ON THE ASSOCIATION OF ORTHOPYROXENE-GARNET-BIOTITE FOUND IN THE LÜTZOW-HOLMBUKTA REGION, EAST ANTARCTICA

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Abstract: Acid to intermediate metamorphites with the stable association of orthopyroxene, garnet and biotite are sporadically found in the Langhovde and Skarvsnes areas, Lützow-Holmbukta. The rocks are developed in close association with garnet-biotite gneiss and/or charnockitic rocks. The essential mineral assemblage of the rocks in question is characterized by the association of plagioclase-quartz-K feldspar-orthopyroxene-biotite-garnet-ilmenite. Based on the chemical analyses of the constituent minerals, discussion is given on the phase relations among orthopyroxene, garnet and biotite under the granulite facies metamorphic condition in the region, compared especially with those in the case of peninsular India.

1. Introduction

The region around Lützow-Holmbukta is underlain by various kinds of metamorphic and granitic rocks. Since the field work by the first wintering party of the Japanese Antarctic Research Expedition (JARE-1) of 1956–1958, Japanese geologists have conducted the geological survey of the region. The geological and petrological studies on the metamorphic and granitic rocks of the region have been accumulated in the last two decades.

BANNO *et al.* (1964a, b) made petrological studies on the metamorphites of the region to clarify that granulite facies metamorphites are widely distributed and that the metamorphic condition belongs to the lower sub-facies of the granulite facies, comparative to that of the Madras area, India. SUWA (1968) pointed out that the metamorphites of the region belong to the G2 sub-facies, which is the second lowest of the load pressure among his 4-fold division of the granulite facies. The areal distribution of the granulite facies metamorphites in the region has been steadily clarified through the continuous works to publish the geological map series.

On the other hand, some workers have studied the metamorphites from the viewpoint of polymetamorphism. KIZAKI (1964) paid attention to the occurrences of such hydrous minerals as hornblende and biotite, and of metamorphosed basic dykes, and discriminated the earlier granulite facies metamorphism from the later amphibolite facies one. Recently, YOSHIDA (1978, 1979) has discerned four deformation stages and four recrystallization episodes, the physical conditions of the latter being estimated.

Recent progress of the Japanese antarctic geological researches is summarized in Memoirs of National Institute of Polar Research (1979) and has clarified the framework of metamorphisms around Lützow-Holmbukta. However, to be investigated in the further are the chemical characteristics of the principal metamorphic minerals and the stability relation among them.

One of the most interesting mineral parageneses is represented by the association of orthopyroxene, garnet and biotite. Although the petrological significance of the association was indicated by BANNO *et al.* (1964a), it has not been found around Lützow-Holmbukta. Recently, YOSHIDA (1978) has reported the association of orthopyroxene, garnet, biotite, plagioclase, K feldspar, quartz and ore (Y69100803, Table 4.1, p. 120) from charnockitic variety of Yomogiri Island. He also shown in the same table the association with the additional phases of hornblende and/or clinopyroxene. NAKAI *et al.* (1979) have found the association of orthopyroxene, garnet, biotite, plagioclase, K feldspar, quartz, magnetite and hematite in garnet-biotite gneiss from the Telen area.

During the field surveys by JARE-18, the author has newly found some rocks with the association of orthopyroxene-garnet-biotite in the Lützow-Holmbukta region, and he intends to show chemical characteristics of each mineral and to discuss the phase relations among the minerals under the granulite facies metamorphism realized in the region.

2. Geological Setting

The metamorphites with the association of orthopyroxene-garnet-biotite-K feldspar-plagioclase-quartz-ilmenite have been found in the areas of Langhovde and Skarvsnes. Geology and geological structure of the areas have been summarized by MATSUMOTO *et al.* (1979). The rocks exposed are classified into the following 11 types; metabasites, charnockitic rocks, hornblende gneiss, marble, garnet-biotite gneiss, porphyroblastic gneiss, garnet gneiss, migmatitic gneiss, garnet-bearing granitic gneiss, microcline granite and gneissose microcline granite and pegmatite. Among the metamorphites, charnockitic rocks and garnet-biotite gneiss are most predominantly developed.

In the areas concerned, it must be noted that orthopyroxene ubiquitously occurs in the ultrabasic, basic and intermediate rocks. Also important is the common occurrence of Ti-rich biotite and Mg-rich garnet in the pelitic metamorphic rocks. The chemical characters mentioned above are compatible with those from granulite facies metamorphic terrains (BANNO *et al.*, 1964a, b; SUWA, 1968).

Migmatitic and granitic gneiss, if not all, are considered to be the products of the superposed amphibolite facies metamorphism.

Judged from the mineral association, the rocks in question were probably formed under the granulite facies condition, under which most of the surrounding metamorphites were formed.

3. Modes of Occurrence and Petrography of Metamorphites with the Association of Orthopyroxene-Garnet-Biotite

The rocks in question are occasionally found in the Lützow-Holmbukta region. The modes of occurrence and petrographical and mineralogical characteristics of

Table 1. Mineral assemblages of rocks in discussion, from Lützow-Holmbukta and peninsular India regions.

Sp. No.	Loc.	Q	Kf	Pl	Bi	Op	Gar	Il	Other	References
Lützow-Holmbukta										
77020603	Lh	+	6	5	4	1	2,3	+		This work
77012314	Sv	+	11	10	9	7	8	+		ditto
57112402	Lh	−	+	+	17	12	−	+	Cp, Hb	BANNO *et al.* (1964a)
57110802	Sv	−	+	+	18	13	−	+	Cp, Hb	ditto
68032310	WO	+	+	+	19	+	−	+	Hb	KANISAWA *et al.* (1979)
57110506	Sv	+	+	+	20	−	14	+		BANNO *et al.* (1964a)
57111105	Sv	+	+	+	21	−	15	+		ditto
57110505	Sv	+	+	+	22	−	16	+		ditto
68032313	WO	+	+	+	23	−	+	+		KANISAWA *et al.* (1979)
Peninsular India										
S/Ch 121	PT	+	+	+	34	24	31	+		SEN and SAHU (1970)
S/Ch 592	PT	+	+	+	35	25	32	+		ditto
Ch 113	M	+	+	+	+	26	33	+		HOWIE and SUBRAMANIAM (1957)
382	K	+	+	+	36	27	+	(+)		LEELANANDAM (1967) for Op and LEELANANDAM (1970) for Bi
S1	K	+	+	+	37	28	+	(+)		
B 14	K	+	+	+	38	+	+	(+)		
P 45	K	+	+	+	39	29	−	(+)		
S/Ch 381A	PT	+	+	+	40	30	−	+		SEN and SAHU (1970)
2270	M	+	+	+	41	+	−	+	Cp, Hb	HOWIE (1955)
458	K	+	+	+	42	−	+	(+)	Sill, Spl	LEELANANDAM (1970)

This table shows the mineral assemblages of rocks discussed in the text. The numbers in the table refer to the numbers in other tables where the compositions of minerals are given. The symbols of plus and bar mean present and absent, respectively. Abbreviations of localities are as follows: [Lützow-Holmbukta region] Lh; Langhovde, Sv; Skarvsnes, WO; West Ongul Island, [Peninsular India] PT; Pallavaram-Tambaram, M; Madras, K; Kondapalli. Abbreviations of minerals are as follows: Q; quartz, Kf; K feldspar, Pl; plagioclase, Bi; biotite, Op; orthopyroxene, Gar; garnet, Il; ilmenite, Cp; clinopyroxene, Hb; hornblende, Sill; sillimanite, Sp; spinel. The symbol of plus in parentheses means the presence of ore mineral, probably of ilmenite.

the rocks from the Langhovde and Skarvsnes areas will be summarized in the following.

Table 1 summarizes the mineral assemblages of rocks from the Lützow-Holmbukta and peninsular India regions, the phase relations of which are discussed in the following chapter.

3.1. The Langhovde area

The specimen 77020603 was found at the point (lat. 69°11′22″ S, long. 39°34′50″ E) about 400 m north of the summit of Mt. Tyôtô. The surrounding rocks are characterized by the alternation of garnet-biotite gneiss (garnet-biotite-quartz-K feldspar-plagioclase) and charnockitic rock (orthopyroxene-clinopyroxene-quartz-K feldspar-plagioclase-hornblende-biotite). Dark-coloured metabasites occur concordantly in the surroundings.

Table 2. Modal compositions and bulk chemical compositions of the metamorphites with the association of orthopyroxene-garnet-biotite from Lützow-Holmbukta.*

Specimen No.	77020603	77012314
Locality	Langhovde	Skarvsnes
Modal composition		
Quartz	7.6	20.6
Plagioclase	50.0	48.1
K feldspar	14.3	13.3
Orthopyroxene	14.2	6.6
Biotite	10.4	9.4
Garnet	1.3	0.7
Ilmenite	1.7	1.0
Others	0.5	0.3
Total	100.0	100.0
Bulk chemical composition		
SiO_2	57.4	64.6
TiO_2	1.6	1.0
Al_2O_3	17.2	16.0
FeO**	8.0	5.1
MnO	0.1	0.1
MgO	3.4	1.9
CaO	5.2	3.2
Na_2O	3.2	3.8
K_2O	3.7	3.1
Total	99.8	98.8

* Estimated values from modal composition and constituent mineral chemistry.

** Total Fe as FeO.

The rock in question occurs in garnet-biotite gneiss as a concordantly intercalated layer. The boundary with the garnet-biotite gneiss is not marked and gradual. The rock is dark brown in colour and shows more or less marked foliation characterized by banding of biotite-rich melanocratic layer and quartz-feldspathic leucocratic one. Porphyroblastic reddish garnet, visible by the naked eye, sporadically develops in the melanoclatic layer.

Under the microscope, the fine- to medium-grained granoblastic texture is characteristic. The essential mineral assemblage of the rock is plagioclase, orthopyroxene, biotite, K feldspar, quartz, garnet and ilmenite. Accessory minerals are zircon and apatite. Modal composition and bulk rock chemistry estimated by modal composition and mineral chemistry are given in Table 2. The bulk composition suggests that the rock has an intermediate composition, and plagioclase

Table 3. Chemical compositions of the main constituent minerals in the specimen 77020603 from the Langhovde area.

	1	2	3	4	5	6
SiO_2	49.0	36.7	37.0	35.5	59.0	64.1
TiO_2	0.10	0.04	0.05	6.57	0.07	0.10
Al_2O_3	1.41	20.9	20.6	13.1	25.5	18.1
FeO*	31.6	29.3	29.3	22.1	tr.	tr.
MnO	0.54	1.79	1.74	0.05	tr.	tr.
MgO	16.3	4.11	4.24	9.91	0.02	0.02
CaO	0.60	5.59	5.39	0.12	10.1	0.06
Na_2O	0.02	0.02	0.03	0.05	6.20	0.40
K_2O	0.01	0.03	0.02	9.92	0.53	16.7
Total	99.6	98.5	98.4	97.3	101.4	99.5
			Numbers of ions			
O	6.000	24.000	24.000	22.000	32.000	32.000
Si	1.928	5.928	5.968	5.436	10.470	11.965
Ti	0.003	0.005	0.007	0.756	0.010	0.013
Al	0.065	3.980	3.929	2.354	5.330	3.991
Fe	1.040	3.954	3.960	2.824	—	—
Mn	0.018	0.245	0.239	0.007	—	—
Mg	0.955	0.991	1.020	2.258	0.006	0.005
Ca	0.025	0.969	0.933	0.019	1.920	0.013
Na	0.001	0.005	0.008	0.016	2.133	0.146
K	0.001	0.005	0.004	1.935	0.119	3.978

1. Orthopyroxene. 2. Garnet-rim. 3. Garnet-core. 4. Biotite. 5. Plagioclase. 6. K feldspar.

* Total Fe as FeO.

is the predominant feldspar rather than K feldspar. Therefore, the rock would belong to the category of an enderbite (TILLEY, 1936).

Chemical compositions of major constituent minerals are shown in Table 3. The grain of orthopyroxene is developed showing a shieve-like texture with the composition of $Ca_{1.2}Mg_{46.9}Fe+Mn_{51.9}$, plotted in the ferrohypersthene region. The Al_2O_3 content is not so high, compared with that of a typical example of the granulite facies metamorphic terrain, such as Madras. Some discussion on this account will be mentioned later. Garnet is idiomorphic with regular shape, showing weakly-zoned structure with rather Mg-rich core. The composition is fairly almandinous containing 16% pyrope molecules. Deep brown to reddish brown biotite is developed with the parallel arrangement. It is not xenocrystic but intergranularly developed and idiomorphic. The ratio of Fe/Fe+Mg is 0.56, higher than that of the Madras samples. Plagioclase is unzoned and always antiperthitic with irregular-shaped blebs of K feldspar. The composition of host crystal is $Ab_{51.1}An_{46.1}Or_{2.8}$. The bleb of K feldspar has the composition of $Ab_{0.5}An_{3.3}Or_{96.2}$. K feldspar is also developed as idiomorphic grains but rather small in amount, showing the composition of $Ab_{0.4}An_{3.5}Or_{96.0}$ (Table 3, No. 6). Ore minerals are always ilmenite, showing distinct chemical zonation. The ratio of Ti/Fe increases from the core to the rim, for example from 0.78 to 1.00.

3.2. *The Skarvsnes area*

The specimen 77012314 was found at the point (lat. 69°28′50″ S, long. 39°42′15″ E) about 750 m northeast of Lake Suribati. The surrounding rocks are garnet gneiss (quartz-K feldspar-plagioclase-garnet-biotite), garnet-biotite gneiss (biotite-garnet-quartz-K feldspar-plagioclase) and charnockitic rock (orthopyroxene-clinopyroxene-quartz-K feldspar-plagioclase-hornblende-biotite). The rock now concerned occurs as a concordantly intercalated layer in the charnockitic rock. It is brown in colour and seems to be an intermediate lithofacies between the garnet-biotite gneiss and the charnockitic rock. Melanocratic layer composed mainly of biotite is more or less marked, but the banding structure is not so clearly observed as in the case of the Langhovde specimen.

Under the microscope, the texture is fine- to medium-grained granoblastic. As shown in Table 2, the essential mineral assemblage is plagioclase-quartz-K feldspar-biotite-orthopyroxene-garnet-ilmenite. Accessory minerals are apatite and zircon. Plagioclase is markedly predominant than K feldspar, as in the case of the Langhovde specimen, and the estimated bulk chemical composition shows that the rock is rather acidic than the specimen described before.

Chemical compositions of the main constituent minerals are given in Table 4. Orthopyroxene is rather idiomorphic and sometimes shows a shieve-like texture. It rarely and partly has been brokendown to the aggregate of fine-grained biotite and quartz. Orthopyroxene is ferrohypersthene with the composition of $Ca_{0.7}Mg_{42.7}$

Table 4. Chemical compositions of the main constituent minerals in the specimen 77012314 from the Skarvsnes area.

	7	8	9	10	11
SiO_2	48.7	36.9	36.1	59.3	64.7
TiO_2	0.20	0.08	4.99	0.03	0.04
Al_2O_3	1.34	20.7	14.1	25.0	18.4
FeO*	33.8	32.1	23.0	tr.	tr.
MnO	0.77	2.33	0.09	tr.	tr.
MgO	14.7	3.81	9.68	0.01	0.01
CaO	0.35	4.02	0.04	6.60	0.07
Na_2O	0.01	0.02	0.04	7.57	0.88
K_2O	0.02	0.02	9.64	0.38	15.0
Total	99.9	100.0	97.7	98.9	99.1
			Numbers of ions		
O	6.000	24.000	22.000	32.000	32.000
Si	1.931	5.933	5.491	10.701	12.006
Ti	0.006	0.009	0.571	0.004	0.006
Al	0.062	3.912	2.524	5.311	4.026
Fe	1.122	4.318	2.931	–	–
Mn	0.026	0.318	0.012	–	–
Mg	0.868	0.913	2.196	0.001	0.003
Ca	0.015	0.693	0.006	1.276	0.014
Na	0.001	0.007	0.013	2.649	0.318
K	0.001	0.004	1.873	0.088	3.553

7. Orthopyroxene. 8. Garnet. 9. Biotite. 10. Plagioclase. 11. K feldspar.
* Total Fe as FeO.

$Fe+Mn_{56.5}$. The alumina content is as low as 1.34 wt%. Garnet is developed as regular-shaped crystals, showing no sign of distinct zonation. The composition is almandinous with 15% pyrope molecules. Idiomorphic biotite is parallely arranged and shows a brown to reddish brown tint. The TiO_2 content is as high as 5 wt% and the Fe/Fe+Mg ratio attains to 0.57. Plagioclase is always antiperthitic and sometimes myrmekitic. The composition of the host crystal is $Ab_{66.0}An_{31.0}Or_{2.2}$. K feldspar is perthitic and intergranular, with the composition of $Ab_{8.2}An_{0.4}Or_{91.4}$. Ilmenite always accompanies.

4. Phase Relations among Orthopyroxene, Garnet and Biotite

BANNO *et al.* (1964a) pointed out, through detailed analyses of the phase equilibrium relation involving biotite, that the biotites in the Lützow-Holmbukta region are incompatible with orthopyroxene-garnet assemblage of Sacksen and probably of Madras, and that the biotites would be unstable in the typical granulite facies terrain such as Sacksen and Madras.

The specimens described here would give the data for considering the stability relation among orthopyroxene, garnet and biotite, along the line given by BANNO *et al.* (1964a). The phase relation among the minerals in the rock devoid of muscovite and containing K feldspar can be advantageously represented by the use of A′FM diagram of REIHARDT (1968).

Figure 1 shows the paragenetic relations of antarctic orthopyroxene, garnet and biotite with additional phases of K feldspar, plagioclase, quartz and ilmenite. The parameters for the diagram are as follows; $A' = Al_2O_3 - (Na_2O + K_2O + CaO)$, $F = FeO - (Fe_2O_3 + TiO_2)$ and $M = MgO$. Tables 5 and 6 show the published analyses of orthopyroxene and garnet, and biotite from Lützow-Holmbukta, respectively. It is distinctly seen from the figure that the composition of biotites from Lützow-Holmbukta varies in a wide range of the Fe/Mg ratio. The composition of biotites associated not only with orthopyroxene but garnet lies on Fe-richer side than those

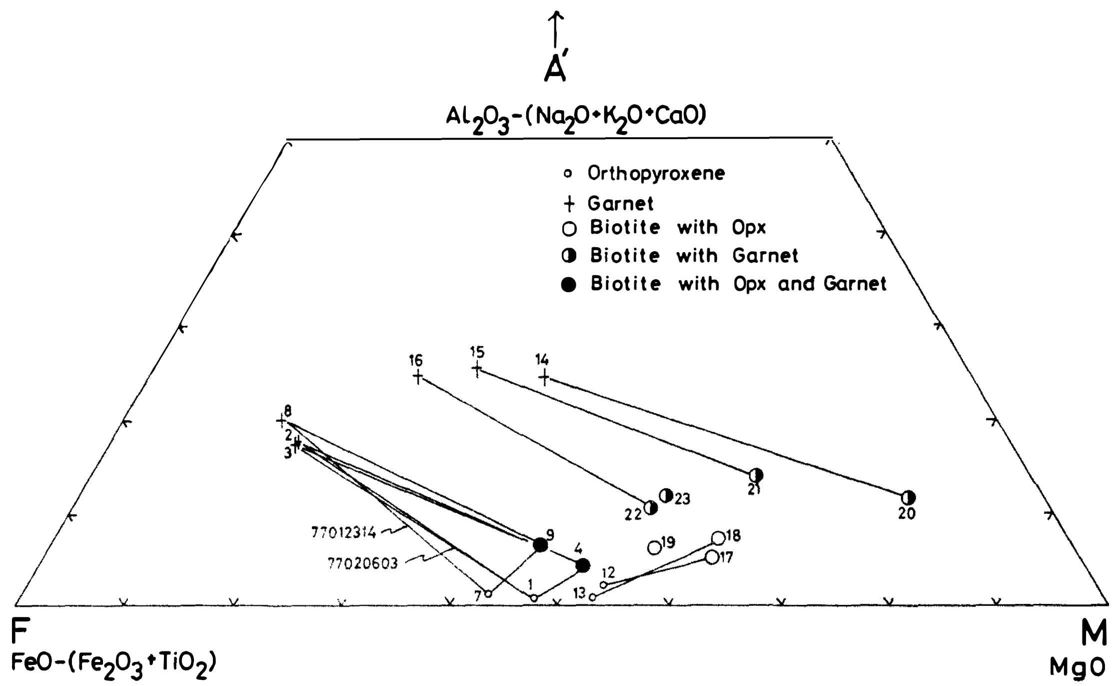

Fig. 1. A′FM projection (partial) for the three assemblages from the Lützow-Holmbukta region. The numbers attached to individual symbols refer to those in Table 1 and to the columner numbers in Tables 2, 3, 4 and 5. Quartz, K feldspar, plagioclase and ilmenite are members of all assemblages except for two specimens of 57112402 (Nos. 12 and 17) and 57110802 (Nos. 13 and 18), both of which have no quartz.

Table 5. Published chemical compositions of orthopyroxene and garnet from Lützow-Holmbukta region.

	Orthopyroxne		Garnet		
	12	13	14	15	16
SiO_2	49.49	49.76	38.74	39.59	38.52
TiO_2	0.25	0.19	0.07	0.08	0.06
Al_2O_3	1.62	0.73	22.09	23.07	23.68
Fe_2O_3	1.19	1.70	2.97	1.88	1.31
FeO	28.01	28.54	23.23	23.20	25.77
MnO	0.57	0.76	0.47	0.34	0.38
MgO	17.88	17.47	11.20	8.21	6.82
CaO	0.00	0.10	1.10	2.56	3.23
Na_2O	0.00	0.08	0.23	0.18	0.21
K_2O	tr.	0.03	0.11	0.09	0.09
H_2O+	1.01	0.65	0.05	0.27	0.08
H_2O-	0.17	0.07	0.02	0.09	0.07
Cr_2O_3	n.d.	n.d.	0.07	n.d.	n.d.
Total	100.19	100.08	100.35	99.56	100.22
Numbers of ions					
O	6.000	6.000	24.000	24.000	24.000
Si	1.927	1.942	5.874	6.047	5.916
Ti	0.007	0.005	0.008	0.009	0.007
Al	0.074	0.034	3.948	4.154	4.288
Fe‴	0.035	0.050	0.338	0.217	0.151
Fe″	0.912	0.931	2.946	2.964	3.311
Mn	0.019	0.025	0.060	0.044	0.050
Mg	1.037	1.015	2.530	1.869	1.561
Ca	0.000	0.004	0.178	0.419	0.532
Na	0.000	0.006	0.068	0.053	0.063
K	0.000	0.001	0.022	0.018	0.018

12. JARE 57112402 (Lh), 13. JARE 57110802 (Sv) syenite (charnockitic variety). 14. JARE 57110506 (Sv) garnet-biotite banded gneiss. 15. JARE 57111105, 16. JARE 57110505 (Sv) garnet gneiss.
Lh; Langhovde, Sv; Skarvsnes.
See Table 1 for the reference and the mineral assemblage of each specimen.

associated only with orthopyroxene or garnet. The maximum value of $F/F+M$ of biotite occurring together with orthopyroxene and garnet attains to 0.52 (77012314, No. 9). The alumina content of biotite is rather high in biotites associated only with garnet as a ferromagnesian mineral.

Figure 2 shows the phase relations of orthopyroxene, garnet and biotite from Indian samples, the published analytical data of which are shown in Tables 7 and 8. Also shown in the figure are the triangular fields and arbitrarily outlined com-

Table 6. Published chemical compositions of biotite from Lützow-Holmbukta region.

	17	18	19	20	21	22	23
SiO_2	36.33	36.51	36.43	37.66	35.46	32.25	37.41
TiO_2	5.22	5.22	5.70	4.86	5.72	5.00	5.15
Al_2O_3	14.46	13.75	14.17	17.09	17.09	15.24	16.19
Fe_2O_3	1.40	2.74	0.51	0.77	1.27	3.81	1.91
FeO	17.30	17.47	18.60	9.71	14.93	19.38	16.72
MnO	0.07	0.13	0.06	0.00	0.02	0.01	0.03
MgO	12.28	11.62	10.88	17.59	12.65	10.82	9.86
CaO	0.00	0.05	0.19	0.00	0.00	0.00	0.25
Na_2O	0.19	0.28	0.33	0.22	0.23	0.22	0.44
K_2O	8.96	8.93	9.47	9.30	8.91	8.87	8.94
H_2O+	3.29	2.84	3.29	2.53	2.98	1.62	2.98
H_2O-	0.47	0.32	0.14	0.04	0.59	0.32	0.13
Cr_2O_3	n.d.	n.d.	n.d.	0.16	n.d.	n.d.	n.d.
F	n.d.	n.d.	0.66	n.d.	n.d.	n.d.	n.d.
Total	99.97	99.86	100.43	99.93	99.85	97.54	100.01
				Numbers of ions			
O	22.000	22.000	22.000	22.000	22.000	22.000	22.000
Si	5.460	5.512	5.512	5.373	5.255	5.015	5.545
Ti	0.589	0.592	0.648	0.521	0.638	0.585	0.574
Al	2.221	2.446	2.526	2.875	2.986	2.794	2.827
Fe'''	0.159	0.311	0.058	0.082	0.142	0.446	0.214
Fe''	2.174	2.114	2.352	1.158	1.851	2.520	2.072
Mn	0.009	0.016	0.008	0.000	0.003	0.001	0.004
Mg	2.750	2.613	2.452	3.740	2.794	2.508	2.177
Ca	0.000	0.016	0.031	0.000	0.000	0.000	0.040
Na	0.055	0.082	0.096	0.062	0.066	0.066	0.126
K	1.717	1.719	1.826	1.692	1.685	1.759	1.690

17. JARE 57112402, 18. JARE 57110802 (Lh) syenite (charnockitic variety). 19. 68032310 (WO) enderbite. 20. JARE 57110506 (Sv) garnet-biotite banded gneiss. 21. JARE 57111105, 22. JARE 57110505 (Sv) garnet gneiss. 23. 68032313 (WO) garnet-biotite gneiss.
Lh; Langhovde, Sv; Skarvsnes, WO; West Ongul Island.
See Table 1 for the reference and the mineral assemblage of each specimen.

positional field for biotite of specimens from Lützow-Holmbukta, already shown in Fig. 1.

Howie (1955) and Howie and Subramaniam (1957) clarified the mineral characteristics of charnockite suites from the Madras area, to show the stable association of orthopyroxene-garnet-biotite-K feldspar-plagioclase-quartz-ilmenite-magnetite (Ch 113). Unfortunately the composition of the biotite in the association has not been known by the author's article research. Only the plot of an ortho-

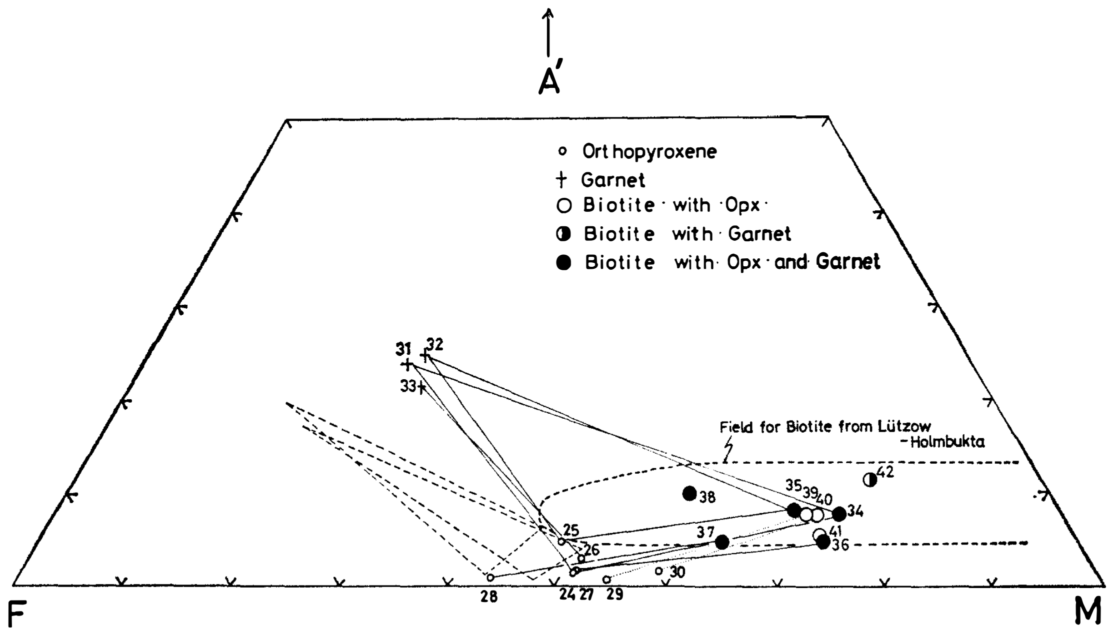

Fig. 2. A'FM projection (partial) for the three assemblages from peninsular India. A', F and M as in Fig. 1. The numbers attached to individual symbols refer to those in Table 1 and to the columner numbers in Tables 7 and 8. All the specimens have additional phases of quartz, K feldspar, plagioclase and ore minerals. Almost all of the ore minerals are ilmenite. Solid lines show the joins among the minerals in three-phase paragenesis. Dotted lines show orthopyroxene-biotite joins in the assemblages without garnet. Dashed triangles are the three-phase assemblages from the Lützow-Holmbukta region as shown in Fig. 1. Compositional field of biotite from Lützow-Holmbukta is also given.

pyroxene-garnet pair (Nos. 26 and 33) from the association is shown in the figure. HOWIE (1955) gave one analysis of biotite (2270), which is associated with orthopyroxene, clinopyroxene, hornblende, plagioclase, K feldspar, quartz and ore devoid of garnet. The composition is also plotted in the figure for reference (No. 41).

SEN and SAHU (1970) have shown the phase relations of orthopyroxene, garnet and biotite in three charnockitic rocks from the Pallavaram-Tambaram area, near the type area of Madras. Out of the three samples, two (S/Ch 121 and S/Ch 592) are characterized by the association of plagioclase-quartz-alkali feldspar-orthopyroxene-garnet-biotite-ilmenite, which is very similar to that of the Lützow-Holmbukta specimens. The remaining one (S/Ch 381A) is lacking garnet in the association. The compositions of orthopyroxene, garnet and biotite are plotted in Fig. 2. It is worthy of note that the triangular fields shift to the Mg-richer side from those of Lützow-Holmbukta and become wider. The ratio of F/F+M of

Table 7. Published chemical compositions of orthopyroxene and garnet from peninsuar India.

	Orthopyroxene							Garnet		
	24	25	26	27	28	29	30	31	32	33
SiO_2	50.53	49.00	50.05	49.84	48.81	50.45	50.57	38.58	38.04	38.02
TiO_2	0.25	tr.	0.30	0.35	0.42	0.33	0.24	tr.	0.60	0.03
Al_2O_3	4.63	5.33	4.08	2.75	2.07	1.67	3.17	22.56	21.54	21.02
Fe_2O_3	0.42	0.79	0.68	0.36	1.10	0.70	0.38	1.34	2.67	1.98
FeO	25.99	27.95	27.50	28.91	31.89	27.31	24.00	28.34	28.20	28.12
MnO	0.20	0.18	0.27	0.54	0.40	0.52	0.37	0.55	0.54	0.64
MgO	15.30	15.75	16.51	17.23	14.18	17.94	19.50	7.40	7.71	7.87
CaO	1.81	0.66	0.46	0.39	0.66	0.68	0.79	2.07	1.40	2.25
Na_2O	0.04	tr.	0.09	0.06	0.01	0.06	0.13	n.d.	n.d.	0.11
K_2O	0.02	0.04	0.03	0.04	0.02	0.06	0.02	n.d.	n.d.	0.01
H_2O+	n.d.	n.d.	0.02	n.d.	n.d.	0.16	n.d.	n.d.	n.d.	n.d.
H_2O-	n.d.	n.d.	0.11	0.08	0.14	0.03	n.d.	n.d.	n.d.	0.09
Total	99.19	99.70	100.10	100.55	99.70	99.91	99.17	100.84	100.70	100.14
					Numbers of ions					
O	6.000	6.000	6.000	6.000	6.000	6.000	6.000	24.000	24.000	24.000
Si	1.934	1.882	1.918	1.913	1.926	1.941	1.921	5.936	5.886	5.936
Ti	0.007	—	0.009	0.010	0.012	0.010	0.007	—	0.070	0.008
Al	0.209	0.242	0.184	0.124	0.096	0.076	0.142	4.092	3.929	3.860
Fe′′′	0.012	0.023	0.019	0.010	0.033	0.020	0.011	0.155	0.311	0.240
Fe′′	0.832	0.899	0.879	0.928	1.053	0.879	0.762	3.647	3.649	3.670
Mn	0.006	0.006	0.009	0.018	0.013	0.017	0.012	0.072	0.071	0.084
Mg	0.873	0.902	0.943	0.986	0.834	1.028	1.104	1.697	1.778	1.826
Ca	0.074	0.027	0.019	0.016	0.028	0.028	0.032	0.341	0.232	0.374
Na	0.003	—	0.009	0.004	0.001	0.004	0.010	—	—	0.036
K	0.001	0.002	0.002	0.002	0.001	0.003	0.001	—	—	0.002

24 and 31. S/Ch 121 (PT) garnetiferous tonalite (charnockitic variety). 25 and 32. S/Ch 592 (PT) garnetiferous quartz-syenite (charnockitic variety). 26 and 33. Ch 113 (M) garnetiferous enderbite. 27. 382 (K), 28. S1 (K) acid or intermediate charnockite. 29. P45 (K) basic charnockite. 30. S/Ch 381A (PT) tonalite (charnockitic variety).

PT; Pallavaram-Tambaram, M; Madras, K; Kondapalli.

See Table 1 for the reference and the mineral assemblage of each specimen.

Table 8. Published chemical compositions of biotite from peninsular India.

	34	35	36	37	38	39	40	41	42
SiO_2	39.31	39.87	37.94	37.38	35.77	36.66	39.40	38.66	37.26
TiO_2	4.74	4.30	4.54	4.64	5.26	5.40	4.31	4.43	4.88
Al_2O_3	15.14	14.24	13.57	13.16	15.64	14.40	14.55	13.96	16.60
Fe_2O_3	1.31	1.54	1.05	1.34	2.07	1.38	0.81	1.54	1.69
FeO	11.65	13.81	13.29	16.74	17.38	14.12	13.00	13.15	11.02
MnO	tr.	0.27	0.04	0.05	0.01	0.09	tr.	0.11	0.04
MgO	13.48	14.68	15.53	13.18	11.52	14.33	15.39	14.65	15.55
CaO	0.93	0.30	n.d.	n.d.	n.d.	n.d.	0.50	0.60	n.d.
Na_2O	0.27	0.32	0.12	0.10	0.19	0.23	0.11	0.71	0.17
K_2O	8.77	8.02	9.89	9.63	9.41	9.26	8.13	8.34	9.55
H_2O+	0.01	2.82	1.35	1.68	1.90	1.70	2.28	2.96	1.87
H_2O-	0.37	0.37	0.02	0.02	0.04	0.02	0.61	0.05	0.05
BaO+SrO	0.83	0.33	n.d.	n.d.	n.d.	n.d.	0.85	n.d.	n.d.
F	n.d.	n.d.	2.68	2.77	1.22	2.13	n.d.	0.3	1.92
Cl	n.d.	n.d.	0.22	0.62	0.14	0.32	n.d.	n.d.	0.29
Total	99.81	100.87	100.24	101.31	100.55	100.04	99.94	99.46	100.89
					Numbers of ions				
O	22.000	22.000	22.000	22.000	22.000	22.000	22.000	22.000	22.000
Si	5.739	5.751	5.617	5.616	5.341	5.456	5.719	5.671	5.400
Ti	0.520	0.466	0.505	0.524	0.591	0.604	0.470	0.489	0.532
Al	2.606	2.422	2.368	2.330	2.753	2.526	2.490	2.414	2.836
Fe'''	0.144	0.167	0.117	0.151	0.233	0.155	0.088	0.170	0.184
Fe''	1.422	1.666	1.645	2.103	2.170	1.757	1.578	1.613	1.336
Mn	—	0.033	0.005	0.006	0.001	0.011	—	0.014	0.005
Mg	2.933	3.156	3.426	2.951	2.564	3.178	3.329	3.203	3.359
Ca	0.146	0.046	—	—	—	—	0.078	0.094	—
Na	0.076	0.089	0.034	0.029	0.055	0.066	0.031	0.202	0.048
K	1.634	1.476	1.868	1.846	1.793	1.758	1.506	1.561	1.766

34. S/Ch 121 (PT) garnetiferous tonalite (charnockitic variety). 35. S/Ch 592 (PT) garnetiferous quartz-syenite (charnockitic variety). 36. 382, 37. S1 (K) acid or intermediate charnockite. 38. B14 (K) charnockitic biotite gneiss. 39. P45 (K) basic charnockite. 40. S/Ch 381A (PT) tonalite (charnockitic variety). 41. 2270 (M) intermediate charnockite. 42. 458 (K) khondalite. PT; Pallavaram-Tambaram, K; Kondapalli, M; Madras.

See Table 1 for the reference and the mineral assemblage of each specimen.

biotites paragenetic with orthopyroxene and garnet is as low as 0.22 in the sample S/Ch 121 (No. 34) and 0.26 in S/Ch 592 (No. 35). It is remarkable that the compositional field for biotite lies on the Mg-richer side compared with that of antarctic samples. The tie lines between orthopyroxene and garnet of three phase triangles are situated close to each other and to that of the sample Ch 113 (Nos. 26 and 33 in Fig. 2) described by HOWIE and SUBRAMANIAM (1957) from the type area.

LEELANANDAM (1970) have given the mineralogy of biotite and hornblende from charnockites, khondalites, charnockitic biotite gneiss and pegmatite of the Kondapalli area, about 320 km north of the type area near Madras. According to his results, these hydrous minerals are chemically equilibrated with such anhydrous minerals as orthopyroxene, garnet and/or clinopyroxene during the Archean granulite facies metamorphism and the metamorphic conditions are similar to those in the Madras area. Among the analysed biotites from acid to intermediate charnockite, khondalite and charnockitic biotite gneiss, three (Nos. 36, 37 and 38 in Fig. 2) occur together with orthopyroxene-garnet-plagioclase-K feldspar-quartz-ore, one (No. 39) with orthopyroxene-plagioclase-K feldspar-quartz-ore and one (No. 42) with garnet-plagioclase-K feldspar-quartz-ore. Ore minerals must be ilmenite and/or magnetite as in the case of the Madras samples. The compositions of biotites from Kondapalli closely associated with garnet and orthopyroxene are rather Fe-rich compared with those of the Madras samples, the maximum value of the F/F+M ratio attaining to 0.36 (No. 38). It is, however, rather a low value, like the Madras one, compared with that of antarctic samples.

Taken as a whole, comparison of the phase relations between Lützow-Holmbukta and peninsular India is summarized in the following. The triangular fields of the Indian samples are wider and lie on the Mg-richer side than those of Antarctica (Fig. 2). Orthopyroxenes from Madras are more aluminous. Moreover, it is clear from the figure that the compositional field of biotites from acid to intermediate rocks of peninsular India is rather narrower and lies on the Mg-richer side than that of the Lützow-Holmbukta region. The compositions of biotite associated only with garnet or orthopyroxene lie on the Mg-richer side in the samples from both regions.

WEAVER *et al.* (1978) have summarized the petrochemical characters of the Madras granulite facies metamorphites to give the result that they were formed under the physical conditions of 720–840°C, 9–10 kb. In the Antarctic region, as indicated by GREW (1980), there occur stable associations of quartz-sapphirine and sillimanite-orthopyroxene in metamorphosed quartzite from the Napier complex, Enderby Land. The metamorphic temperature is estimated by him to be around 900°C, and the load pressure to be higher than 7 kb. He (personal communication) has the opinion, through the works in India, that the metamorphic conditions are very similar between Enderby Land and the Madras area. While, in the Lützow-Holmbukta region neither the association of quartz-sapphirine nor that of sillimanite-orthopyroxene has been found yet. Therefore, it is probable that metamorphic conditions under the granulite facies metamorphism in the Lützow-Holmbukta region are rather lower-grade than those in Enderby Land and probably in peninsular India. It is not unreasonable to consider that the biotites from the Lützow-Holmbukta region are unstable under the physical condition in peninsular India and probably in Enderby Land, because the joins of orthopyroxene-garnet from the Madras area intersect the compositional field of biotite from the Lützow-Holmbukta region. The assemblages of orthopyroxene-garnet-biotite from the latter region lie on the Fe-richer side, while those from the former area must show the limits of Fe-Mg substitution lying on the Mg-rich side (Figs. 1 and 2).

Generally speaking, as the metamorphic grade increases in the granulite facies metamorphism, the triangular field seems to become wider and shift to the Mg-rich side in the A′FM diagram, the compositional field for biotite narrower to the Mg-rich side and the alumina content in orthopyroxene higher. In other words, during the progressive change of the granulite facies metamorphic conditions, rather Fe-rich biotite, stable under the lower grade, may become unstable to produce the association of alumina-rich orthopyroxene and rather Mg-rich biotite under the higher grade.

The Lützow-Holmbukta region belongs to the lower grade sub-facies of the granulite facies compared with the area of Madras, as already stated by BANNO *et al.* (1964a), and probably of Enderby Land. It is probable that the Antarctic region and peninsular India once constituted a part of supercontinental Gondowanaland. If it is the case, the chemical difference of the three-phase paragenesis in acid to intermediate rocks of Lützow-Holmbukta and peninsular India may refer to the regional difference of physical conditions in the original metamorphic complex. The Enderby Land may be rather similar to the latter area than to the former.

5. Conclusions

In this paper, the descriptions of acid to intermediate metamorphites with the stable association of orthopyroxene-garnet-biotite-plagioclase-K feldspar-quartz-ilmenite from the areas of Langhovde and Skarvsnes, Lützow-Holmbukta have been given with the following results.

1) The rocks occur in close association with garnet-biotite gneiss and/or charnockitic rock, both of which have the critical petrographical and mineralogical characters of the formation under the granulite facies metamorphism.

2) Three phase paragenetic field of orthopyroxene-garnet-biotite and compositional field for biotites of the specimens lie on the Fe-richer side in the A′FM diagram, compared with those of peninsular India, the typical terrain of granulite facies metamorphism.

3) The association concerned in Lützow-Holmbukta must have been formed under the granulite facies metamorphic condition but of a rather lower-grade than peninsular India and Enderby Land.

4) The above-mentioned difference may suggest the regional difference of physical conditions of the granulite facies metamorphism in the original metamorphic complex.

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