PRELIMINARY NOTE ON THE METAMORPHIC CONDITIONS AROUND LÜTZOW-HOLM BAY, EAST ANTARCTICA

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Abstract: The metamorphic conditions in the Lützow-Holm Bay region during the main phase of the granulite facies metamorphism (perhaps around 1000 Ma) are preliminarily estimated by the use of experimentally determined mineral breakdown curves and of some geothermometers and geobarometers. Calculated conditions are in the range of 725±25°C and 6.3±1.3 kb. The values suggest that the region has undergone metamorphic conditions similar to Molodezhnaya Station and Prince Charles Mountains, each of which is considered to belong to the zone affected by the granulite facies metamorphism around 1000 Ma. The metamorphic conditions estimated here seem to be compatible also with those in the western part of the Prince Olav Coast.

1. Introduction

The Lützow-Holm Bay region is underlain by various kinds of metamorphic and plutonic rocks. The metamorphites in the region are characterized by the common occurrence of the associations of sillimanite+K-feldspar+biotite±garnet in quartzo-feldspathic gneiss and of orthopyroxene+clinopyroxene±hornblende in metabasite. As stated by BANNO *et al.* (1964) and SUWA (1968), the petrological characters of the metamorphites suggest that the metamorphism around the region must have been graded up to the granulite facies. Recently, the present author (1982) described the association of orthopyroxene+garnet+biotite from the Langhovde and Skarvsnes areas to give the same conclusion stated above. The metamorphic age of the granulite facies metamorphism around the region is considered to be around 1000 Ma (YOSHIDA, 1979).

Meanwhile, in the Prince Olav Coast lying on the northeast of Lützow-Holm Bay, HIROI *et al.* (1982, 1983) clarified through the detailed geological and petrological investigations, that the region could be divided into two zones of A and B. The former zone is characterized by the occurrence of staurolite and Ca-poor amphiboles, while the latter by spinel+garnet+sillimanite and orthopyroxene. Throughout the region sillimanite+relict kyanite association is found. In their opinions, the region has undergone kyanite-sillimanite type metamorphism and is the westwardly progressive metamorphic terrain from the amphibolite facies to the granulite one.

The controversial point is on the time and spatial relationship of metamorphism between Lützow-Holm Bay and the Prince Olav Coast. In this paper, the present author intends to estimate the metamorphic conditions during the main phase of metamorphism in the Lützow-Holm Bay region and to compare them with those in the

Prince Olav Coast. After that, the geological setting of the Lützow-Holm Bay region in East Antarctica will be briefly summarized.

2. Metamorphites in the Lützow-Holm Bay Region

The metamorphic rocks around Lützow-Holm Bay have been investigated in detail during the last two decades. From the Ongul Islands to the Skallen areas (Fig. 1), there occur various kinds of metamorphites. In the Ongul Islands, pyroxene gneiss, garnet gneiss, hornblende gneiss and metabasites are developed (YANAI *et al.*, 1974).

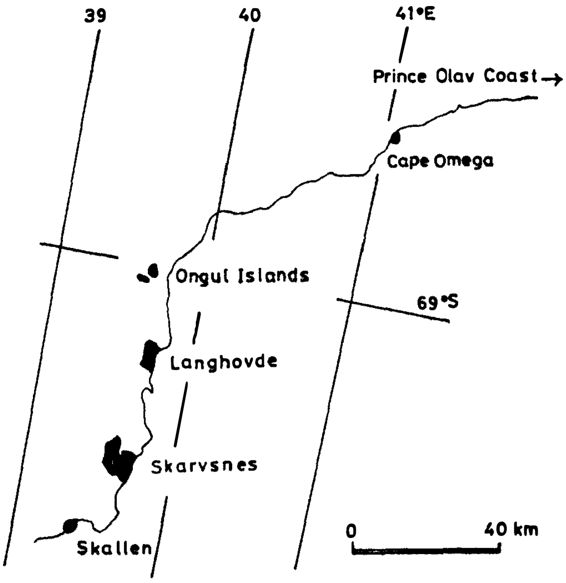

Fig. 1. Location map of the discussed areas in the Lützow-Holm Bay region, East Antarctica.

The associations of garnet + K-feldspar + biotite and orthopyroxene + clinopyroxene are characteristic. In the area from Langhovde and Skarvsnes, the metamorphites are composed mainly of metabasites, hornblende gneiss, marble and paragneiss in close association with charnockitic rocks (MATSUMOTO *et al.*, 1979). The associations of garnet + K-feldspar + biotite and orthopyroxene + clinopyroxene are characteristic. In the area, SUZUKI (1982) found the metamorphites with the association of orthopyroxene + garnet + biotite + plagioclase + K-feldspar + quartz + ilmenite closely associated with garnet-biotite gneiss and/or charnockitic rocks, and concluded that the metamorphic conditions could be lower than those of the typical granulite facies metamorphic terrain of Madras, peninsular India. In the Skallen area, the metamorphites are composed of paragneiss, brown gneiss, metabasite, calcareous gneiss and quartzite closely associated with charnockitic rock (YOSHIDA, 1977). The petrological significance of the associations of garnet + sillimanite + K-feldspar + plagioclase + biotite in a paragneiss and orthopyroxene + clinopyroxene + garnet in metabasites is briefly summarized (SUZUKI and YOSHIDA, 1983).

Generally speaking, from the Ongul Islands to the Skallen area, basic metamorphites are characterized by the association of orthopyroxene + clinopyroxene ± garnet and paragneiss (pelitic and quartzitic metamorphic equivalents) by K-feldspar + garnet + biotite ± sillimanite. Judging from the mineral associations mentioned above, the region as a whole belongs to the granulite facies metamorphic terrain. In the following chapter, the metamorphic conditions in the region will be estimated.

3. Metamorphic Conditions of the Lützow-Holm Bay Region

As stated before, the metamorphic rocks in the Lützow-Holm Bay region show critical associations of garnet + orthopyroxene + biotite + K-feldspar and garnet + biotite + K-feldspar ± sillimanite in paragneisses and of orthopyroxene + clinopyroxene ± garnet ± hornblende in metabasites.

First, the temperature and pressure regime of the Lützow-Holm Bay region will be estimated by the use of experimentally determined mineral breakdown curves in the P-T space. None of the garnet + orthopyroxene + biotite rocks in the Langhovde and Skarvsnes areas and garnet + biotite gneiss in the Skallen area contain primary muscovite, but they contain instead K-feldspar and K-feldspar + sillimanite, respectively. Therefore, the rocks should be plotted on the higher-temperature side of a muscovite breakdown curve in the sillimanite field (Fig. 4). In metabasites, orthopyroxene and clinopyroxene closely associated with hornblende are commonly found. Therefore, the metamorphic conditions in the P-T space should be lying around the appearance of orthopyroxene.

Next, the equilibrium relationship among the main constituent minerals, namely garnet, biotite and pyroxenes, will be tested. The association of garnet and biotite is commonly found in the region concerned. In the Langhovde and Skarvsnes areas are found the rocks with the association of garnet + biotite + orthopyroxene + K-feldspar + plagioclase + quartz + ilmenite, their petrological characteristics having already been given by the present author (1982). The samples from the Skallen area, as stated by SUZUKI and YOSHIDA (1983), are composed mainly of garnet, sillimanite, K-feldspar, plagioclase, quartz, biotite, rutile and ilmenite. As for the sample 69020601, the mineral paragenesis and the chemical compositions of main constituent minerals are given in Tables A-1 and A-2 in Appendix, respectively. The distribution of Mg and Fe between coexisting garnet and biotite pairs is shown in Fig. 2. As easily visualized in the figure, the garnet-biotite pairs are plotted on the line of $K_D = 0.3086$, regardless of the compositional difference of garnet between rim and core parts in each grain. Thus, it can well be said that the pairs of garnet and biotite as a whole are in equilibrium with each other under the same physical conditions throughout the region concerned.

In the same way, the distribution of Mg and Fe between coexisting orthopyroxene and garnet in the samples from the Langhovde, Skarvsnes and Skallen areas is checked (Fig. 3). Samples from the former two areas are just the same as those checked above. Samples from the Skallen area are metabasites with the association of orthopyroxene + clinopyroxene + garnet + plagioclase + quartz + hornblende ± biotite + ilmenite + magnetite (SUZUKI and YOSHIDA, 1983), whose mineral associations are given in Table A-1 in Appendix, and chemical composition of each mineral in Tables A-3 and A-4 in Appendix. Although there exist some exceptional pairs slightly divergent from the line, almost all of the plots are lying on the line of $K_D = 0.2780$. The plots of ortho-

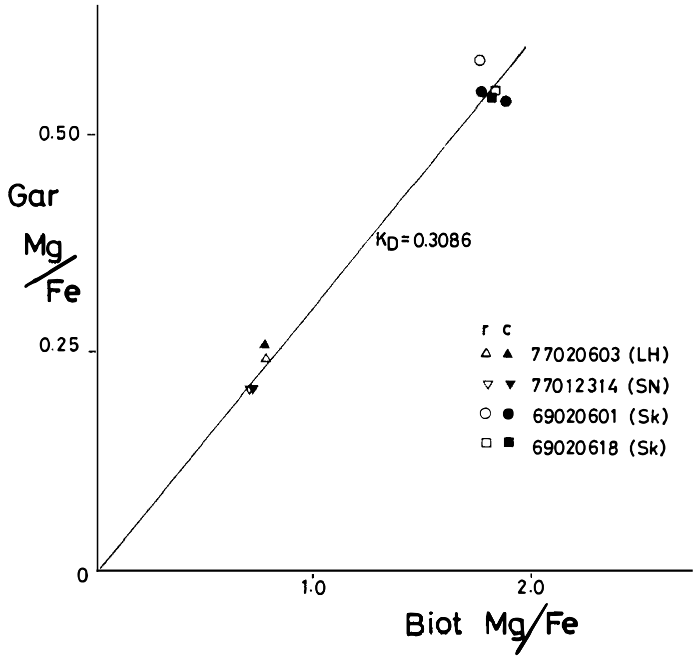

Fig. 2. The distribution of Mg and Fe in coexisting biotite and garnet. Samples from Langhovde (LH) and Skarvsnes (SN) are garnet-biotite-orthopyroxene gneiss (SUZUKI, 1982), and those from Skallen (Sk) are garnet-biotite-sillimanite gneiss (SUZUKI and YOSHIDA, 1983). r and c mean rim and core parts of garnet, respectively.

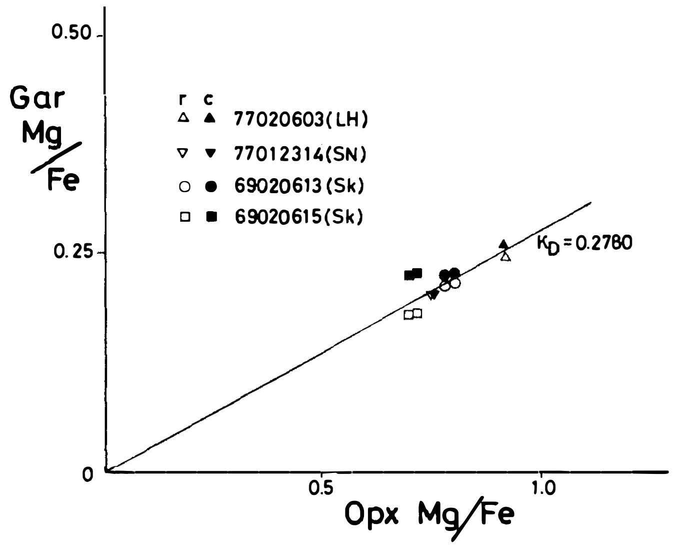

Fig. 3. The distribution of Mg and Fe in coexisting orthopyroxene and ganet. Abbreviations are as in Fig. 2.

pyroxene-clinopyroxene pairs from the Skallen area, although not shown here, are lying on the line of $K_D = 0.6090$.

Judging from the Fe-Mg distribution relationship among the mineral pairs, as in the case of garnet-biotite pairs, orthopyroxene garnet and orthopyroxene clinopyroxene pairs are in equilibrium with each other, respectively. Therefore, the meta-

Table 1. Temperature estimates based on garnet-biotite (THOMPSON, 1976) and pressure estimates based on garnet-orthopyroxene-plagioclase (WELLS, 1979) in the garnet-orthopyroxene-biotite gneiss from Langhovde (LH) and Skarvsnes (SK) areas.

Sample No.	Minerals	X^{Gar}_{Gros}	X^{Gar}_{Alm}	X^{Gar}_{Pyr}	Fe/Mg^{Gar}	Fe/Mg^{Bi}	ln K_D	T °C
77020603	Gar_c-Bi	0.1517	0.6437	0.1658	3.8824	1.2507	1.1328	746
(LH)	Gar_r-Bi	0.1573	0.6420	0.1609	3.9899	1.2507	1.1601	735
77012314 (SK)	Gar_c-Bi	0.1110	0.6918	0.1463	4.7286	1.3347	1.2649	698

Sample No.	Minerals	$X^{Op\ M1}_{Mg}$	$X^{Op\ M2}_{Mg}$	X^{Pl}_{An}	γ^{Gar}_{Gros} *	γ^{Gar}_{Pyr}	γ^{Pl}_{An} **	P kb
77020603	Gar_c-Op-Pl	0.4880	0.4670	0.461	1.1246	1.1113	1.3328	5.3
(LH)	Gar_r-Op-Pl	0.4880	0.4670	0.461	1.1222	1.1188	1.3461	5.2
77012314 (SK)	Gar_c-Op-Pl	0.4430	0.4246	0.310	1.1240	1.0889	1.4594	5.1

* $RT \ln\gamma^{Gar}_{Gros} = W_{Ca\text{-}Mg}X^2_{Mg} + W_{Ca\text{-}Fe}X^2_{Fe} + (W_{Ca\text{-}Mg} + W_{Ca\text{-}Fe} - W_{Mg\text{-}Fe})X_{Mg}X_{Fe}$

** $\gamma^{Pl}_{An} = \frac{(1+X_{An})^2}{4X_{An}} \exp\left\{\frac{(1-X_{An})^2}{RT}(2050+9392\,X_{An})\right\}$

Abbreviations are as follows: Gar; garnet, Bi; biotite, Op; orthopyroxene, Pl; plagioclase, Gros; grossular, Alm; almandine, Pyr; pyrope, An; anorthite, c; core, r; rim.

morphic temperature and pressure can be estimated based upon some geothermometers and geobarometers using the coexisting minerals mentioned above.

Using the samples with the association of orthopyroxene + garnet + biotite from the Langhovde and Skarvsnes areas, metamorphic conditions are estimated (Table 1). The metamorphic temperature is calculated by the use of garnet-biotite geothermometer of an empirical relationship based upon natural occurrence calibrated by the mineralogical data (THOMPSON, 1976). The results are in the range from 698 to 746°C. Pressure is calculated using the geobarometer based upon the reaction of orthopyroxene + anorthite = garnet + quartz (WELLS, 1979). In the calculation, the activity coefficients of grossular and pyrope in garnet (γ_{Gros} and γ_{Pyr}) are calculated with the equation after NEWTON (1978). The interaction parameters (W) of Ca-Mg, Ca-Fe and Fe-Mg and activity coefficient of anorthite in plagioclase (γ_{An}) are calculated following the equation by NEWTON and HASELTON (1981). The results are in the range of 5.1 to 5.3 kb. Although the pressure values calculated here are rather lower than those estimated in the Skallen area shown below, the pressure and temperature conditions are included in the range calculated in the latter area.

Using some metamorphites from the Skallen area, the metamorphic conditions in the area are estimated. In the estimates, activity coefficients of grossular and pyrope in garnet and of anorthite in plagioclase are calculated following the same manner as in the case stated above. Using the paragneiss with the association of garnet + biotite + K-feldspar + sillimanite + plagioclase + quartz, metamorphic temperature is estimated by THOMPSON's method (1976) and pressure by the equilibrium relationship between garnet and plagioclase associated with sillimanite and quartz (GHENT, 1976). As shown in Table 2, the pairs of garnet-core and biotite give the P-T condition in the range of 712–736°C and 6.8–7.6 kb, while those of garnet-rim and biotite give a rather

Table 2. Temperature estimates based on garnet-biotite (THOMPSON, 1976) and pressure estimates based on garnet-plagioclase coexisting with quartz and sillimanite (GHENT, 1976) in the Skallen area (Sample No. 69020601).

Minerals	X_{Gros}^{Gar}	X_{Alm}^{Gar}	X_{Pyr}^{Gar}	Fe/Mg^{Gar}	Fe/Mg^{Bi}	X_{An}^{Pl}	γ_{Gros}^{Gar}	γ_{An}^{Pl}	T °C	P kb
$Gar1_c$-Bi1	—	—	—	1.8299	0.5375	—	—	—	712	—
$Gar1_c$-Pl	0.0306	0.6217	0.3397	—	—	0.227	1.3554	1.3485	—	6.8
$Gar2_c$-Bi2	—	—	—	1.8001	0.5659	—	—	—	736	—
$Gar2_c$-Pl	0.0328	0.6167	0.3426	—	—	0.227	1.3402	1.3082	—	7.6
$Gar2_r$-Bi2	—	—	—	1.6820	0.5659	—	—	—	762	—
$Gar2_r$-Pl	0.0218	0.6089	0.3620	—	—	0.227	1.3480	1.2679	—	6.3

Abbreviations and methods for calculating activity coefficients are as in Table 1.

Table 3. Temperature estimates based on orthopyroxene-clinopyroxene and pressure estimates based on the reaction orthopyroxene+plagioclase=garnet+quartz in the Skallen area.

Sample No.	Pair	X_{Fe}^{Op}	$X_{Mg}^{Op\ M1}$	$X_{Mg}^{Op\ M2}$	$X_{Mg}^{Cp\ M1}$	$X_{Mg}^{Cp\ M2}$	T °C*
69020613	Op1-Cp1	0.5631	0.4510	0.4213	0.5621	0.0524	748
	Op2-Cp2	0.5559	0.4567	0.4282	0.5603	0.0431	727
69020615	Op1-Cp1	0.5849	0.4173	0.3948	0.5412	0.0403	721
	Op2-Cp2	0.5876	0.3998	0.3883	0.5193	0.0510	748

Sample No.	Minerals	X_{Gros}^{Gar}	X_{Alm}^{Gar}	X_{Pyr}^{Gar}	X_{An}^{Pl}	γ_{Gros}^{Gar}	γ_{Pyr}^{Gar}	γ_{An}^{Pl}	P kb**
69020613	Gar_c-Op1-Pl_c	0.1881	0.6305	0.1427	0.661	1.1010	1.1436	1.1011	5.1
	Gar_c-Op2-Pl_c	0.1881	0.6305	0.1427	0.661	1.1051	1.1497	1.1119	5.0
69020615	Gar_c-Op1-Pl_c	0.2670	0.5660	0.1379	0.652	1.0930	1.2259	1.1260	6.8
	Gar_c-Op2-Pl_c	0.2670	0.5660	0.1379	0.652	1.0883	1.2139	1.1112	7.0

* Calculated after the method by WOOD and BANNO (1973), subtracting 50°C.
** Calculated after the method by WELLS (1979).
Methods for calculating activity coefficients and abbreviations are same as in Table 1, except Cp; clinopyroxene.

higher temperature and lower pressure condition. Although the significance of small difference between the values estimated from the compositions of core and rim parts of garnet has not yet been clarified, the estimated conditions as a whole appear to be consistent with the stable occurrence of sillimanite and K-feldspar in the sample.

Using the stable association of orthopyroxene+clinopyroxene+garnet+plagioclase in metabasites from the Skallen area, metamorphic conditions in the area are calculated as shown in Table 3. The temperature is obtained from the empirical relationship of the Fe/Mg ratio of orthopyroxene and clinopyroxene pair (WOOD and BANNO, 1973). As stated by WOOD (1975), the calculation probably includes the overestimation in the order of 50°C. Thus, in the table the values show the results after the subtraction. Pressure is calculated with the method of WELLS (1979). The temperature is ranging from 721 to 748°C, which are fairly consistent with that estimated from the biotite-garnet pairs in paragneiss. The pressure condition is ranging from 5.0 to 7.0 kb in the calculation using the compositions of garnet-core. Although not shown in the table, the compositions of rim part in garnet and plagioclase give the pressure values in the range of 4.2 to 4.5 kb. Although the significance of the values is not so plausible, because the calculation is based upon the same temperature values as in the case of garnet-core, the relatively lower value of pressure in the rim part of garnet may be noteworthy.

All points considered, the metamorphic conditions in the Skallen area during the main phase of the granulite facies metamorphism seem to be graded up to 725 ± 25°C and 6.3 ± 1.3 kb. The values include those estimated in the areas of Langhovde and Skarvsnes shown before. There seem to exist no evidences to suggest any systematic thermal gradient in the areas.

The petrogenetic grid shown in Fig. 4 is, thus, based upon the geothermometric and geobarometric calculations and upon mineral stability relationship. Shaded area in Fig. 4 gives the inferred field of pressure and temperature during the main phase of the granulite facies metamorphism in the Lützow-Holm Bay region. In the figure the metamorphic conditions in peninsular India, Molodezhnaya Station and the Napier complex in the Enderby Land are also shown for reference. As can be seen in the figure, the metamorphic condition in the Lützow-Holm Bay region is lower graded than those in the older granulite facies terrains of peninsular India and the Enderby Land.

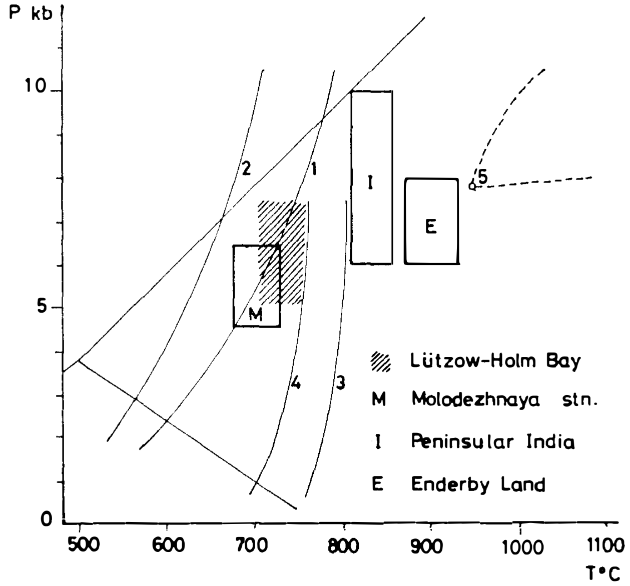

Fig. 4. Pressure and temperature conditions of the Lützow-Holm Bay region compared with some of the other granulite facies metamorphic terrains. Sources of data: Al_2SiO_5 stability fields (HOLDAWAY, 1971); Metamorphic conditions of Enderby Land, Molodezhnaya Station and Peninsular India (GREW, 1980, 1981 and 1982, respectively); 1. Muscovite+quartz=K-feldspar+Al_2SiO_5+H_2O, $X_{H_2O}=1.0$ (KERRICK, 1972); 2. Same as 1, except $X_{H_2O}=0.5$; 3. Hornblende+quartz=hornblende+orthopyroxene+clinopyroxene+plagioclase, $X_{H_2O}=1.0$ (BINNS, 1969); 4. Same as 3 except $X_{H_2O}=0.3$; 5. Invariant point sapphirine+orthopyroxene+sillimanite+cordierite+quartz (NEWTON et al., 1974).

4. Discussions

Petrological studies on the metamorphic rocks in East Antarctica have been accumulated in the last two decades. In this section, the metamorphic condition in the Lützow-Holm Bay region estimated above will be compared with those in the other parts of East Antarctica.

In the Prince Olav Coast lying on the northeast of Lützow-Holm Bay, YOSHIKURA *et al.* (1979) and KANISAWA and YANAI (1982) have concluded that the metamorphic condition was in the range of 600 to 650°C and 5 kb. HIROI *et al.* (1982, 1983), however, stated that the area could be considered to be a progressive metamorphic terrain from the amphibolite facies to the granulite one, belonging to the kyanite-sillimanite type facies series. In their opinion, the metamorphic grade seems to be graded up towards the Lützow-Holm Bay region. In this connection, it must be noted that the associations of orthopyroxene + garnet + K-feldspar and sillimanite + K-feldspar are sometimes found in biotite gneiss in the Cape Omega area, just on the east of Lützow-Holm Bay (SUZUKI, in preparation). Therefore, it can well be said that the highest grade inferred in the western part of the Prince Olav Coast seems to be compatible with that estimated here in Lützow-Holm Bay and that the metamorphic grade is increasing progressively from the Prince Olav Coast towards Lützow-Holm Bay.

In the easternmost part of the Prince Olav Coast, where Molodezhnaya Station is situated, metamorphites have been investigated in detail by GREW (1981). According to him, paragneiss is characterized by the mineral associations (all with quartz, K-feldspar and plagioclase) of garnet + biotite + sillimanite ± cordierite and orthopyroxene + garnet + biotite. Estimated temperature and pressure conditions during the main phase of the granulite facies metamorphism around 1000 Ma in the area are around 700 ± 30°C and 5.5 ± 1.1 kb. The conditions are quite similar to those estimated here in the Lützow-Holm Bay region, but are rather lower in pressure (Fig. 4).

The problem is the time and spatial relationship of metamorphism in the region from Lützow-Holm Bay to the Prince Olav Coast and in Molodezhnaya Station. As stated before, the metamorphic grade of the former region seems to be progressively graded up to the west, therefore, it cannot be inferred that the metamorphic grade has progressively increased from the eastern part of the Prince Olav Coast towards Molodezhnaya Station. As stated by HIROI *et al.* (1982, 1983), metamorphites in Molodezhnaya Station belong to the Rayner complex and seem to have been "retrogressively" broken down from the higher graded Archaean complex. In any way, it must be noted that the metamorphic conditions of Molodezhnaya Station and the highest of those in the Lützow-Holm Bay region are similar to each other.

TINGEY (1982) summarized the geological evolution of the Prince Charles Mountains to give the result that the area has undergone the amphibolite to the granulite facies metamorphism during the age of 800 to 1100 Ma. According to him, in the northern area the metamorphic grade is higher and the pelitic rocks contain sillimanite, while in the southern area the retrograde association of staurolite and kyanite is observed. The contrast of the two areas and the metamorphic grade in each area seem to be quite similar to those observed between Lützow-Holm Bay and the Prince Olav Coast.

In the Windmill Islands, BLIGHT and OLIVER (1982) clarified that the metamorphic assemblages of the highest grade are characterized by biotite + garnet + sillimanite + cordierite and orthopyroxene + clinopyroxene + garnet. The estimated conditions are around 760°C and 5.5 to 6.5 kb, quite similar to those of the Molodezhnaya Station area, though the metamorphic age may be rather older.

All things considered, the zone in East Antarctica affected by the metamorphism around 1000 Ma seems to extend from Lützow-Holm Bay through the Rayner complex in the Enderby Land to the Prince Charles Mountains. The zone may extend farther to the Windmill Islands. The metamorphic conditions in the areas are rather similar to each other. However, it must be noted that among the areas Lützow-Holm Bay is rather singular, because there occurs no cordierite in contrast to the ubiquitous occurrence of the mineral in the other areas. It can be considered that the Lützow-Holm Bay region has suffered by rather higher pressure condition than the other area of the zone mentioned above.

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Appendix

Among the metamorphites now discussed, those from the Langhoved and Skarvsnes areas have already been described by the present author (1982). Thus, the mineral associations and the chemical compositions of the main constituent minerals of metamorphites from the Skallen area will be given here.

Table A-1. Mineral assemblages of rocks in discussion, from the Skallen area, Lützow-Holm Bay.

Sample No.	Gt	Bi	Opx	Cpx	Hb	Sil	Q	Kf	Pl	Il	Mt	Rt
69020601	1,2,3	4,5	—	—	—	+	+	+	6	+	—	+
69020613	7,8	—	9,10	11,12	13	—	+	—	+	+	+	—
69020615	14,15	+	16,17	18,19	+	—	+	—	20	+	+	—

This table shows the mineral assemblages of rocks discussed in the text. The numbers in the table refer to the numbers in Tables A-2, A-3 and A-4, where the compositions of minerals are given. The symbols of plus and bar mean present and absent, respectively. Abbreviations of minerals are as follows: Gt; garnet, Bi; biotite, Opx; orthopyroxene, Cpx; clinopyroxene, Hb; hornblende, Sil; sillimanite, Q; quartz, Kf; K feldspar, Pl; plagioclase, Il; ilmenite, Mt; magnetite, Rt; rutile.

Table A-2. Chemical compositions of the main constituent minerals in the sample 69020601 from the Skallen area.

	1 Gt-1c	2 Gt-2r	3 Gt-2c	4 Bi-1	5 Bi-2	6 Pl
SiO_2	39.4	38.3	38.3	36.8	35.4	61.5
TiO_2	0.07	0.04	0.05	6.90	3.60	0.03
Al_2O_3	21.6	21.5	22.0	15.5	15.7	23.2
FeO*	28.9	28.5	29.0	13.2	14.8	0.03
MnO	0.37	0.34	0.36	0.09	0.11	0.01
MgO	8.87	9.50	9.03	13.8	14.7	0.01
CaO	1.11	0.79	1.20	tr.	0.01	4.71
Na_2O	tr.	tr.	tr.	0.14	0.12	8.89
K_2O	0.02	0.02	0.02	9.37	9.51	0.14
Total	100.34	98.99	99.96	95.80	93.95	98.52
			Numbers of ions			
O	24.000	24.000	24.000	22.000	22.000	32.000
Si	6.059	5.977	5.941	5.426	5.391	11.069
Ti	0.008	0.005	0.006	0.766	0.412	0.004
Al	3.918	3.953	4.012	2.700	2.815	4.914
Fe	3.722	3.716	3.755	1.627	1.885	0.005
Mn	0.048	0.045	0.048	0.011	0.015	0.002
Mg	2.034	2.209	2.086	3.027	3.331	0.003
Ca	0.183	0.133	0.200	—	0.002	0.909
Na	—	—	—	0.041	0.036	3.101
K	0.003	0.005	0.003	1.763	1.845	0.031

1: Garnet-1 core, 2: Garnet-2 rim, 3: Garnet-2 core, 4: Biotite 1, 5: Biotite-2, 6: Plagioclase.
* Total Fe as FeO.

Table A-3. Chemical compositions of the main constituent minerals in the sample 69020613 from the Skallen area.

	7 Gt-r	8 Gt-c	9 Opx-1	10 Opx-2	11 Cpx-1	12 Cpx-2	13 Hb
SiO_2	37.7	36.8	48.7	48.9	49.3	50.0	38.8
TiO_2	0.15	0.11	0.18	0.18	0.34	0.35	2.39
Al_2O_3	21.0	21.1	0.95	0.81	2.23	2.44	11.9
FeO*	29.8	29.7	33.9	33.4	15.1	14.6	21.5
MnO	1.85	1.80	0.90	0.87	0.44	0.43	0.25
MgO	3.73	3.77	14.8	15.0	10.6	10.6	7.35
CaO	6.93	6.92	0.86	0.77	21.4	22.1	11.4
Na_2O	0.02	0.03	0.03	0.03	0.38	0.36	1.12
K_2O	0.02	0.03	0.03	0.03	0.03	0.02	2.30
Total	101.20	100.26	100.35	99.99	99.82	100.90	97.01
				Numbers of ions			
O	24.000	24.000	6.000	6.000	6.000	6.000	23.000
Si	5.942	5.871	1.929	1.938	1.907	1.907	6.109
Ti	0.018	0.013	0.005	0.005	0.010	0.010	0.283
Al	3.901	3.959	0.045	0.038	0.102	0.110	2.203
Fe	3.931	3.963	1.124	1.108	0.489	0.466	2.829
Mn	0.246	0.243	0.030	0.029	0.014	0.014	0.034
Mg	0.876	0.897	0.872	0.885	0.609	0.604	1.724
Ca	1.171	1.182	0.036	0.033	0.885	0.904	1.923
Na	0.006	0.010	0.002	0.002	0.029	0.026	0.342
K	0.004	0.006	0.001	0.001	0.001	0.001	0.461

7: Garnet rim, 8: Garnet core, 9: Orthopyroxene-1, 10: Orthopyroxene-2, 11: Clinopyroxene-1, 12: Clinopyroxene-2, 13: Hornblende.
* Total Fe as FeO.

Table A-4. Chemical compositions of main constituent minerals in the sample 69020615 from the Skallen area.

	14 Gt-r	15 Gt-c	16 Opx-1	17 Opx-2	18 Cpx-1	19 Cpx-2	20 Pl
SiO_2	38.2	38.4	48.8	50.0	49.7	51.6	47.1
TiO_2	0.08	0.11	0.12	0.09	0.33	0.30	0.01
Al_2O_3	20.1	20.4	1.06	1.13	2.21	2.08	33.3
FeO*	29.4	26.7	34.2	34.1	14.8	14.7	0.33
MnO	1.97	1.36	0.79	0.80	0.43	0.38	0.06
MgO	3.05	3.65	13.6	13.4	10.1	10.1	0.01
CaO	7.42	9.83	0.74	0.68	21.8	21.4	17.2
Na_2O	0.02	tr.	0.01	tr.	0.37	0.33	1.82
K_2O	0.01	0.01	0.02	0.02	0.01	0.01	0.07
Total	100.25	100.46	99.34	100.22	99.75	100.90	99.90
				Numbers of ions			
O	24.000	24.000	6.000	6.000	6.000	6.000	32.000
Si	6.081	6.044	1.952	1.973	1.920	1.956	8.672
Ti	0.010	0.013	0.004	0.003	0.009	0.008	0.001
Al	3.764	3.783	0.050	0.052	0.101	0.093	7.238
Fe	3.913	3.514	1.144	1.124	0.480	0.465	0.051
Mn	0.266	0.181	0.027	0.027	0.014	0.012	0.009
Mg	0.723	0.856	0.812	0.789	0.581	0.570	0.002
Ca	1.266	1.658	0.032	0.029	0.901	0.871	3.402
Na	0.007	—	0.001	—	0.028	0.024	0.650
K	0.001	0.001	0.001	0.001	0.001	0.001	0.017

14: Garnet rim, 15: Garnet core, 16: Orthopyroxene-1, 17: Orthopyroxene-2, 18: Clinopyroxene-1, 19: Clinopyroxene-2, 20: Plagioclase.
* Total Fe as FeO.