

ARCHEAN GRANULITES FROM MT. RIISER-LARSEN IN ENDERBY LAND, EAST ANTARCTICA

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Abstract: Mt. Riiser-Larsen in Enderby Land, which is a part of the Napier Complex in the East Antarctic Shield, is underlain by the Archean granulites formed under the pyroxene granulite-facies condition. Characteristic mineral associations of sapphirine+quartz, orthopyroxene+sillimanite+quartz and garnet+sillimanite+quartz, all of which are breakdown products after cordierite, have coexisted stably at the peak of metamorphism. The variety of these mineral associations would be largely attributed to the chemical compositions of the rocks, namely the Mg/Fe ratio.

On the basis of the phase relations determined experimentally and/or theoretically, and with the use of geothermometers and geobarometers, the P - T conditions at the peak of metamorphism are estimated to have been around 900°C, 8–10 kbars. On the other hand, P_{H_2O} must have been considerably lower than P_{Total} , which is suggested by the absence of migmatitic facies and hydrous phases in the mineral assemblages.

1. Introduction

The Amundsen Bay region of Enderby Land, East Antarctica, is geologically referred to as the Napier Complex, which is underlain by the extremely old granulites with unique mineral associations.

In this decade, the region has received much attention from the geological interests on the following two subjects;

(1) Geochronology: Since the first geochronological data of 4.0 ± 0.2 Ga using Pb-Pb and U-Pb methods by SOBOTOVICH *et al.* (1976), many geologists have investigated the granulites of the Napier Complex from the geochronological point of view. However, GREW and MANTON (1979) dissented from the data of SOBOTOVICH *et al.* (1976) on ambiguities in drawing an isochron. Instead, they proposed an age of 2.5 Ga for charnockitic pegmatite which may be coeval with the last stage metamorphism. Since then, the age of 2.5 Ga has been accepted as the most reliable one dating the last stage metamorphic event. Recently, BLACK and JAMES (1979) and

BLACK *et al.* (1983) have reported ages of 3.7–3.8 Ga with the use of zircon by an ionic microprobe analysis, and considered this value as indicating the initial crustal formation. For reference, the surrounding geological terrains including the Rayner Complex, Prince Olav Coast and Lützow-Holm Bay regions are underlain by much younger rocks which have been dated to be around 0.5–1.1 Ga (GREW and MANTON, 1979; SAITO and SATO, 1964; TINGEY, 1982; YANAI and UEDA, 1974).

(2) Mineralogy: During the 1950s to 1960s, many Australian geologists have vigorously visited this region and the first natural association of sapphire+quartz was reported (DALLWITZ, 1968). After that, osumilite was discovered as an additional phase in the sapphire-quartz granulite over many localities in the Napier Complex (*e.g.* SHERATON *et al.*, 1980; GREW, 1980, 1982). These mineral associations are quite unique in the Antarctic granulites and can serve as useful indicators for considering the metamorphic conditions of the Napier Complex.

In this paper, the authors will present the petrographical and mineralogical characteristics of the granulites from Mt. Riiser-Larsen in the Amundsen Bay region of Enderby Land, and discuss the metamorphic conditions based on the data obtained through the geological program of the 23rd Japanese Antarctic Research Expedition (JARE-23) in 1982.

2. Regional Geologic Setting

The Napier Complex occupies the northeastern part of Enderby Land including the region around Casey Bay, Amundsen Bay and Cape Ann (Fig. 1). This area is referred to as Tula Mountains which consist of many nunataks separated by ground glaciers.

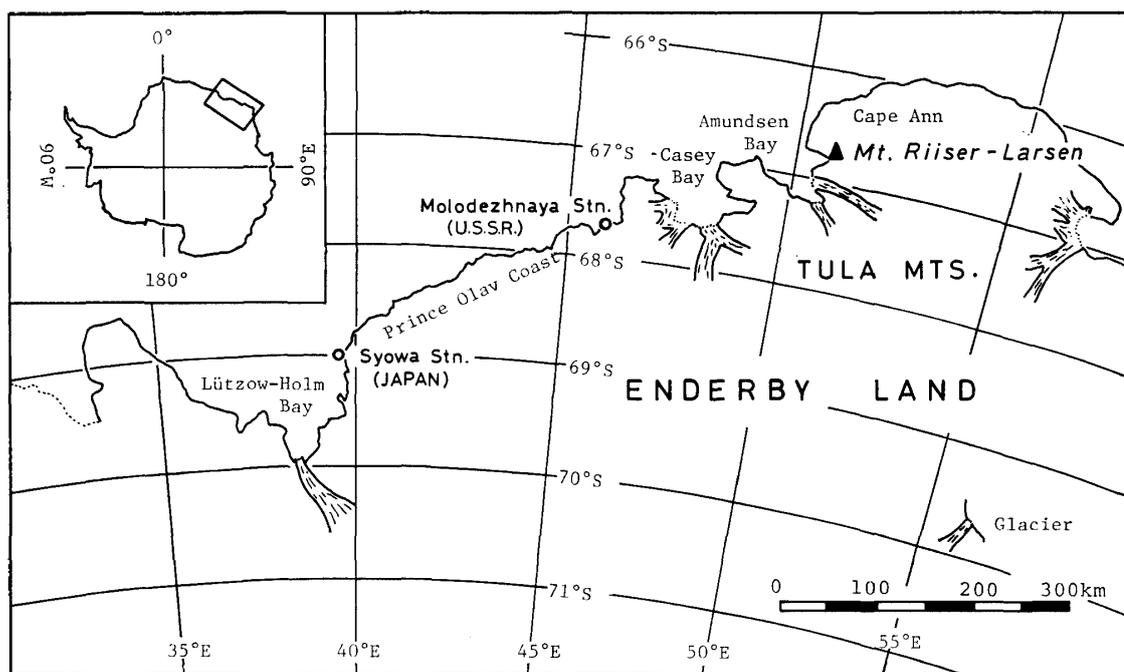


Fig. 1. Locality map of Mt. Riiser-Larsen and the surrounding areas.

Geology of this area has recently been revealed in contrast with that of the adjacent Rayner Complex (Fig. 2).

KAMENEV (1972), RAVICH and KAMENEV (1975) gave the geological and petrographical summaries with mineral assemblages and optical data of minerals from the Napier Complex. On the basis of the geochronological and petrographical data, they defined the Napier Complex as "the highest temperature and most deep-seated parageneses of the granulite facies and are the oldest in the crystalline basement" (RAVICH and KAMENEV, 1975), and estimated the metamorphic condition at 840–1267°C, 9.8–11.6 kbars from the garnet-hypersthene-clinopyroxene mineral association.

SHERATON *et al.* (1980) summarized the petrography of this area and distinguished two major geologic units—the Archean Napier Complex and the Proterozoic Rayner Complex. The former is composed mainly of felsic gneisses, mafic rocks and metapelites which are composed predominantly of unhydrous minerals such as sapphirine, orthopyroxene, garnet, feldspar and quartz. These rocks are estimated by them to have been metamorphosed at least at 950°C and pressures of 8–10 kbars. On the contrary, hydrous phases such as hornblende and/or biotite appear in the rocks from the Rayner Complex and the gneisses are occasionally migmatitic. This is probably

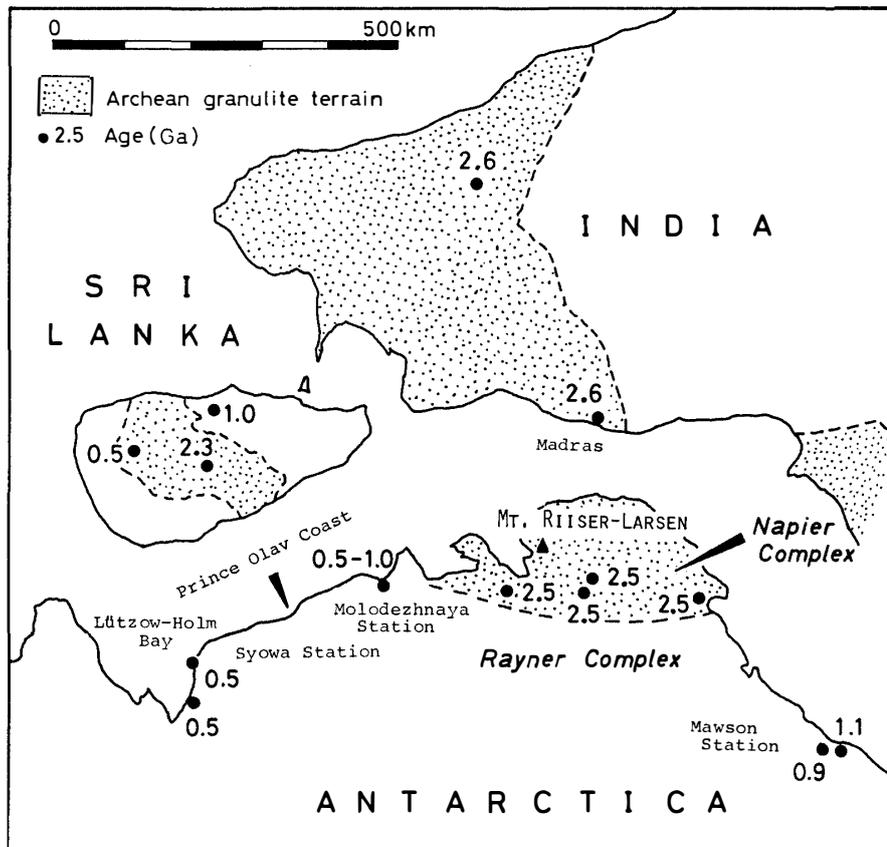


Fig. 2. Distribution of Archean granulites and geochronological data for the Napier Complex and the surrounding areas including Peninsular India and Sri Lanka as counterparts of Antarctica in the reconstruction of Gondwanaland (after GREW and MANTON, 1979).

reflecting the difference in P_{H_2O} as well as the metamorphic conditions. Although the geological boundary between these two complexes has not been revealed, the present geological and petrographical observations led them to the conclusion that the Rayner Complex is a part of the re-metamorphosed Archean Napier Complex in Proterozoic, about 0.8–1.1 Ga ago.

With respect to the reconstruction of Gondwanaland, the following speculations are proposed; that the Napier Complex is correlated with the granulite-facies terrain of Peninsular India and the Highland series of Sri Lanka (BARRON *et al.*, 1978), while the Rayner Complex is considered to be a continuation of the Vijayan series of Sri Lanka (CRAWFORD and OLIVER, 1969). These geological relations are schematically illustrated in Fig. 2.

3. Petrography and Mineralogy

Mt. Riiser-Larsen, a lofty peak at a height of about 800 m, is situated on the northeastern coast of Amundsen Bay in Enderby Land (Fig. 1), and consists of several steep ridges. The photograph of Mt. Riiser-Larsen is shown in Fig. 3. The metamorphic rocks concerned in this paper were all collected from this mountain.

The metamorphic rocks from Mt. Riiser-Larsen are classified into several types mainly based on the mineral assemblages as summarized in Table 1. These rocks generally lack distinct foliation, but a well-layered sequence of stratiform due to the difference of lithofacies is occasionally preserved, indicating that these rocks were mostly of sedimentary origin. Each rock type summarized in Table 1 almost corresponds to the layered sequence at an outcrop, but among them, mafic granulites which

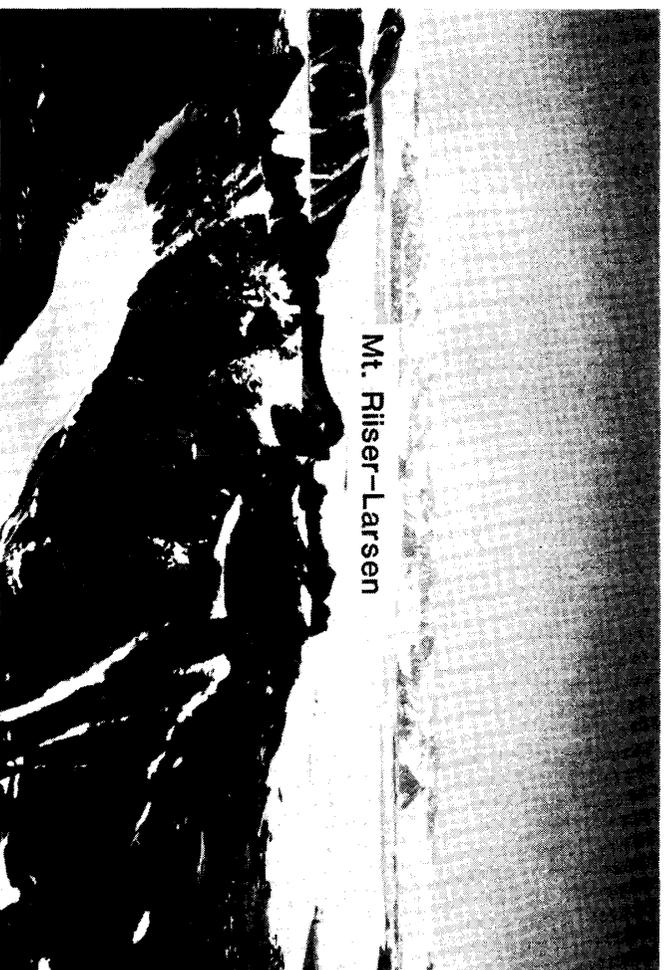


Fig. 3. Mt. Riiser-Larsen and unnamed nunataks in Enderby Land. Note the partly recognized layered sequence of stratiform on the surface of the mountain body.

Table 1. Mineral assemblages observed in the granulites from Mt. Riiser-Larsen.

I. Sapphirine granulite	III. Enderbite
1. Sa-Qz	1. Opx-Pl-Ilm-Qz
2. Sa-Opx-Qz-Pl-Kf	IV. Mafic granulite
3. Sa-Opx-Sill-Qz	1. Cpx-Opx-Pl
4. Sa-Opx-Gar	2. Opx-(Pl)
5. Sa-Os-Cord-Kf	V. Quartzite
6. Sa-Os-Cord-Kf-Opx	1. Sp-Qz
II. Garnet-sillimanite rock	2. Gar-Qz
1. Gar-Sill-Qz	
2. Gar-Sill-Kf-Qz	
3. Gar-Sill-Pl-Qz	
4. Gar-Sill-Opx-(Sa)	

Abbreviations Sa: Sapphirine, Qz: Quartz, Opx: Orthopyroxene, Sill: Sillimanite, Gar: Garnet, Cord: Cordierite, Os: Osumilite, Kf: K-feldspar, Pl: Plagioclase, Ilm: Ilmenite, Cpx: Clinopyroxene, Sp: Spinel.

(Mineral assemblage described in Tables 2 to 8 are based on this table.)

are composed mainly of pyroxene occur as dykes or in a lenticular form. They are possibly of igneous origin judging from the mode of occurrence and the chemical compositions of the constituent minerals as will be stated later. The occurrence of migmatite or anatectic facies, however, has been scarcely observed as far as we surveyed. This evidence probably reflects considerably low P_{H_2O} during the metamorphism in spite of the presence of high-temperature assemblages such as sapphirine+quartz.

Mineral analyses in this paper were all performed by EPMA using JEOL JCSA-733 at the National Institute of Polar Research. Specimen current was kept at about 0.02 microampere and accelerating voltage at 15 kV. Synthesized pure oxides and natural minerals were used for standards, with intensity data having been adjusted to BENCE and ALBEE'S (1968) correction method.

3.1. Sapphirine granulite

This rock is characterized by the occurrence of sapphirine in the mineral assemblages. Other constituent minerals are orthopyroxene, sillimanite, garnet, quartz, plagioclase and K-feldspar. Osumilite is discovered as an additional phase, but its mode of occurrence is different from those of other minerals as will be described later.

Sapphirine is distributed randomly in rocks; in some cases it occupies one "domain" as a symplectitic form or it develops as a seam in a thin section, and occasionally it occurs as independent idiomorphic crystals up to a few centimeters in length. Sapphirine is pleochroic from light blue to clear blue with low birefringence. The most remarkable feature is that sapphirine is commonly in direct contact with quartz. As is presented in Fig. 5a, aggregates of sapphirine and quartz often occupy one "domain" in which the optical orientation of all sapphirine grains is coincident to each other. The "domain" is estimated to be chemically equivalent to cordierite.

Representative EPMA analyses of sapphirine are presented in Table 2, and

Table 2. Representative EPMA analyses of sapphireine.

Specimen No. Mineral assemblage Analysis No.	AM-Y-01 I-1 12	AM-Y-03 I-2 46	AM-I-01 I-4 30	AM-Y-10 II-4 23
SiO ₂	13.38	13.41	14.25	13.42
Al ₂ O ₃	61.64	51.55	61.09	62.27
Cr ₂ O ₃	—	.01	—	—
FeO*	5.54	5.66	6.82	6.72
MnO	—	.02	.01	—
MgO	18.14	18.01	17.73	17.14
CaO	.03	—	.02	—
Na ₂ O	.01	.03	—	—
Total	98.74	98.69	99.92	99.55
On the basis of 20 oxygens				
Si	1.597	1.602	1.688	1.596
Al (IV)	4.403	4.398	4.312	4.404
Al (VI)	4.269	4.273	4.241	4.320
Cr	—	.001	—	—
Fe ^{3+***}	.134	.124	.091	.084
Fe ²⁺	.419	.442	.585	.584
Mn	—	.002	.001	—
Mg	3.229	3.209	3.132	2.734
Ca	.003	—	.002	—
Na	.001	.007	—	—
Mg/(Fe ²⁺ + Mg)	.885	.879	.843	.824

* Total Fe as FeO. ** Calculated after HIGGINS *et al.* (1979).

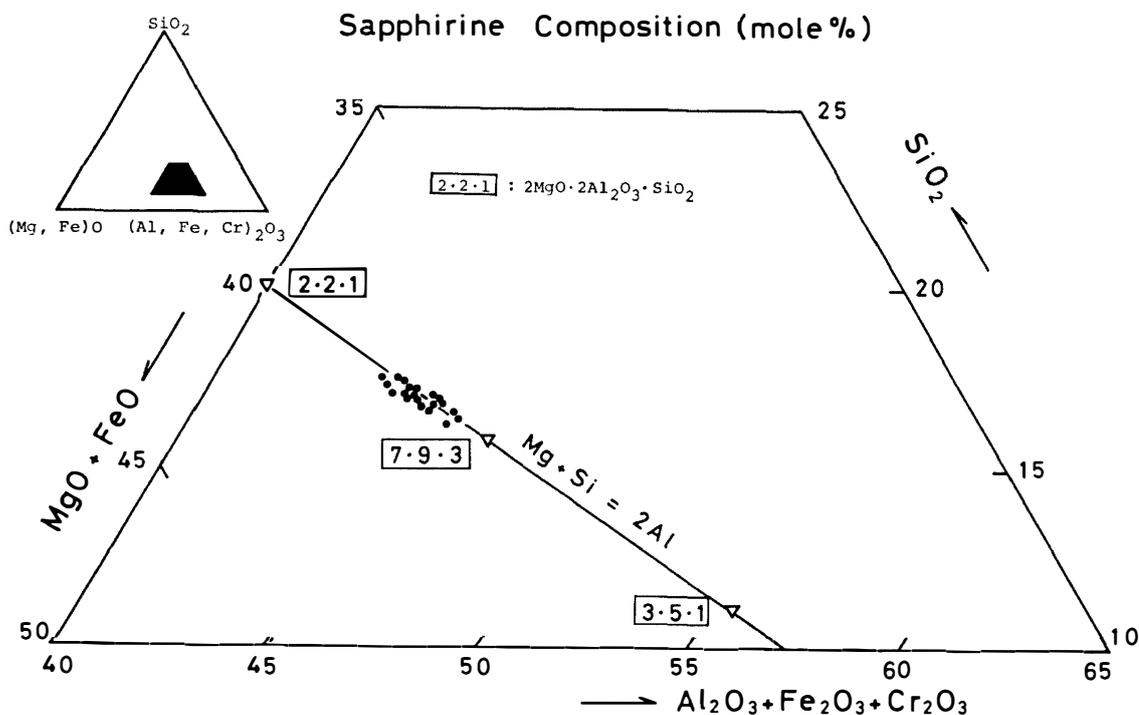


Fig. 4. Compositions of sapphireine from Mt. R iser-Larsen on the SiO₂-(FeO + MgO)-(Al₂O₃ + Fe₂O₃ + Cr₂O₃) diagram. Calculation of Fe³⁺/Fe²⁺ ratio is after HIGGINS *et al.* (1979).

Table 3. Representative EPMA analyses of pyroxene.

Specimen No. Mineral assemblage Analysis No.	AM-Y-01	AM-Y-03	AM-I-01	AM-Y-10	AM-216-09	AM-216-04		AM-216-06
	I-2	I-2	I-4	II-4	III-1	IV-1		IV-2
	13	53	12	4	52	31 (Cpx)	43 (Opx)	16
SiO ₂	48.83	49.18	49.52	53.16	50.64	50.42	54.64	51.52
TiO ₂	.36	.07	.14	.06	—	.27	.06	.01
Al ₂ O ₃	10.65	10.63	9.19	3.75	2.54	3.48	2.27	2.27
Cr ₂ O ₃	.05	—	—	.07	.16	.87	.63	.14
FeO	12.92	12.56	14.24	15.99	26.17	3.08	9.01	23.66
MnO	.10	.13	.10	.04	.53	.23	.27	.24
MgO	26.98	26.89	26.12	26.05	18.83	16.15	31.81	21.47
CaO	.05	.06	.05	.13	.83	23.28	.27	.40
Na ₂ O	.03	.02	.03	.01	—	.34	—	.04
K ₂ O	—	—	—	—	.01	—	—	—
Total	99.97	99.54	99.39	99.26	99.71	98.12	98.96	99.75
On the basis of 6 oxygens								
Si	1.714	1.756	1.785	1.927	1.932	1.883	1.931	1.936
Al (IV)	.259	.244	.215	.073	.068	.117	.069	.064
Al (VI)	.188	.203	.175	.087	.046	.036	.025	.036
Ti	.010	.002	.004	.002	—	.007	.002	—
Cr	.001	—	—	.002	.005	.026	.018	.004
Fe	.385	.375	.429	.485	.835	.096	.266	.743
Mn	.003	.004	.003	.001	.017	.007	.008	.008
Mg	1.434	1.431	1.403	1.408	1.071	.899	1.675	1.202
Ca	.002	.002	.002	.005	.034	.931	.010	.016
Na	.002	.001	.002	.001	—	.025	—	.003
K	—	—	—	—	—	—	—	—
Mg/(Fe+Mg)	.788	.792	.766	.744	.562	.904	.863	.618

Granulites from Mt. Riiser-Larsen in Enderby Land

their compositions with respect to the SiO_2 –($\text{FeO} + \text{MgO}$)–($\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 + \text{Cr}_2\text{O}_3$) ratios are plotted in Fig. 4.

The mode of occurrence of orthopyroxene associated with sapphirine is presented in Fig. 5b, and the chemical compositions are listed in Table 3. The high Al_2O_3 content (around 10 wt% in average) and low CaO content are characteristics of the orthopyroxene in the sapphirine granulite (Analysis Nos. 13, 53 and 12 in Table 3). Orthopyroxene is partly replaced by phlogopite which is probably developed due to hydration along with the cooling of these rocks.

Osumilite is one of the key minerals in the granulites from Mt. Riiser-Larsen. It is commonly found in the sapphirine granulite, and is pleochroic from colorless to faint yellow. It should be noted that osumilite is always surrounded by symplectitic intergrowth of cordierite, K-feldspar and dendritic orthopyroxene (Figs. 5c and 6a), which separate osumilite from sapphirine, orthopyroxene and other constituent minerals. ELLIS *et al.* (1980) stated that the osumilite with such symplectite might be a relic mineral. Chemical compositions of osumilite are listed in Table 4. Their $\text{Mg}/(\text{Fe} + \text{Mg})$ ratios are exceedingly high and the occurrence of osumilite is considered to be restricted in rocks with a relatively high Mg/Fe ratio judging from the compositions of the other constituent minerals. The stability of osumilite under the granulite facies condition will be discussed in a separate paper.

Plagioclase and K-feldspar are recognized as independent grains. They are associated with other constituent minerals except for osumilite. Plagioclase is gen-

Table 4. Representative EPMA analyses of osumilite.

Specimen No. Mineral assemblage Analysis No.	AM-Y-01 1-6 25	AM-Y-03 1-6 81	AM-216-10 1-6 53
SiO_2	61.09	61.36	61.33
TiO_2	.45	.14	.02
Al_2O_3	22.68	22.96	23.03
FeO	1.35	1.35	2.03
MnO	—	.01	.09
MgO	8.78	8.33	8.13
CaO	.03	—	.01
Na_2O	.20	.17	.46
K_2O	4.43	4.51	4.26
Total	99.01	98.83	99.36
On the basis of 30 oxygens			
Si	10.170	10.219	10.192
Ti	.057	.017	.002
Al	4.450	4.506	4.511
Fe	.187	.187	.282
Mn	—	.002	.013
Mg	2.178	2.069	2.014
Ca	.005	—	.002
Na	.065	.054	.147
K	.941	.959	.904
$\text{Mg}/(\text{Fe} + \text{Mg})$.921	.917	.877

erally sodic with the Ab content around 80 to 88 (Analysis No. 92 in Table 7). K-feldspar is characterized by microperthite. The modal composition of feldspars is about 30 to 40% by visual estimation.

3.2. Garnet-sillimanite rock

This rock is characterized by the association of garnet and sillimanite. These two minerals are closely associated with each other as shown in Fig. 6b, or sillimanite is occasionally included in garnet (Fig. 6c), suggesting stable coexistence. Other constituent minerals are quartz, plagioclase and K-feldspar. EPMA analyses of garnet and sillimanite are listed in Tables 5 and 6, respectively.

Garnet, which is pinkish in hand specimen, is enriched in pyrope up to 56 mole%. Both spessartine and grossular components are extremely low.

Sillimanite occurs as idiomorphic crystals and the single cleavage in stout prisms is characteristic. The compositions of these sillimanites are stoichiometric $(Al, Fe^{3+})_2 SiO_5$. The Fe_2O_3 content ranges from 0.06 to 0.24 wt% (Analysis Nos. 21

Table 5. Representative EPMA analyses of garnet.

Specimen No. Mineral assemblage Analysis No.	AM-I-01 I-4 21	AM-Y-07 II-1 4	AM-Y-10 II-4 14	AM-216-02 V-2 83
SiO ₂	40.16	39.62	40.08	38.99
TiO ₂	—	.02	.07	—
Al ₂ O ₃	22.69	22.46	22.92	22.13
Cr ₂ O ₃	.01	—	—	.03
FeO	19.90	22.14	20.30	26.90
MnO	.25	.51	.21	.29
MgO	15.56	14.07	14.71	10.18
CaO	1.04	.79	1.32	1.34
Na ₂ O	.01	.03	.01	—
K ₂ O	—	—	.01	.01
Total	99.62	99.64	99.63	99.77
On the basis of 12 oxygens				
Si	2.982	2.975	2.981	2.992
Al (IV)	.018	.025	.019	.008
Al (VI)	1.968	1.963	1.991	1.994
Ti	—	.001	.004	—
Cr	.001	—	—	.002
Fe	1.236	1.390	1.263	1.726
Mn	.016	.033	.013	.019
Mg	1.723	1.574	1.631	1.153
Ca	.083	.064	.105	.110
Na	.001	.004	.001	—
K	—	—	.001	.001
Almandine	40.42	45.41	41.93	57.38
Spessartine	.52	1.07	.43	.63
Pyrope	56.35	51.43	54.15	38.33
Grossular	2.71	2.09	3.49	3.66
Mg/(Fe + Mg)	.582	.531	.564	.400

Table 6. Representative EPMA analyses of sillimanite.

Specimen No. Mineral assemblage Analysis No.	AM-Y-03 I-3 65	AM-Y-07 II-2 21	AM-Y-10 II-3 10
SiO ₂	36.75	36.77	36.31
TiO ₂	.02	.08	.04
Al ₂ O ₃	61.32	62.34	62.52
Cr ₂ O ₃	.04	—	—
Fe ₂ O ₃ *	.51	.24	.13
MnO	—	—	—
MgO	—	—	.01
Total	98.64	99.43	99.01
On the basis of 5 oxygens			
Si	1.007	.998	.990
Ti	.000	.002	.001
Al	1.979	1.995	2.009
Cr	.001	—	—
Fe ³⁺	.011	.005	.003
Mn	—	—	—
Mg	—	—	.000

* Total Fe as Fe₂O₃.

Table 7. Representative EPMA analyses of feldspar.

Specimen No. Mineral assemblage Analysis No.	AM-Y-03 I-2 92	AM-Y-07 II-2 22	AM-Y-10 II-3 9	AM-216-09 III-1 59	AM-216-04 IV-1 44	AM-216-06 IV-2 18
SiO ₂	65.56	64.92	58.07	55.10	45.16	45.27
TiO ₂	.10	.06	—	—	—	—
Al ₂ O ₃	20.54	20.17	27.34	27.90	34.57	35.86
FeO	—	—	—	.12	.10	.06
MnO	.04	—	—	—	—	—
MgO	.04	—	.01	—	.01	—
CaO	2.17	1.48	8.15	10.93	18.34	17.15
Na ₂ O	10.55	4.60	6.81	5.48	1.32	1.30
K ₂ O	.43	9.11	.21	.34	.04	.01
Total	99.43	100.34	100.59	99.87	99.54	99.65
On the basis of 8 oxygens						
Si	2.904	2.982	2.581	2.492	2.094	2.086
Al	1.072	1.072	1.432	1.488	1.890	1.974
Ti	.016	.004	—	—	—	—
Fe	—	—	—	.004	.004	.002
Mn	.008	—	—	—	—	—
Mg	.016	—	.001	—	.001	—
Ca	.103	.072	.388	.528	.911	.847
Na	.906	.440	.587	.480	.119	.116
K	.030	.524	.012	.020	.002	.001
An	.099	.072	.393	.514	.883	.879
Ab	.872	.404	.595	.466	.115	.120
Or	.029	.524	.012	.020	.002	.001

and 10 in Table 6). Other elements do not exceed 0.1 wt%.

The An content of plagioclase associated with garnet and sillimanite is around 39 (Analysis No. 9 in Table 7).

3.3. Enderbite

Enderbite is defined as potassium-poor type of charnockite in which feldspars are mostly of plagioclase instead of K-feldspar. Constituent minerals are orthopyroxene, plagioclase, quartz and ilmenite with zircon and rutile as accessories. As is shown in Fig. 7a, an equigranular texture is commonly observed. Orthopyroxene is strongly pleochroic from light brown to reddish brown. Among pyroxenes from Mt. Riiser-Larsen, orthopyroxene in enderbite is less magnesian being $Mg/(Fe+Mg)=0.55-0.58$ (Analysis No. 52 in Table 3). Plagioclase is characterized by albite twin and its An content varies from 50 to 53 (Analysis No. 59 in Table 7). Ilmenite occurs as an opaque phase whose composition corresponds to ilmenite-hematite solid solution carrying some MgO (Analysis No. 58 in Table 8).

3.4. Mafic granulite

This group is classified into two types based on the pyroxene assemblages as

Table 8. Representative EPMA analyses of ilmenite and spinel.

Specimen No. Mineral assemblage	AM-216-09	AM-Y-08	
	III-1	V-1	
Analysis No.	58	9	12
SiO ₂	.47	.06	.02
TiO ₂	47.03	.01	.02
Al ₂ O ₃	.28	58.21	59.63
Cr ₂ O ₃	.15	2.35	2.47
FeO*	46.77	30.13	27.84
MnO	.20	.05	.13
MgO	1.28	8.55	9.97
CaO	.04	—	—
NiO	—	.20	.30
Total	96.22	99.56	100.38
O	6	4	4
Si	.024	.002	.001
Ti	1.825	.000	.000
Al	.017	1.908	1.917
Cr	.006	.052	.053
Fe ^{3+***}	.278	.038	.029
Fe ²⁺	1.740	.663	.606
Mn	.009	.001	.003
Mg	.098	.355	.406
Ca	.002	—	—
Ni	—	.005	.007
Mg/(Fe ²⁺ + Mg)		.349	.400

* Total Fe as FeO.

** Fe³⁺ is calculated after CARMICHAEL (1967) for ilmenite and assuming Si+Ti+Al+Cr+Fe³⁺=2.000 for spinel.

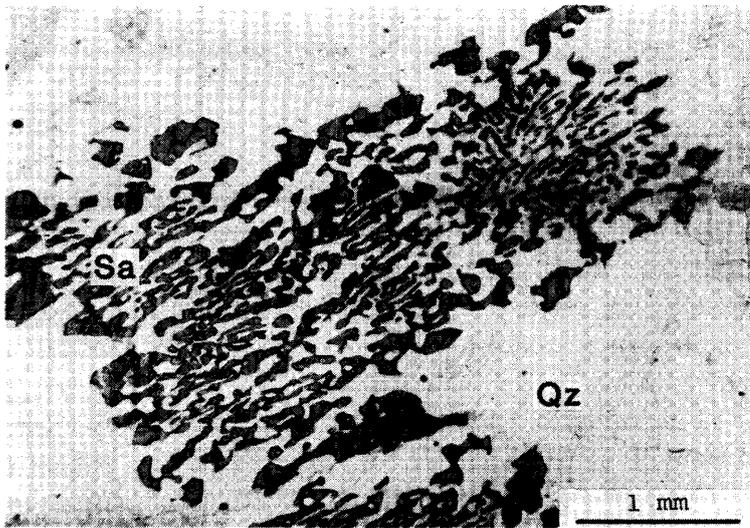


Fig. 5a. The mode of occurrence of sapphirine and quartz in the sapphirine granulite. The aggregate of sapphirine and quartz commonly occupy one domain in symplectitic form as shown in this figure.

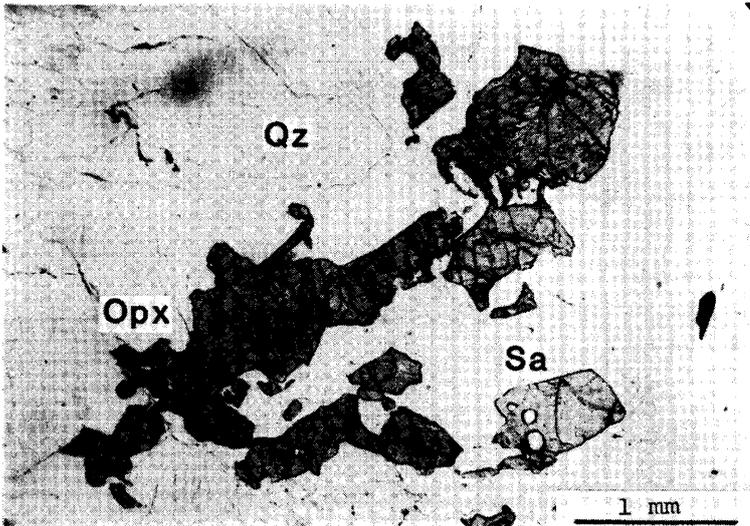


Fig. 5b. Coexistence of sapphirine and orthopyroxene in the sapphirine granulite.

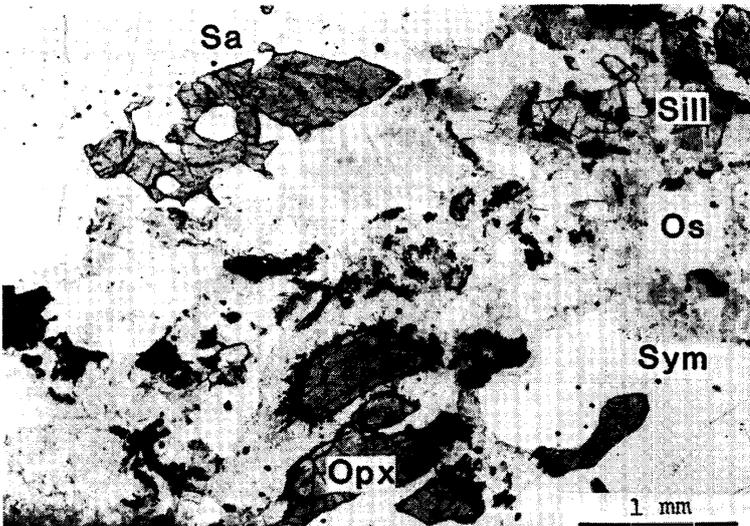


Fig. 5c. Coexistence of sapphirine, orthopyroxene and sillimanite with additional phase of osumilite. Osumilite is ordinarily surrounded by symplectite (Sym) composed of cordierite, K-feldspar and dendritic orthopyroxene.

Fig. 5. Photomicrographs of sapphirine granulite from Mt. Riiser-Larsen. Abbreviations are the same as those in Table 1.

Fig. 6a. The mode of occurrence of osumilite. Note the symplectitic intergrowth of cordierite, K-feldspar and quartz developed around osumilite grain. Crossed nicol.

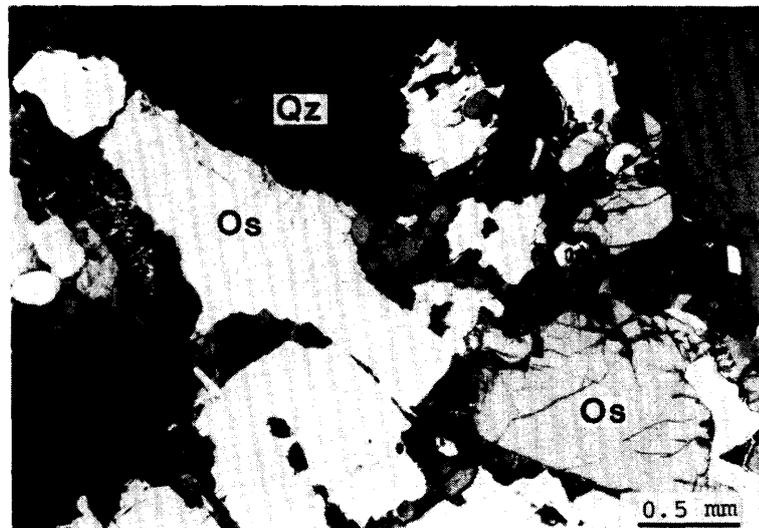


Fig. 6b. Coexistence of garnet and sillimanite in the garnet-sillimanite rock.

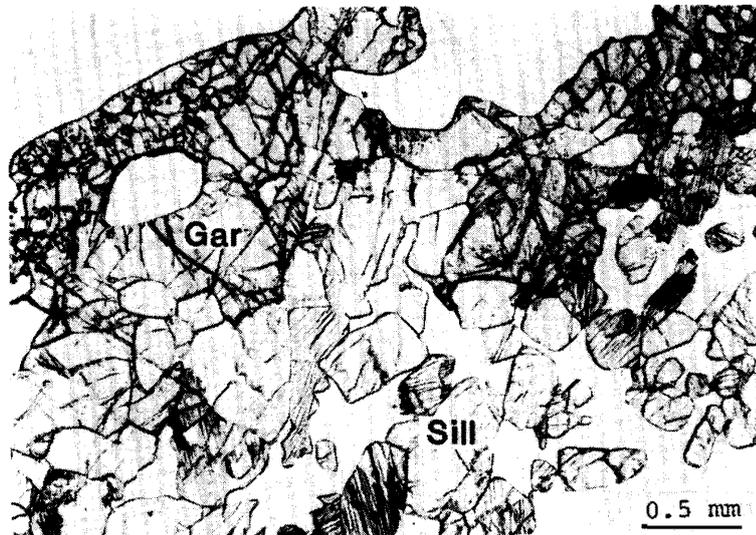


Fig. 6c. Coexistence of garnet and sillimanite. In this case, sillimanite is included in garnet.

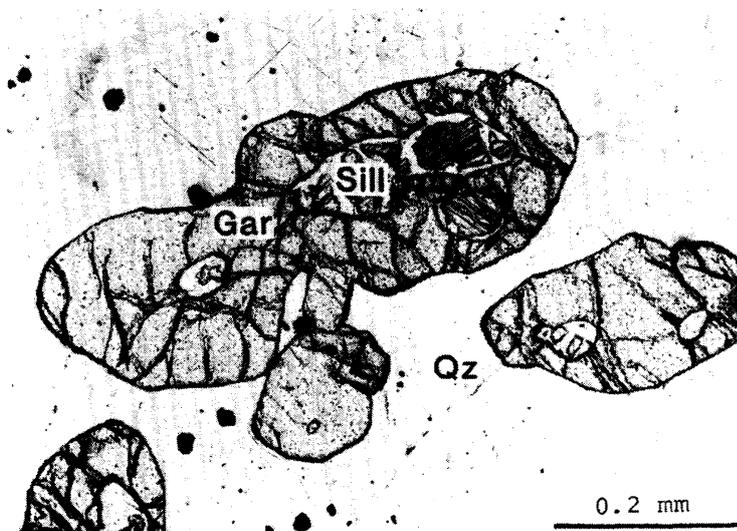


Fig. 6. Photomicrographs showing the mode of occurrence of osumilite and the texture of garnet-sillimanite rock. Abbreviations are the same as those in Table 1.

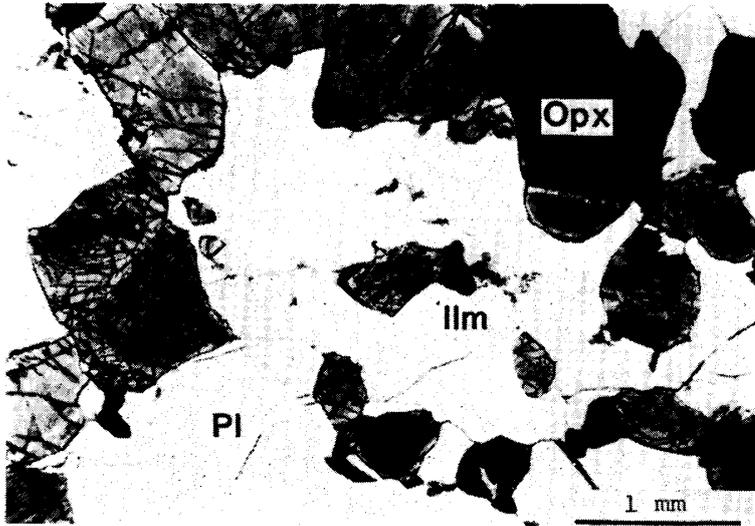


Fig. 7a. Typical texture of enderbite. Orthopyroxene, plagioclase and ilmenite are the main constituents showing equigranular texture.

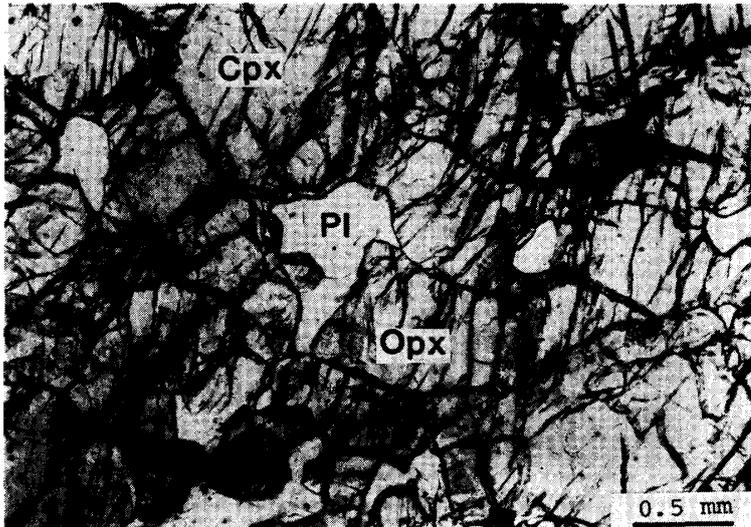


Fig. 7b. Mafic granulite composed of orthopyroxene, clino-orthopyroxene and plagioclase. Pyroxenes are relatively Cr-rich (around $\text{Cr}_2\text{O}_3=1$ wt%) and plagioclase is highly calcic (around $\text{An}=88$) compared with those in other rock types.

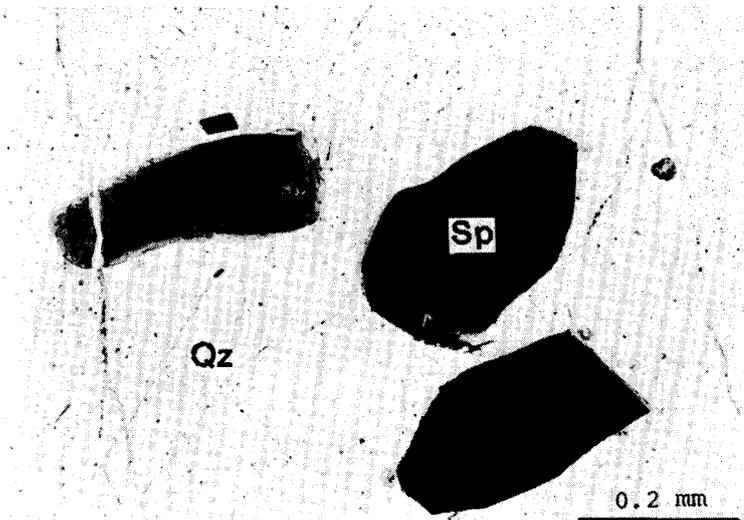


Fig. 7c. Spinel+quartz association in the quartzite. The two phases are in direct contact with each other. The spinel is almost hercynite-spinel solid solution with a small amount of ZnO.

Fig. 7. Photomicrographs showing the texture of enderbite, mafic granulite and spinel-bearing quartzite. Abbreviations are the same as those in Table 1.

follows: One is composed of two-pyroxene and is named two-pyroxene granulite. The other is called orthopyroxenite free from clinopyroxene. In both types, plagioclase is included as an additional phase, but its modal composition is considerably low.

In the two-pyroxene granulite, clinopyroxene is visible as light green crystals in hand specimen. As EPMA analyses imply (Analysis Nos. 31 and 43 in Table 3), this is probably due to the high Cr_2O_3 content (around 1 wt%). The present value is remarkably high among pyroxenes from Mt. Riiser-Larsen (see Table 3). Orthopyroxene in the orthopyroxenite is reddish brown with distinct pleochroism under the microscope. Deep brownish laths of unidentified phase (rutile?) are commonly observed. Plagioclase from both types is highly calcic with the An content around 85–90 (Analysis Nos. 44 and 18 in Table 7). Pyroxene and plagioclase present typical equigranular texture as shown in Fig. 7b.

3.5. Quartzite

Remarkable associations of spinel+quartz, garnet+quartz are observed in metamorphosed quartzite. The rock is unique because the quartz is seen to be dark bluish grey for the spinel-bearing type and milky white for the garnet-bearing type, respectively. This is probably reflecting the presence of minor element, for example Ti, in the quartz. Spinel or garnet occurs as independent grains which are in direct contact with quartz (Fig. 7c).

Spinel belongs to hercynite-spinel solid solution and are free from Zn because of total oxides nearly close to 100 (Analysis Nos. 9 and 12 in Table 8).

Garnets are deeply corroded and they occasionally contain xenotime with a metamictic halo, and are less magnesian than those in other rock types with pyrope concentration around 40% (Analysis No. 83 in Table 5).

4. Physical Conditions of Metamorphism

On the basis of the petrographical and mineralogical data, physical conditions at the peak of metamorphism of Mt. Riiser-Larsen are estimated as follows.

4.1. The stability of sapphirine+quartz association

Although sapphirine is not rare in silica-undersaturated high-grade rocks, it does coexist stably with quartz in the granulites from Mt. Riiser-Larsen. Since the association of sapphirine+quartz is chemically equivalent to cordierite, this association is a breakdown product after cordierite expressed as the following reaction,



which would proceed to the right-hand side under the higher-pressure condition. Experimental and theoretical determinations of the phase relation for reaction (1) have been performed by NEWTON (1972), CHATTERJEE and SCHREYER (1972) and NEWTON *et al.* (1974) for the Mg end-member. The experimental results suggest that the sapphirine+quartz association is stable under high temperature and pressure conditions of metamorphism. According to them, Mg-cordierite would break into

sapphirine+quartz at least at 7–8 kbars under a unhydrous condition. On the other hand, when this reaction occurred under the hydrous condition, cordierite would be stable by as much as a few kilobars above the dry breakdown limit (NEWTON, 1972). However, judging from the petrographical evidence that the granulites from Mt. Riiser-Larsen are almost free from primary hydrous minerals, $P_{\text{H}_2\text{O}}$ must have been much lower than P_{Total} during the metamorphism. Therefore, it does not seem unreasonable to apply the dry experimental results to the sapphirine+quartz association in question. Since the dP/dT for reaction (1) is calculated to be considerably small (almost parallel to the thermal axis), the minimum pressure is estimated to be around 7–8 kbars.

In addition to the association of sapphirine+quartz, orthopyroxene and sillimanite occasionally appear in the assemblage. Since the coexistence of these four phases is recognized in a thin section (Fig. 5c), the following reaction would be also possible,



Reaction (2) is divariant in the system $\text{FeO-MgO-Al}_2\text{O}_3\text{-SiO}_2$. However, because the $\text{Mg}/(\text{Fe}+\text{Mg})$ ratio for sapphirine and orthopyroxene is high as shown in Tables 2 and 3, the authors consider reactions (1) and (2) in the system $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$ to first approximation. The phase relations for these reactions are illustrated in Fig. 9 with the data quoted from CHATTERJEE and SCHREYER (1972) and NEWTON *et al.* (1974). On the position of the invariant point where five phases (cordierite, orthopyroxene, sillimanite, sapphirine and quartz) coexist, NEWTON (1972), CHATTERJEE and SCHREYER (1972) and NEWTON *et al.* (1974) proposed the values about 1000°C, 10 kbars for the synthetic system following the experimental results. For the natural system, on the other hand, NEWTON *et al.* (1974) shifted the invariant point to a considerably lower temperature around 800°C, 7 kbars on the basis of the calorimetric calculation. This discrepancy is due to the difference in composition and cationic ordering state between synthetic and natural minerals.

4.2. *The garnet+sillimanite+quartz association*

The association of pyrope-rich garnet+sillimanite+quartz also suggests high pressure and temperature conditions of metamorphism. Like the case of the sapphirine+quartz, this association is considered to be a breakdown product after cordierite as expressed by the reaction,



Reactions (1) and (3) differ in the Mg/Fe ratios of the ferromagnesian silicates, namely sapphirine and garnet. As is presented in Tables 2 and 5, the $\text{Mg}/(\text{Fe}+\text{Mg})$ ratio of sapphirine is higher than that of garnet. Then, the authors consider the phase relations in the $\text{FeO-MgO-Al}_2\text{O}_3\text{-SiO}_2$ system in which SiO_2 is treated as an excess component (Fig. 8). If it is assumed that all the granulites from Mt. Riiser-Larsen have undergone the metamorphism of the same physical conditions, the apparent variations in mineral assemblages probably reflect the difference in the bulk chemical compositions of the rocks.

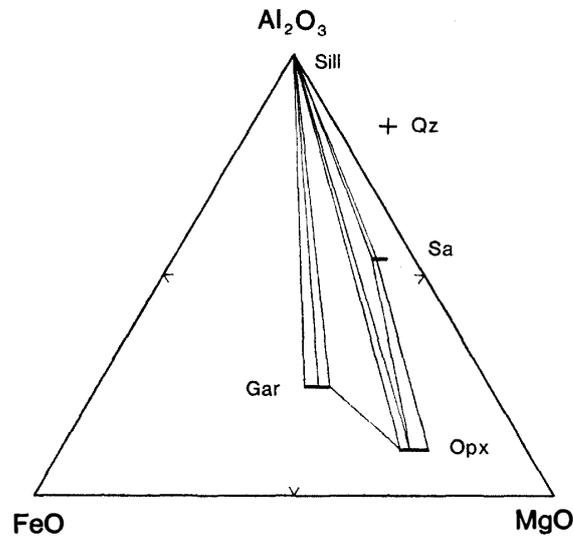


Fig. 8. Schematic projection of sapphirine (Sa), orthopyroxene (Opx), garnet (Gar) and sillimanite (Sill) from Mt. Riiser-Larsen in the system Al_2O_3 -FeO-MgO with excess SiO_2 as quartz (Qz).

Although the experimental and theoretical considerations on garnet-cordierite equilibrium have been performed by CURRIE (1971), HENSEN and GREEN (1971, 1972, 1973) and THOMPSON (1976), the serious discrepancy on the temperature dependence of K_D (distribution coefficient of Fe-Mg between cordierite and garnet) has been the main point of controversy (CURRIE, 1974; HENSEN, 1977; WOOD, 1973). This problem has not been settled yet, but, when the reactant cordierite is missing, the pyrope component in garnet reasonably indicates the minimum pressure for the crystallization (NEWTON, 1978). In Fig. 9, the univariant curve for Fe end-member reaction is illustrated for reference only. Mg end-member reaction (Mg-Cordierite=Pyrope + Sillimanite + Quartz) would be metastable.

4.3. Geothermometry

In order to estimate the metamorphic temperature, pyroxene geothermometers by WOOD and BANNO (1973) and WELLS (1977) are applied to the two-pyroxene as-

Table 9. Temperatures calculated from clinopyroxene-orthopyroxene geothermometer.

Pair No.	Cpx		Opx		K_D	T_1	T_2
	X_{Mg}	$\alpha_{Mg_2Si_2O_6}$	X_{Mg}	$\alpha_{Mg_2Si_2O_6}$			
1	0.930	0.025	0.856	0.695	1.58	890	795
2	0.904	0.028	0.863	0.698	1.49	930	839
3	0.899	0.029	0.857	0.700	1.49	903	811
4	0.896	0.033	0.871	0.708	1.28	937	840

T_1 : WOOD and BANNO (1973); T_2 : WELLS (1977).

X_{Mg} : Mg/(Fe + Mg) in pyroxene.

α : Activity of $Mg_2Si_2O_6$ in pyroxene.

K_D : Distribution coefficient defined as (Fe/Mg) Opx/(Fe/Mg) Cpx.

semblage in the mafic granulite. Pyroxene analyses used for this calculation are listed in Table 3 (Specimen No. AM-216-04) and the results are listed in Table 9 for four pairs. Calculated temperatures are 890–937°C by WOOD and BANNO's method and 795–840°C by WELLS' method, respectively.

These calculated temperatures are very high enough to suggest the granulite-facies condition. But WELLS' temperatures are seemed to be relatively under-estimated because it is difficult to explain the more common occurrence of sapphirine+quartz association rather than orthopyroxene+sillimanite in the rocks. Consequently, the authors prefer the temperatures by WOOD and BANNO (around 900°C), which are consistent with those proposed by SHERATON *et al.* (1980) and GREW (1980).

4.4. Geobarometry

Pressure estimation is attempted for orthopyroxene+garnet and plagioclase+garnet+sillimanite+quartz assemblages. Although there are some discrepancies between the apparent barometers in applying the thermodynamic properties of the phases to the natural system, in the authors' calculations, two barometers were applied just as they were. The results are listed in Table 10.

Table 10. Pressures calculated from geobarometers.

1. Opx-Garnet (WOOD and BANNO, 1973)							
Pair	Opx			Garnet	<i>T</i>	<i>P</i>	
	$X_{M_2}^{Mg}$	$X_{M_1}^{Mg}$	$X_{M_1}^{Al}$	X_{Gt}^{Mg}			
1	0.739	0.675	0.088	0.502	900	10.6	
2	0.753	0.678	0.099	0.564	900	9.3	
2. Plagioclase-Garnet-Sillimanite-Quartz (<i>P</i> ₁ : SCHMID and WOOD, 1976; <i>P</i> ₂ : GHENT, 1976)							
Pair	Plagioclase		Garnet		<i>T</i>	<i>P</i> ₁	<i>P</i> ₂
	X_{An}	α_{An}	X_{Gr}	α_{Gr}			
3	0.387	0.494	0.0345	0.0563	900	9.2	8.9
4	0.393	0.501	0.0348	0.0606	900	9.5	9.3
5	0.408	0.521	0.0404	0.0670	900	9.8	9.6

The geobarometer by WOOD and BANNO (1973) is applied to the orthopyroxene+garnet association. Both phases are assumed to be ideal solid solutions with respect to Fe-Mg exchange, and for garnet, non-ideality of Ca-Mg substitution is neglected. From the EPMA analyses, Mg and Al fraction in *M*₁ and *M*₂ sites for orthopyroxene (abbreviated as $X_{M_2}^{Mg}$, $X_{M_1}^{Mg}$ and $X_{M_1}^{Al}$) and pyrope component in garnet (X_{Gt}^{Mg}) are calculated respectively. If the equilibrium temperature is assumed to be 900°C on the basis of the phase relations and pyroxene thermometer, pressures of 9.3 to 10.6 kbars are calculated.

On the other hand,

$$3 \text{ Plagioclase} = \text{Garnet} + 2 \text{ Sillimanite} + \text{Quartz}, \quad (4)$$

is one of the useful potential geobarometers and geothermometers, based on the Ca distribution between plagioclase ($\text{CaAl}_2\text{Si}_2\text{O}_8$) and garnet ($\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$) in the presence of sillimanite and quartz. In this paper, the methods of GHENT (1976) and SCHMID and WOOD (1976) are adopted.

When the present barometers are applied to the natural system, several parameters determined experimentally and/or theoretically are introduced.

For eq. (4), distribution coefficient K_D (Gar-Pl), which is defined as the following equation,

$$K_D^{\text{Ca}}(\text{Gar-Pl}) = (\alpha_{\text{Grossular}}^{\text{Gar}}) / (\alpha_{\text{Anorthite}}^{\text{Pl}})^3 \\ = (\gamma_{\text{Gr}} X_{\text{Gr}})^3 / (\gamma_{\text{An}} X_{\text{An}})^3, \quad (5)$$

depends on temperature and pressure (where α_i^A = activity, γ_i = activity coefficient and X_i = mole fraction for component i in a phase A , respectively). Then, the first procedure is to get γ for anorthite and grossular.

For γ of anorthite, a constant value of 1.276 proposed by ORVILLE (1972) is adopted. Garnet is assumed to be a ternary mixture of a regular solution; almandine, pyrope and grossular (spessartine component in garnet is extremely low as presented in Table 5). Then, $\gamma_{\text{Grossular}}$ is obtained through the following equations as given by GANGULY and KENNEDY (1974) and GANGULY (1976),

$$RT \ln \gamma_1 = W_{1-2} X_2^2 + W_{1-3} X_3^2 + (W_{1-2} + W_{1-3} - W_{2-3}) X_2 X_3, \quad (6)$$

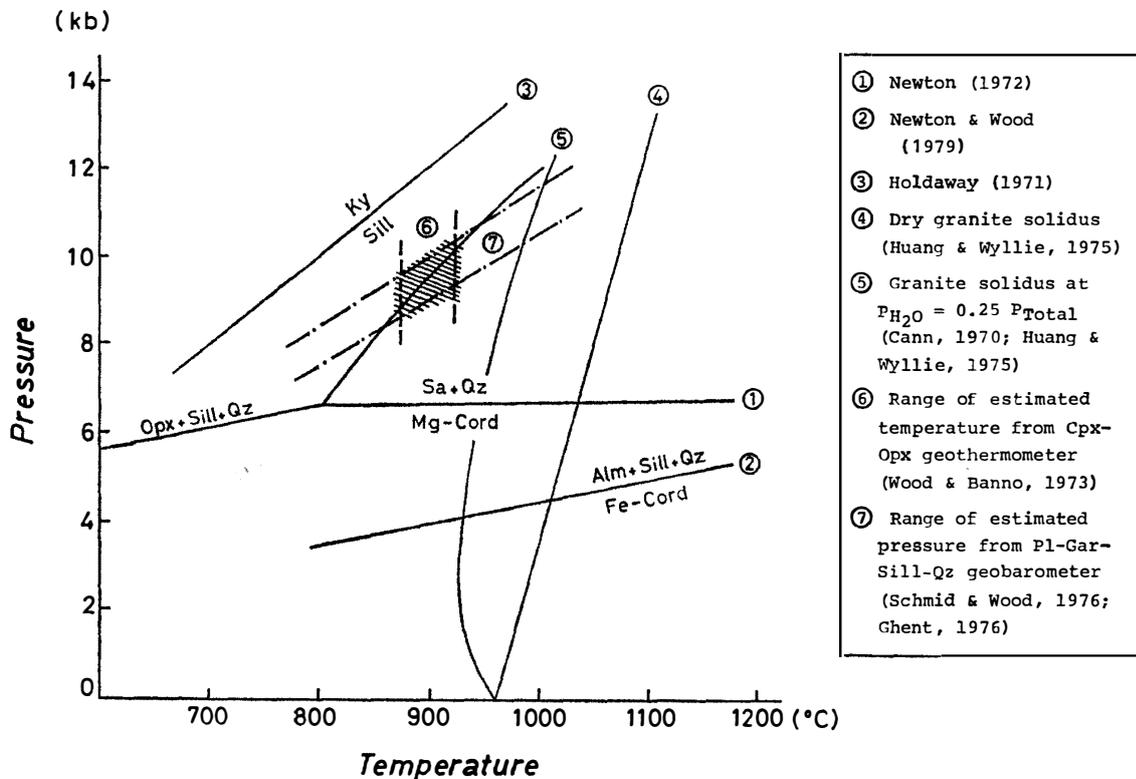


Fig. 9. Estimated P - T conditions for the granulites from Mt. Riiser-Larsen (shaded area) determined from phase relations with geothermometric and geobarometric calculations. It is far behind the granite solidus, which may explain the absence of anatectic melt. Abbreviations as in Table 1.

where W_{1-2} is a Margules or interaction parameter between components 1 and 2, *etc.* If a garnet is assumed to be an ideal solution, all $W=0$ then $\gamma=1$. Determination of the Margules parameters has been performed by GANGULY and KENNEDY (1974), HENSEN *et al.* (1975), OKA and MATSUMOTO (1974), WOOD (1977) and NEWTON (1978). Following NEWTON (1978), $W_{Ca-Mg}=3.2$, $W_{Ca-Fe}=0$ and $W_{Mg-Fe}=2.5$ in kcal at 727°C are used here. Thus, eq. (6) is reduced to

$$\ln \gamma_{Gr} = 1.621X_{Py}^2 + 0.352X_{Alm}X_{Py} \quad (7)$$

On the basis of the γ thus obtained and X_{An} , X_{Gr} from EPMA analyses, distribution coefficient $K_D^{Ca}(\text{Gar-P1})$ is calculated from eq. (5).

Pressure P is obtained by adopting $K_D^{Ca}(\text{Gar-P1})$ into equations of SCHMID and WOOD (1976)* and GHENT (1976)** assuming the equilibrium temperature T .

The geobarometric estimations calculated through three kinds of barometers are surprisingly identical, so it may well be concluded that pressures around 9–10 kbars are probably adequate.

5. Discussions

On the basis of the petrographical observations that the associations sapphirine + quartz, orthopyroxene + sillimanite + quartz and garnet + sillimanite + quartz have been stable at the peak of metamorphism, and calculated values of P and T based on the geothermometers and geobarometers, the P – T conditions of metamorphism for the Mt. Riiser-Larsen granulites are estimated to be around 900°C and 8–10 kbars. On the other hand, P_{H_2O} must have been considerably lower than P_{Total} , because of the absence of migmatite and/or anatectic facies and primary hydrous phases in the mineral assemblages.

Characteristic mineral associations sapphirine + quartz and garnet + sillimanite + quartz are the breakdown products after cordierite under such high P – T conditions, but the difference in these mineral associations is largely due to the bulk chemical compositions of the rocks judging from the mineral chemistry. That is, it is stressed that the occurrence of sapphirine + quartz association is restricted in rocks with a relatively high Mg/Fe ratio. On the other hand, rocks with garnet + sillimanite + quartz association are less magnesian than those containing sapphirine + quartz.

GREW (1980), SHERATON *et al.* (1980) and ELLIS (1980) proposed the P – T conditions on the whole Napier Complex. Their estimations roughly coincide with the present values except for the relatively under-estimated pressure by GREW (7 kbars). It should not be unnatural assuming the presence of a slight difference in condition within the Napier Complex, but those exceptionally high P – T conditions are a peculiar feature in the East Antarctic Shield in any way. For example, the metamorphic condition of the adjacent Rayner Complex at Molodezhnaya Station has been estimated to be around $700 \pm 30^\circ\text{C}$ at 5.5 ± 1.1 kbars by GREW (1981). More-

$$* \ln K_D^{Ca}(\text{Gar-P1}) = \frac{5123}{T} + \frac{0.6565(P-1)}{T} - 16.02.$$

$$** \log K_D^{Ca}(\text{Gar-P1}) = \frac{2551.4}{T} + \frac{0.2842(P-1)}{T} - 7.1717.$$

over, for the Prince Olav Coast and Lützow-Holm Bay regions which are located to the west of Molodezhnaya Station (see Fig. 1), 600–650°C at 5 kbars (YOSHIKURA *et al.*, 1979; KANISAWA and YANAI, 1982) and $725 \pm 25^\circ\text{C}$ at 6.3 ± 1.3 kbars (SUZUKI, 1983) are proposed respectively. As these areas are underlain by rocks much younger than the Napier granulites as presented in Fig. 2, the evolutionary history for each terrain must have basically different from each other. On the Rayner rocks, however, SHERATON *et al.* (1980) considered that they were re-metamorphosed products after the Archean granulites in Proterozoic mainly based on the tectonic and geochronological analyses.

Incidentally, how had these high P - T conditions of the Napier Complex been achieved in the crustal environment? GREW (1980) attributed the genesis to the possible existence of plutonic bodies (anorthositic?) below the Napier granulites which may be concealed by ice at present. He further explained the occurrence of osumilite in relation to the anorthosite. Similar idea is also stated by ELLIS *et al.* (1980) following the investigation by WELLMAN and TINGEY (1980) that the free air anomalies (up to +90 mGal) are present over the Napier granulites.

If this idea is correct, however, why the Napier Complex alone has remained unaffected by the post-stage metamorphism since 2.5 Ga ago? This question should be one of the basic geological problems for the further studies as well as the geochronological investigations when we consider the tectonic and metamorphic history of the East Antarctic Shield.

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