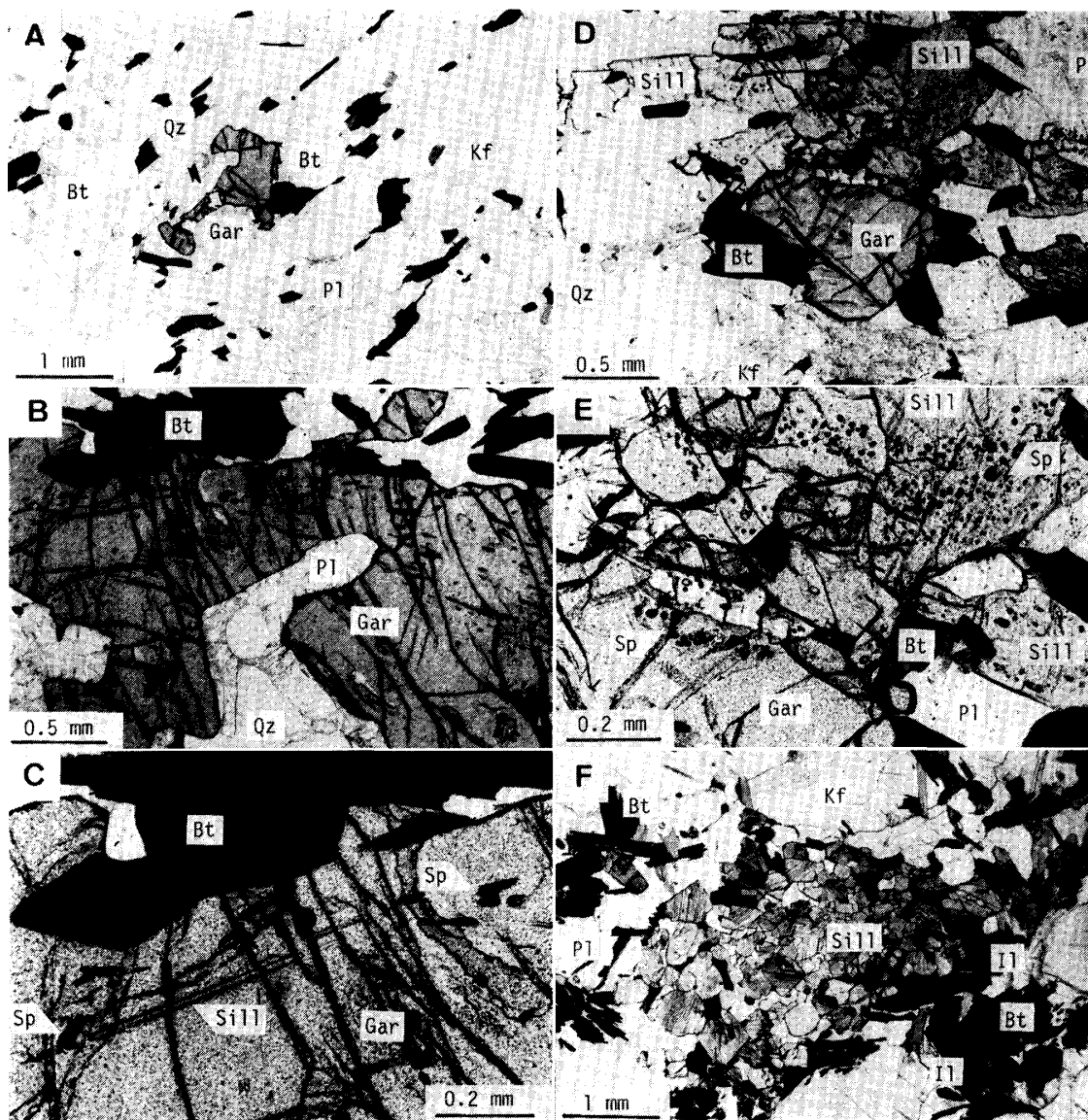


Fig. 3. Photomicrographs showing textures of pelitic gneiss from Botnnuten. Mineral abbreviations as in Table 1. *A*: Garnet-biotite gneiss (57102731). *B*: Garnet-sillimanite-biotite gneiss (57102721). *C*: As *B*. Garnet includes sillimanite needles and spinel grains, but they are not present in the matrix. *D*: Garnet-sillimanite-biotite gneiss (57102723). Matrix sillimanite and biotite are closely associated with garnet. *E*: As *D*. Spinel grains in the matrix sillimanite. *F*: Sillimanite+K-feldspar+biotite assemblage in the garnet-sillimanite-biotite gneiss (57102723).

mation about the recrystallization history of Botnnuten rocks. Among them, quartz grains tend to occur in the inner part of the garnet, whereas needle-like sillimanite and spinel are distributed in the outer part towards margin of the same garnet. Zonal structure of the garnet with respect to the inclusion minerals probably reflects the growing history of the crystal, and the inclusions in each domain recorded the metamorphic reactions which the rocks have experienced.

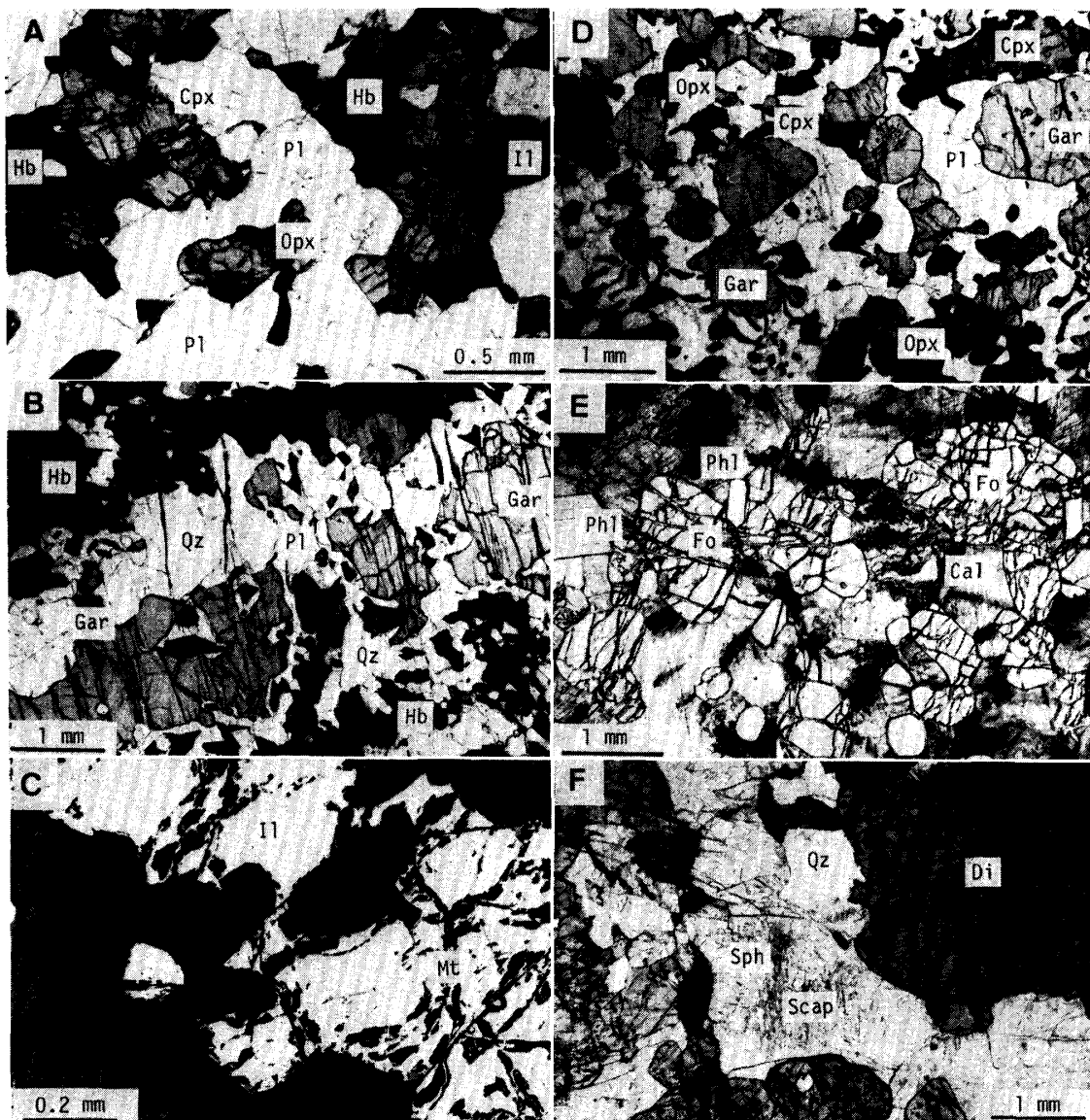


Fig. 4. Photomicrographs showing textures of basic gneiss and calc-silicate rock from Botnnuten. Mineral abbreviations as in Table 1. **A:** Hornblende-pyroxene gneiss (57102719). Hornblende and pyroxenes show equilibrium coexistence. **B:** Garnet-hornblende-pyroxene gneiss (57102726). Garnet is separated from hornblende by plagioclase and quartz. **C:** Ilmenite and magnetite in 57102726, reflected light. Both phases are microscopically homogeneous. **D:** Garnet + clinopyroxene + orthopyroxene + plagioclase assemblage in 57102732. **E:** Impure marble composed mainly of forsterite, phlogopite and calcite (57102730a). **F:** Diopside-scapolite rock with sphene and quartz (57102730b).

The mode of occurrence of sillimanite has two cases; an inclusion in garnet and an idiomorphic crystal in the matrix. The latter is closely associated with garnet and biotite. The sillimanite+K-feldspar+biotite+ilmenite assemblage also seems to be a stable coexistence (Fig. 3F). Spinel grains are included in the matrix sillimanite (Fig. 3E), and they occur more frequently in the sillimanite than in the garnet, though they are never present in the matrix as isolated grains.

2.2. *Basic gneiss*

This rock is composed chiefly of hornblende, clinopyroxene, orthopyroxene, plagioclase, quartz, ilmenite and magnetite in various amounts with or without K-feldspar. Garnet occurs in 57102726 and 57102732. Biotite is present in small amounts occasionally, but it is probably a secondary product.

Hornblende is not uniformly distributed in the gneiss, generally showing a banded structure made up of hornblende-rich and -poor layers. The axial Z color is deep greenish. The textural relationship to pyroxenes suggests their equilibrium coexistence (Fig. 4A).

Garnet occurs sporadically as irregular-shaped grain. In 57102726, the garnet is generally separated from surrounding hornblende by plagioclase and quartz as shown in Fig. 4B. On the other hand, garnet-pyroxene relationship shows stable coexistence as in Fig. 4D. Inclusions in the garnet are rare.

Some plagioclases show marked reverse zonal structure.

Opaque minerals are microscopically homogeneous ilmenite and magnetite (Fig. 4C).

2.3. *Calc-silicate rock*

Calc-silicate rock is interlayered with surrounding gneisses concordantly and the thickness is up to 1–2 m (TATSUMI and KIKUCHI, 1959). Two specimens are described here.

57102730a is an impure marble composed of calcite, dolomite, forsterite and phlogopite (Fig. 4E). 57102730b is composed of clinopyroxene, scapolite with subordinate amounts of sphene, K-feldspar, quartz and apatite (Fig. 4F).

4. Phase Relations and Mineral Chemistry

The constituent minerals in each rock type were chemically analyzed by an electron microprobe analyzer JEOL JCXA-733 at the National Institute of Polar Research. Specimen current was kept at 0.012–0.015 microampere and accelerating voltage at 15 kV. Synthesized pure oxides and natural minerals were used for standards, with intensity data being corrected by BENCE and ALBEE'S (1968) method.

This paper mainly concerns with the phase relations of the pelitic and basic gneisses.

4.1. *Pelitic gneiss*

Petrographically important mineral assemblages are, 1) sillimanite+spinel in garnet, and 2) sillimanite+K-feldspar+biotite in the matrix. These assemblages are considered to have been in equilibrium coexistence respectively and also useful to

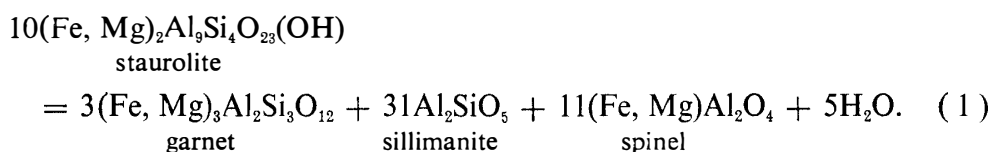
Table 2. Microprobe mineral analyses of garnet-biotite gneiss and garnet-sillimanite-biotite gneiss.

Specimen No.	57102731			57102723								
	201	202	203	8	21	19	28	1	24	101	2	3
Analysis No.	Gar	Bt	Pl	Gar(c)	Gar(r)	Pl(c)	Pl(r)	Bt(i)	Bt(m)	Sp	Il	Sill(m)
Mineral ¹⁾	Gar	Bt	Pl	Gar(c)	Gar(r)	Pl(c)	Pl(r)	Bt(i)	Bt(m)	Sp	Il	Sill(m)
SiO ₂	38.30	35.48	61.39	38.39	38.26	60.02	60.29	35.36	35.10	.05	.03	36.65
TiO ₂	—	5.45	.02	.04	—	—	.04	6.89	5.36	—	50.67	—
Al ₂ O ₃	20.46	16.41	24.58	21.17	21.08	24.08	24.11	16.90	15.92	56.14	.03	61.87
Cr ₂ O ₃	.07	.35	.03	.11	.08	.01	—	.12	.21	1.97	.28	.20
FeO ²⁾	32.28	17.98	.08	30.93	31.55	.02	.08	16.06	16.97	29.83	47.28	1.11
MnO	.83	—	—	.55	.63	.02	—	.02	—	.05	.17	—
MgO	6.35	10.97	—	7.90	7.55	—	—	11.74	11.40	5.45	.67	.02
CaO	.99	—	6.19	1.28	.97	6.44	6.45	—	—	—	.03	.03
Na ₂ O	—	.12	8.01	.02	.03	8.22	7.92	.21	.16	—	—	—
K ₂ O	—	9.44	.29	.03	—	.17	.15	9.04	9.31	—	—	—
ZnO	—	—	—	—	—	—	—	—	—	7.01	—	—
Total	99.28	96.20	100.59	100.42	100.15	98.98	99.07	96.34	94.43	100.50	99.17	99.88
O	12	22	8	12	12	8	8	22	22	4	6	5
Si	3.042	5.342	2.714	2.993	2.998	2.703	2.709	5.256	5.365	.001	.002	.995
Ti	—	.617	.001	.002	—	—	.001	.770	.616	—	1.927	—
Al	1.916	2.912	1.280	1.945	1.947	1.278	1.276	2.960	2.868	1.891	.002	1.979
Cr	.005	.042	.001	.007	.005	.001	—	.015	.025	.045	.011	.004
Fe ³⁺	—	—	—	—	—	—	—	—	—	.063	.131	.023
Fe ²⁺	2.144	2.263	.003	2.017	2.068	.001	.003	1.996	2.169	.650	1.869	—
Mn	.056	—	—	.036	.042	.001	.001	.003	—	.001	.007	—
Mg	.752	2.463	—	.918	.882	—	—	2.601	2.598	.232	.051	.001
Ca	.085	—	.293	.107	.081	.311	.311	—	—	—	.002	.001
Na	—	.035	.687	.003	.005	.717	.690	.060	.047	—	—	—
K	—	1.812	.016	.003	—	.010	.009	1.714	1.815	—	—	—
Zn	—	—	—	—	—	—	—	—	—	.148	—	—
X _{Mg} ³⁾	.260	.521	—	.313	.299	—	—	.566	.545	.263	—	—
An ⁴⁾	—	—	.294	—	—	.299	.308	—	—	—	—	—

1) Abbreviations as in Table 1, c—core, r—rim, i—inclusion, m—matrix. 2) Total Fe as FeO except for sillimanite as Fe₂O₃.

3) X_{Mg}=Mg/(Fe+Mg) (for spinel Fe=Fe²⁺). 4) An=Ca/(Ca+Na+K).

assess the conditions of metamorphism and the recrystallization history inferred from their textural relationships. In addition, common assemblage of garnet + biotite in the pelitic gneiss is provided for geothermometry. The representative microprobe analyses of the constituent minerals are listed in Table 2, and the geometry of the phase relations are illustrated in Fig. 5. The sillimanite needles and spinel grains always occur as inclusions in porphyroblastic garnet in 57102723 as shown in Figs. 3C and 3D. The assemblage garnet + sillimanite + spinel is equivalent to an anhydrous breakdown product of staurolite by the following reaction,



The sillimanite + K-feldspar association in 57102723 implies that muscovite was no more stable in the presence of quartz as follows,

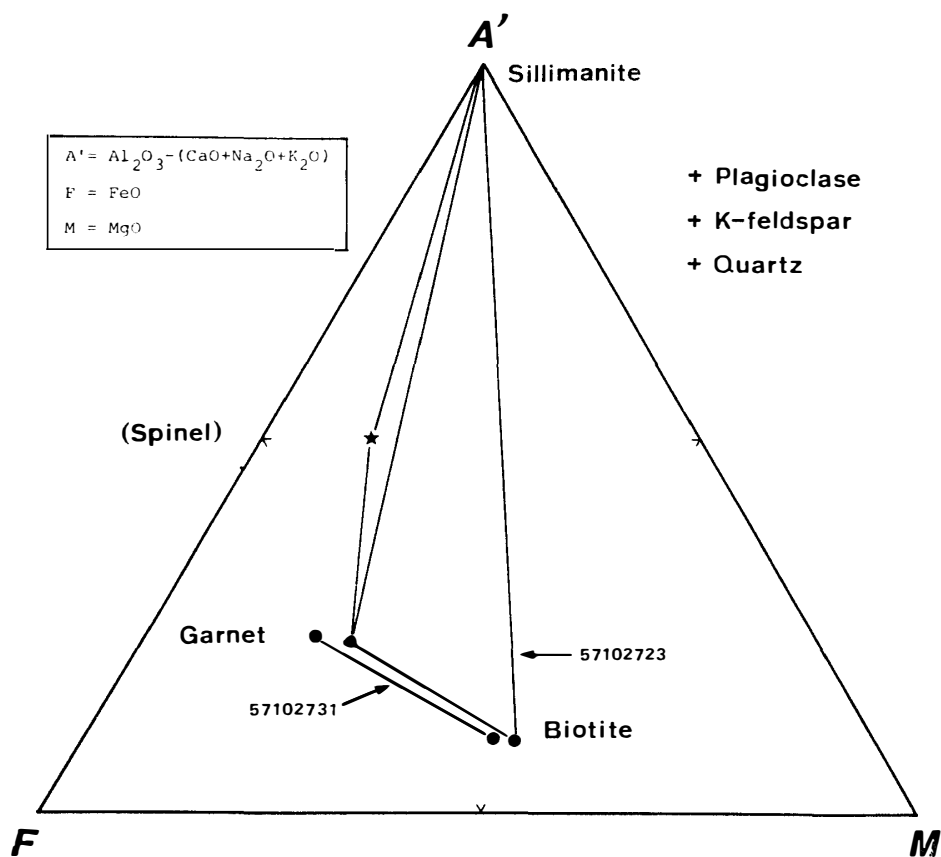
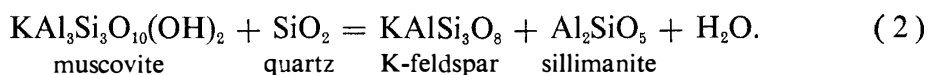
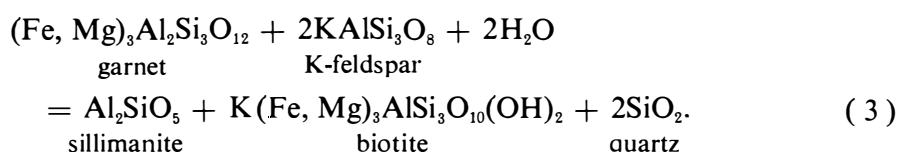


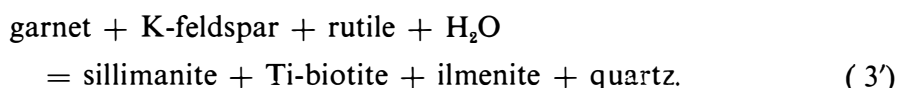
Fig. 5. Phase relations in pelitic gneiss projected onto A'-F-M diagram. Spinel in blanket is always included in garnet and/or sillimanite. Garnet-biotite tie-lines from different samples are almost compatible to each other.

These reactions are interpreted to have occurred in the sillimanite stability field.

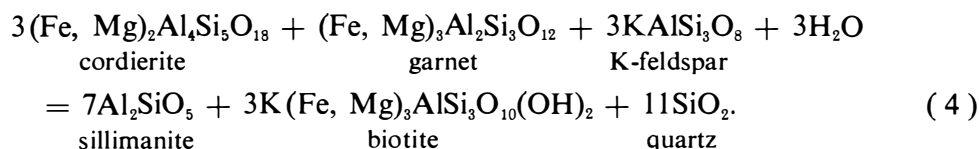
In addition to these phases, the pelitic gneiss carries biotite in significant amounts. As shown in Fig. 3, biotite occurs in close association with garnet, sillimanite and K-feldspar. In 57102723, biotite included in garnet has slightly higher Ti and X_{Mg} values relative to the matrix biotite (Table 2), and it is inferred that there are two stages of biotite formation in this rock. The following reaction would be responsible for the formation of biotite in the matrix if we ignore the Ti content in it,



However, since the biotite contains TiO_2 at around 5 wt%, Ti-bearing phases such as rutile or ilmenite have possibly participated in the reaction as follows,



If the pinite in 57102723 was originally a cordierite, the following equilibrium would have been also possible,



The reactions (3) and (4) show, although qualitatively, that the biotite formation in these rocks needs hydration reactions under the muscovite instability condition.

The reactions (1), (2), (3) and (4) described in the pelitic gneiss have steep positive slopes on a P - T diagram because of the large entropy change of the reactions involving water. It is considered therefore that these reactions are mainly related to the thermal history of Botnnuten rocks.

4.2. Basic gneiss

In the basic gneiss, clinopyroxene, orthopyroxene, hornblende and plagioclase are the main constituents. Garnet occurs additionally in 57102726 and 57102732. Their representative microprobe analyses are listed in Tables 3 and 4, and those of Fe-Ti oxides are in Table 5. Chemical zonations for decrease in X_{Mg} towards rim in the garnet and reversal increase in An component in the coexisting plagioclase are detected, respectively (Table 4).

On the basis of the compositional relationships between two pyroxenes presented in Fig. 6, and the constant Fe-Mg distribution coefficient (K_D) at 1.6–1.7 (Table 7), clinopyroxene and orthopyroxene are judged to be in equilibrium coexistence. Since hornblende is always associated with pyroxenes, the following equilibrium relation would be written,

Table 3. Microprobe mineral analyses of hornblende-pyroxene gneiss.

Specimen No.	57102719				57102722				57102727		
	1	2	14	20	27	25	22	35	47	48	63
Analysis No.											
Mineral ¹⁾	Cpx	Opx	Hb	Pl	Cpx	Opx	Hb	Pl	Cpx	Opx	Pl
SiO ₂	51.61	50.64	42.36	58.71	49.82	49.59	39.96	47.44	50.28	50.39	55.64
TiO ₂	.26	.11	2.00	.03	.29	.06	2.13	.03	.21	.15	—
Al ₂ O ₃	1.72	.89	10.83	26.01	2.47	1.01	11.98	33.03	2.08	1.14	27.56
Cr ₂ O ₃	—	—	.06	—	—	—	.04	.02	.13	.05	—
FeO ²⁾	13.03	31.11	17.85	.02	13.89	32.08	21.10	.26	13.34	30.46	.17
MnO	.94	2.08	.54	—	.32	.77	.25	.02	.27	.58	.02
MgO	11.16	15.52	10.00	—	10.34	14.77	7.35	—	11.30	15.86	—
CaO	20.81	.87	11.25	7.93	21.63	.66	11.20	15.88	21.34	.90	9.95
Na ₂ O	.36	.09	1.83	6.96	.35	.07	1.31	2.14	.31	.04	5.79
K ₂ O	—	—	1.22	.29	—	—	1.75	.05	—	—	.31
Total	99.89	101.31	97.94	99.95	99.11	99.01	97.07	98.87	99.26	99.57	99.44
O	6	6	23	8	6	6	23	8	6	6	8
Si	1.965	1.961	6.416	2.625	1.925	1.966	6.229	2.198	1.933	1.967	2.520
Al (IV)	.035	.039	1.584	—	.075	.034	1.771	—	.067	.033	—
Al (VI)	.042	.001	.350	1.370	.038	.013	.430	1.803	.027	.020	1.471
Ti	.007	.003	.228	.001	.008	.002	.250	.001	.006	.004	—
Cr	—	—	.007	—	—	—	.005	.001	.004	.002	—
Fe	.415	1.007	2.261	.001	.449	1.064	2.751	.010	.429	.994	.006
Mn	.030	.068	.069	—	.010	.026	.033	.001	.009	.019	.001
Mg	.633	.896	2.258	—	.596	.873	1.708	—	.647	.923	—
Ca	.849	.036	1.826	.380	.896	.028	1.871	.788	.879	.038	.483
Na	.027	.007	.537	.603	.026	.005	.396	.192	.023	.003	.508
K	—	—	.236	.017	—	—	.348	.003	—	—	.018
X _{Mg} ³⁾	.604	.471	.500	—	.570	.451	.383	—	.601	.481	—
An ⁴⁾	—	—	—	.380	—	—	—	.802	—	—	.479

1) Abbreviations as in Table 1. 2) Total Fe as FeO. 3) $X_{Mg} = Mg/(Fe + Mg)$. 4) $An = Ca/(Ca + Na + K)$.

Table 4. Microprobe mineral analyses of garnet-hornblende-pyroxene gneiss.

Specimen No.	57102726						57102732					
	64	83	78	68	72	74	57	37	39	50	42	43
Analysis No.	64	83	78	68	72	74	57	37	39	50	42	43
Mineral ¹⁾	Gar	Cpx	Opx	Hb	Pl(c)	Pl(r)	Gar	Cpx	Opx	Hb	Pl(c)	Pl(r)
SiO ₂	37.64	50.59	49.67	41.53	52.86	48.62	38.17	49.70	50.20	39.65	47.49	46.32
TiO ₂	.02	.22	.09	1.68	.04	.04	.02	.30	.09	2.02	—	—
Al ₂ O ₃	21.06	1.89	.89	10.75	28.61	32.14	20.72	2.50	.95	11.84	32.31	33.62
Cr ₂ O ₃	.03	.03	—	—	—	—	.06	—	.03	.07	—	—
FeO ²⁾	27.77	13.66	31.71	18.95	.13	.19	29.15	12.96	31.01	20.55	.14	.39
MnO	2.15	.62	1.12	.20	—	—	1.92	.26	.66	.18	.07	—
MgO	4.05	10.70	14.68	9.49	—	—	4.22	10.98	15.87	7.38	—	—
CaO	7.02	21.14	.60	10.71	11.51	15.65	6.20	21.08	.77	11.62	16.01	17.78
Na ₂ O	—	.30	—	1.57	5.12	2.79	—	.35	.02	1.15	2.19	1.62
K ₂ O	—	—	.03	1.30	.24	.09	—	.03	—	2.04	.03	.06
Total	99.74	99.15	98.79	96.18	98.51	99.52	100.46	98.16	99.60	96.50	98.24	99.79
O	12	6	6	23	8	8	12	6	6	23	8	8
Si	2.988	1.949	1.973	6.429	2.432	2.238	3.013	1.928	1.965	6.222	2.214	2.141
Al (IV)	.012	.051	.027	1.571	—	—	—	.072	.035	1.778	—	—
Al (VI)	1.958	.035	.014	.390	1.552	1.744	1.928	.043	.009	.412	1.776	1.832
Ti	.001	.006	.003	.196	.001	.001	.001	.009	.003	.238	—	—
Cr	.002	.001	—	—	—	—	.004	—	.001	.009	—	—
Fe	1.843	.440	1.053	2.453	.005	.007	1.924	.421	1.015	2.697	.005	.015
Mn	.145	.020	.038	.026	—	—	.128	.009	.022	.024	.003	—
Mg	.479	.615	.869	2.190	—	—	.497	.635	.926	1.727	—	—
Ca	.597	.873	.026	1.776	.567	.772	.524	.876	.032	1.954	.800	.881
Na	—	.022	—	.471	.457	.249	—	.026	.002	.350	.198	.145
K	—	—	.002	.257	.014	.005	—	.001	—	.408	.002	.004
X _{Mg} ³⁾	.206	.583	.452	.472	—	—	.205	.601	.477	.390	—	—
An ⁴⁾	—	—	—	—	.546	.752	—	—	—	—	.800	.855

1) Abbreviations as in Table 1, c and r refer to core and rim, respectively.

2) Total Fe as FeO.

3) X_{Mg}=Mg/(Fe+Mg).

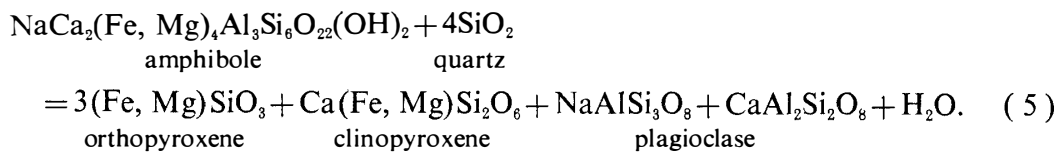
4) An=Ca/(Ca+Na+K).

Table 5. Microprobe analyses of Fe-Ti oxides in basic gneiss.

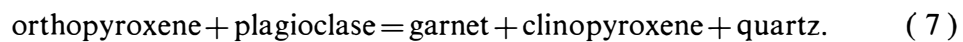
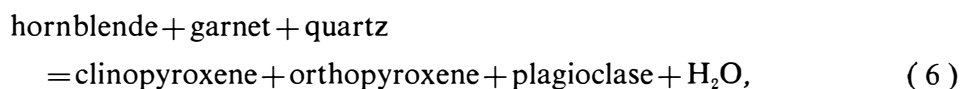
Specimen No.	57102719		57102722		57102726		57102732	
Analysis No.	16	39	40	75	55	2	1	
Mineral ¹⁾	il	il	mt	il	mt	il	mt	
SiO ₂	—	.05	.22	—	—	—	.04	
TiO ₂	51.63	51.28	.13	51.31	.12	48.20	.11	
Al ₂ O ₃	.03	.08	.62	.05	.35	.09	.37	
Cr ₂ O ₃	.03	.01	.20	.04	.16	.03	1.03	
FeO ²⁾	47.42	45.46	85.20	47.11	89.86	52.07	90.94	
MnO	1.28	.63	—	.94	—	.40	—	
MgO	.29	.59	.07	.64	—	.74	.02	
CaO	.03	.02	—	—	—	—	.02	
Total	100.71	98.12	86.44	100.09	90.49	101.53	92.53	
Recalculated analyses ³⁾								
Fe ₂ O ₃	3.16	1.12	62.26	3.41	66.18	11.62	66.65	
FeO	44.57	44.46	29.17	44.04	30.30	41.62	30.95	
Total	101.02	98.24	92.67	100.43	97.11	102.70	99.19	
R ₂ O ₃ ⁴⁾ Mol%	3.05	1.21	—	3.32	—	10.90	—	
Ulvospinel Mol%	—	—	1.31	—	.36	—	.48	
O	6	6	4	6	4	6	4	
Si	—	.003	.009	—	—	—	.002	
Ti	1.939	1.973	.004	1.934	.004	1.782	.003	
Al	.002	.005	.030	.003	.016	.005	.017	
Cr	.001	.001	.007	.002	.005	.001	.032	
Fe ³⁺	.119	.043	1.937	.128	1.972	.430	1.942	
Fe ²⁺	1.862	1.902	1.009	1.846	1.003	1.711	1.002	
Mn	.054	.027	—	.040	—	.017	—	
Mg	.022	.045	.004	.048	—	.054	.001	
Ca	.002	.001	—	—	—	—	.001	

1) Abbreviations as in Table 1. 2) Total Fe as FeO. 3) After CARMICHAEL (1967).

4) R₂O₃=(Al, Cr, Fe³⁺)₂O₃.



As 57102726 and 57102732 contain garnet, the following equilibrium would be also possible,



The equilibria (6) and (7) were petrographically and experimentally investigated by PERCIVAL (1983) and HANSEN (1981), respectively.

As presented in Table 4, the garnet in the basic gneiss carries CaO and MnO in

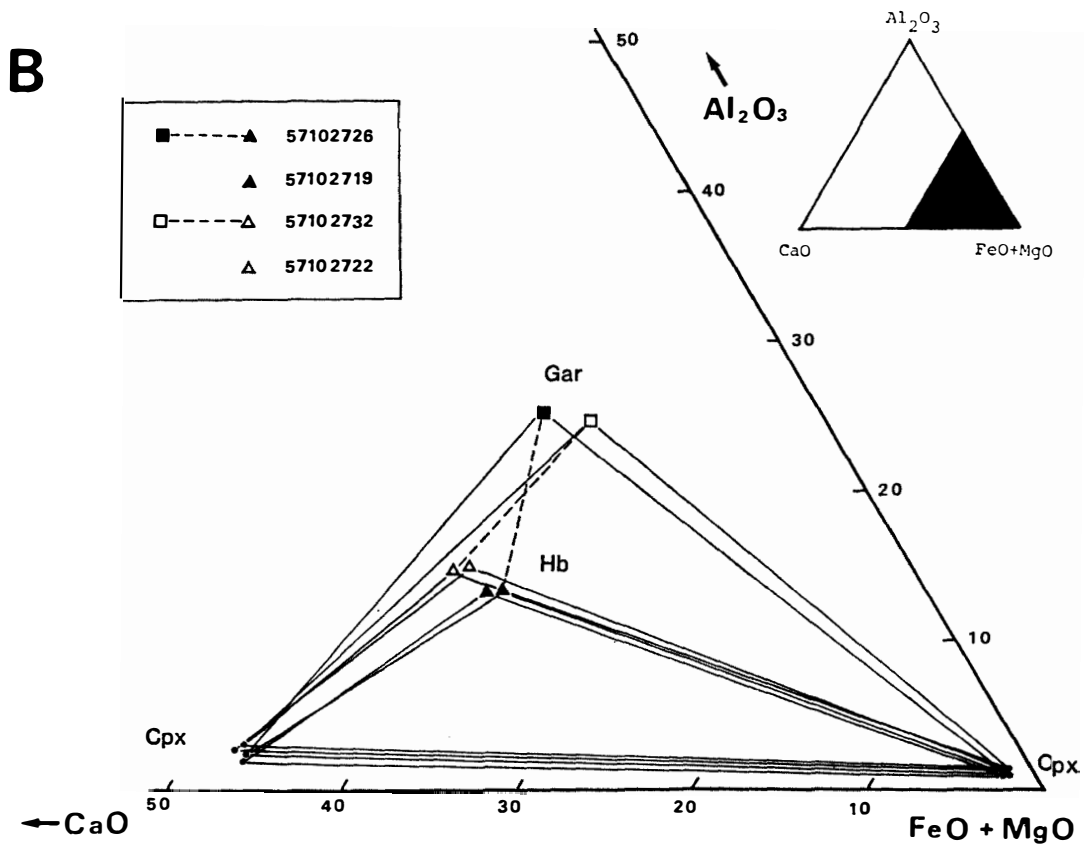
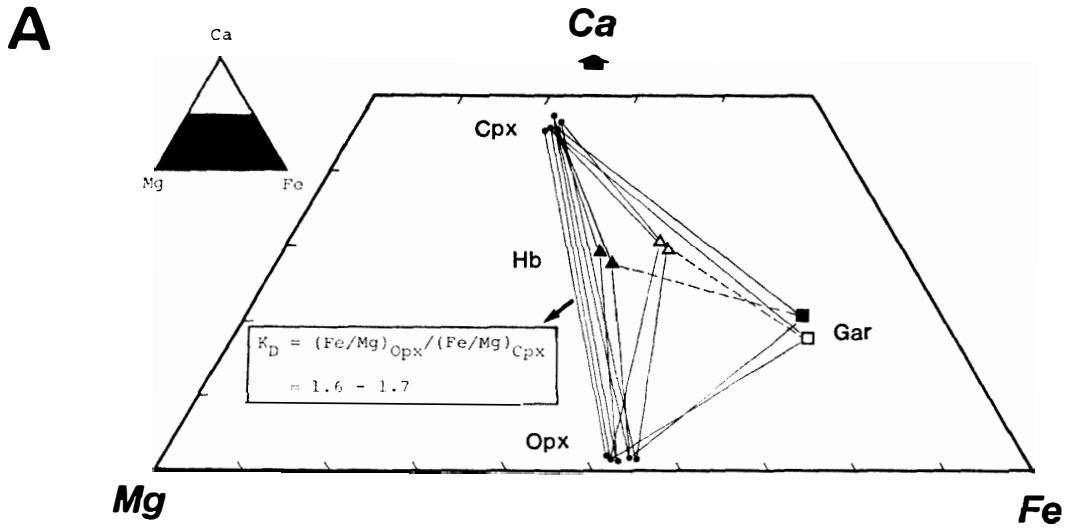


Fig. 6. Phase relations in basic gneiss. A: Ca-Mg-Fe diagram. B: Al₂O₃-(FeO+MgO)-CaO diagram. Note incompatible relations between garnet and hornblende connected by broken lines. Hornblendes are divided into chemically different two types symbolized by solid and open triangles, respectively, reflecting the bulk chemistry of the rocks.

significant amounts. The formation of garnet may be largely attributed to these components rather than the Fe/Mg ratio in the rocks.

The hornblendes are divided into two chemically different groups. One of them is included in 57102719 and 57102726 and the other is in 57102722 and 57102732. The former is characterized by relatively high X_{Mg} , $Na_2O > K_2O$ and low An content in coexisting plagioclase, while the latter has relatively low X_{Mg} , $Na_2O > K_2O$ and high An in coexisting plagioclase (Tables 3 and 4). These differences probably reflect the bulk chemistry of the rocks.

The chemical compositions of the Fe-Ti oxides are presented in Table 5. They are completely re-equilibrated and no more preserve their original compositions at the peak of metamorphism.

5. Physical Conditions of Metamorphism

5.1. Geothermometry

Garnet-biotite geothermometers (THOMPSON, 1976; HOLDAWAY and LEE, 1977; FERRY and SPEAR, 1978) are applied to garnet-biotite pair in the pelitic gneiss (57102723 and 57102731). Source data for the calculation and the results are listed in Tables 2 and 6, respectively. Since the geothermometer is based on the Fe-Mg exchange reaction, it is likely that additional components, *e.g.* Ca, Mg and Mn in garnet and Fe^{3+} and Ti in biotite, affect the thermometry. Consequently, the calculated values in Table 6 should be evaluated with these effects in mind. Among them, the temper-

Table 6. Garnet-biotite geothermometry.

Specimen No.	Gar (Fe/Mg)	Bt (Fe/Mg)	$\ln K_D$	T_1	T_2	T_3
57102723 (1)	2.197	0.767	1.052	777	769	892
(2)	2.345	0.835	1.033	784	776	905
57102731	2.851	0.919	1.132	744	742	843

Pair (1): garnet core-biotite inclusion.

Pair (2): garnet rim next to matrix biotite.

$K_D = (Fe/Mg)_{Gar} / (Fe/Mg)_{Bt}$.

T_1 : THOMPSON (1976), T_2 : HOLDAWAY and LEE (1977), T_3 : FERRY and SPEAR (1978).

Table 7. Clinopyroxene-orthopyroxene geothermometry.

Specimen No.	Cpx		Opx		K_D	T_4	T_5
	X_{Mg}	$a_{Mg_2Si_2O_6}$	X_{Mg}	$a_{Mg_2Si_2O_6}$			
57102719	0.604	0.033	0.471	0.196	1.71	824	869
57102722	0.570	0.024	0.451	0.188	1.62	787	816
57102726	0.583	0.029	0.452	0.188	1.69	809	848
57102727	0.601	0.035	0.481	0.212	1.62	825	869
57102732	0.601	0.033	0.477	0.212	1.65	819	860

$X_{Mg} = Mg / (Fe + Mg)$ in pyroxene, $a_{Mg_2Si_2O_6} = (X_{Mg})_{M2} \cdot (X_{Mg})_{M1}$.

$K_D = (Fe/Mg)_{Opx} / (Fe/Mg)_{Cpx}$.

T_4 : WOOD and BANNO (1973), T_5 : WELLS (1977).

Table 8. Garnet-pyroxene geothermometry.

Specimen No.	Gar		Cpx	Opx	$\ln K_D^*$	T_6	$\ln K_D^{**}$	T_7
	X_{Mg}	X_{Gr}	X_{Mg}	X_{Mg}				
57102726	0.206	0.205	0.583	0.452	1.682	769	1.155	708
57102732	0.205	0.178	0.601	0.477	1.765	723	1.262	653

X_{Mg} = Mg/(Fe + Mg) in mafic silicate, X_{Gr} = Ca/(Fe + Mg + Ca) in garnet.

K_D^* = (Fe/Mg)_{Gar}/(Fe/Mg)_{Cpx}, K_D^{**} = (Fe/Mg)_{Gar}/(Fe/Mg)_{Opx}.

T_6 : ELLIS and GREEN (1979), T_7 : HARLEY (1984).

atures by THOMPSON (1976) and HOLDAWAY and LEE (1977) would be realistic being consistent with the experimentally determined phase relations mentioned before.

The equilibrium temperature is also calculated by several geothermometers for the mineral pairs in the basic gneiss as in Tables 7 and 8. Two-pyroxene geothermometers yield relatively high temperature at 787–825°C by WOOD and BANNO'S (1973) method and 816–869°C by WELLS' (1977) method, respectively. Garnet-pyroxene geothermometers give lower temperature at 723–769°C for garnet-clinopyroxene pair (ELLIS and GREEN, 1979) and 653–708°C for garnet-orthopyroxene pair (HARLEY, 1984).

The discrepancies between the calculated results are mainly due to the non-ideality of the solid-solutions in natural system. We take 750–800°C as reasonable equilibrium temperature for Botnnuten rocks.

5.2. Geobarometry

Two geobarometers are adopted here. One is plagioclase-garnet-sillimanite-quartz (NEWTON and HASLTON, 1981) and the other is garnet-pyroxene-plagioclase-quartz

Table 9. Mineral thermochemical data and geobarometry.

Specimen No. (Pair No.)	Pl		Gar					Cpx		Opx		ΔV (cm ³)	P_1 P_2 (kbar)
	X_{An}	a_{An}	X_{Gr}	X_{Py}	X_{Al}	X_{Sp}	a_{Gr}	X_{Mg}	a_{Di}	X_{Mg}	a_{En}		
57102723 (1)	0.299	0.386	0.035	0.298	0.655	0.012	0.043					–56.7	7.3
(2)	0.308	0.400	0.026	0.287	0.673	0.014	0.033					–57.3	5.8
57102726	0.752	0.758	0.195	0.156	0.602	0.047	0.229	0.583	0.485				5.0
										0.452	0.188		7.2
57102732	0.855	0.815	0.171	0.162	0.626	0.042	0.199	0.601	0.495				3.7
										0.477	0.212		6.0

Pair (1): garnet core-plagioclase core.

Pair (2): garnet rim next to plagioclase rim.

X_{An} = Ca/(Ca + Na + K), a_{An} = $\{X_{An}(1 + X_{An})^2/4\} \cdot \exp \{(1 - X_{An})^2(2050 + 9392X_{An})/RT\}$ (NEWTON *et al.*, 1980).

X_{Gr} = Ca/(Fe + Mn + Mg + Ca), X_{Py} = Mg/(Fe + Mn + Mg + Ca), X_{Al} = Fe/(Fe + Mn + Mg + Ca), X_{Sp} = Mn/(Fe + Mn + Mg + Ca).

a_{Gr} = $X_{Gr} \cdot \exp \{(3300 - 1.5T)(X_{Py}^2 + X_{Py}X_{Al})/RT\}$ (GANGULY and KENNEDY, 1974; CRESSEY *et al.*, 1978).

X_{Mg} = Mg/(Fe + Mg) in pyroxene, a_{Di} = $(X_{Ca})_{M2}(X_{Mg})_{M1}$, a_{En} = $(X_{Mg})_{M2}(X_{Mg})_{M1}$.

ΔV : partial molar volume change.

P_1 : NEWTON and HASLTON (1981), P_2 : PERKINS and NEWTON (1981).

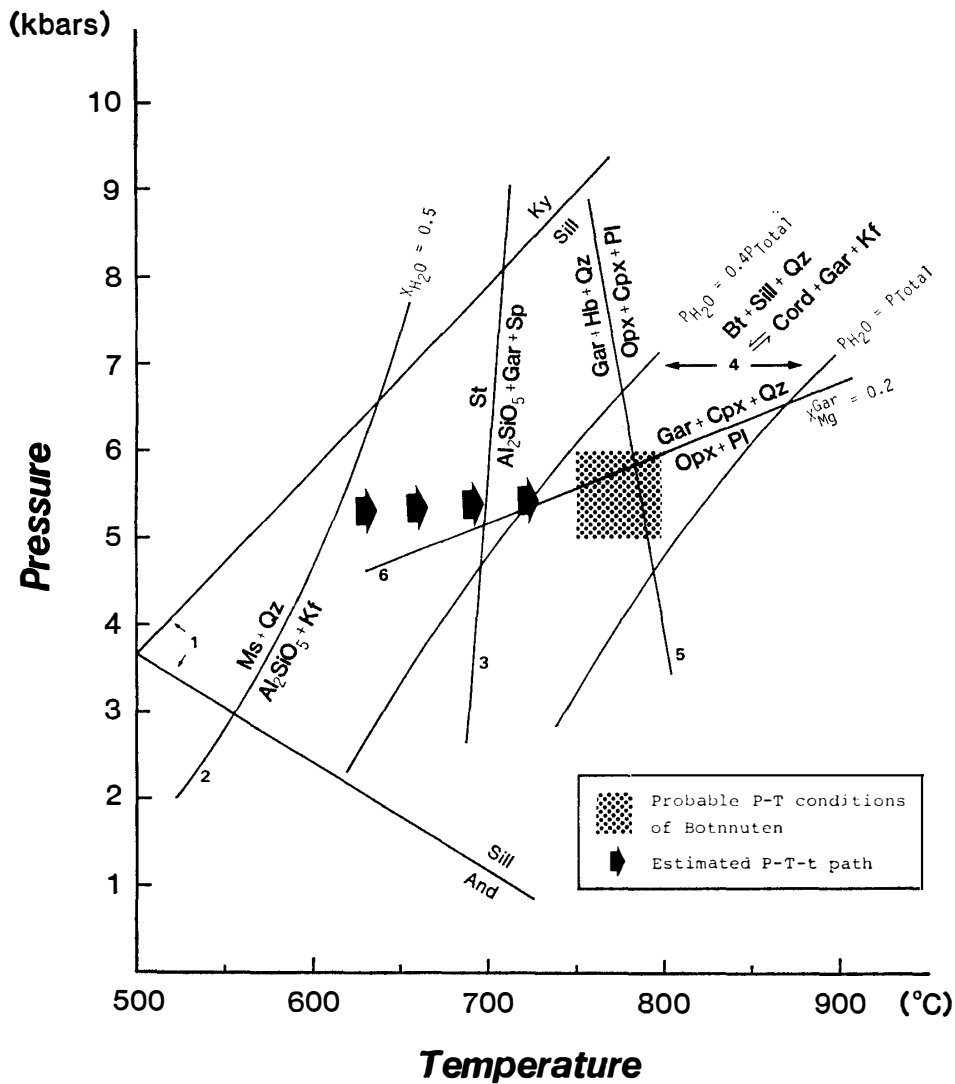


Fig. 7. Probable P - T conditions of Botnnuten rocks and estimated P - T - t path which they have followed. Data source: 1. HOLDAWAY (1971); 2. KERRICK (1972); 3. RICHARDSON (1968); 4. HOLDAWAY and LEE (1977); 5. PERCIVAL (1983); 6. HANSEN (1981).

(PERKINS and NEWTON, 1981). The results are listed in Table 9 with the thermochemical parameters used for the calculations. The equilibrium temperature is assumed to be 780°C.

Since the garnet and plagioclase are more or less chemically zoned, the reliability of the geobarometers would be reduced. However, the experimental evidence by HANSEN (1981) revealed that the association of garnet ($X_{Mg}=0.2$), two-pyroxene, plagioclase and quartz would require 5–6 kbars at 780°C for their stable coexistence. Therefore, the calculated pressures in Table 9 are not so unreasonable.

The P - T conditions of Botnnuten are graphically presented in Fig. 7 along with P - T - t path estimated from the prograde recrystallization and the phase relations mentioned before.

6. Discussions

The petrographical features of Botnnuten rocks and their P - T conditions are compared with those of the surrounding areas including the Lützow-Holm Complex and the Yamato-Belgica Complex.

The most marked petrographical distinction between the complexes would be due to the occurrence of aluminous silicate minerals. As mentioned before, the Lützow-Holm Complex is characterized by a kyanite-sillimanite type metamorphism and associated aluminous silicate minerals such as garnet, staurolite, and sapphirine are reported from several localities (HIROI *et al.*, 1983; MOTOYOSHI *et al.*, 1985). On the other hand, those minerals are scarcely present in rocks of the Yamato-Belgica Complex (SHIRAISHI, 1977; SHIRAISHI *et al.*, 1983; KOJIMA *et al.*, 1982). The common occurrence of garnet and sillimanite in the pelitic gneiss and the recrystallization history inferred from the textural relationships suggest that the petrographical features of Botnnuten rocks should be correlated with those of the Lützow-Holm Complex.

Another comparison will be examined on the P - T conditions. In the Lützow-Holm Bay region, YOSHIDA (1979) presented the wide range of temperature at 643–957°C, and he considered this deviation mainly due to the superposition of multi-stage metamorphism to which the region has been subjected. SUZUKI (1983) estimated the conditions to be $725 \pm 25^\circ\text{C}$ and 6.3 ± 1.3 kbars for the areas including Langhovde, Skarvsnes and Skallen. YOSHIDA and AIKAWA (1983) calculated the equilibrium temperature of metabasites from Skallen to be 823°C in maximum and pressure to be 4.1–6.5 kbars based on several geothermo-barometers. The rocks provided for these studies are mainly from the northern part of the Lützow-Holm Bay region. Recently, MOTOYOSHI *et al.* (1984) and MOTOYOSHI (1985) systematically re-examined the P - T conditions throughout the region based on the newly analyzed data. According to them, the metamorphic conditions are expected to grade up progressively from northeast to southwest along the Sôya Coast, and the highest grade rocks are likely to occur in the southern part of Lützow-Holm Bay. This estimation is also supported by the occurrence of potassium pargasite from the nearby place (MATSUBARA and MOTOYOSHI, 1985). The maximum P - T conditions are estimated to be up to 850°C at 8–10 kbars. In addition, KATSUSHIMA (1985) reported an Fe-rich orthopyroxene ($X_{\text{Fe}} > 0.9$) from the west islands of Langhovde, and he estimated the stable conditions for the orthopyroxens to be above 9 kbars at 800°C on the basis of the experimental results (BOHLEN *et al.*, 1980; BOHLEN and BOETTCHER, 1981). The recent studies have revealed that the P - T conditions of the Lützow-Holm Bay region are higher than those previously estimated.

The P - T conditions of the Yamato Mountains have been estimated by SHIRAISHI *et al.* (1983). Two-pyroxene geothermometer by WOOD and BANNO (1973) yielded the equilibrium temperature to be around 800°C with Fe-Mg distribution coefficient K_D (the definition is in Table 7) at 1.8–2.2. The pressure condition is qualitatively assessed by the association of wollastonite + anorthite instead of grossular + quartz (HIROI *et al.*, 1984b). The maximum pressure would be up to 5.5 kbars at 750°C and 7 kbars at 800°C (BOETTCHER, 1970).

Although the P - T conditions are similar to those of the Yamato-Belgica Complex,

the petrographical features and geothermo-barometries led us to the conclusion that Botnnuten is a low-pressure portion of the Lützow-Holm Complex.

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