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MINERAL PARAGENESIS OF THE SAPPHIRINE-BEARING ROCK FROM THE AUSTKAMPANE AREA OF THE SØR RONDANE MOUNTAINS, EAST ANTARCTICA

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Abstract: A sapphirine-bearing rock occurs in the Austkampane area of the Sør Rondane Mountains, East Antarctica, where sillimanite-garnet-biotite gneisses of the granulite facies are widespread. The constituent minerals of the rock include sapphirine, phlogopite, hydrous cordierite, plagioclase, gedrite, orthopyroxene, spinel, corundum, rutile and ilmenite. The bulk rock analyses show basaltic compositions in a broad sense, but in a strict sense they are enriched in Al_2O_3, MgO, Cr and Ni, suggesting a precursor with troctolitic composition. Among the constituent minerals, it is most characteristic that the sapphirine is never in direct contact with orthopyroxene, and between the two phases occur the hydrous cordierite-spinel symplectite. This indicates that the reaction sapphirine+orthopyroxene+H_2O=hydrous cordierite+spinel may have occurred. In the system MgO-Al_2O_3-SiO_2-H_2O, this reaction is pressure sensitive with a very shallow and negative dP/dT slope at about 4 kbar on the P-T diagram. Geothermometers, including sapphirine-spinel, cordierite-spinel, and Al_2O_3 content at the M1-site of orthopyroxene, yield around 820–870°C for the assemblage prior to the reaction, and about 770°C for the assemblage after the reaction. It follows that the sapphirine-bearing rock may have suffered nearly isothermal decompression after its peak metamorphism. Such a decompression has recently been reported from other terrains of East Antarctica, suggesting the geological episode common in these terrains.

1. Introduction

In the Austkampane area of the Sør Rondane Mountains, East Antarctica, various kinds of metamorphic and plutonic rocks such as metamorphosed peridotite, basic gneiss, pelitic gneiss, psammitic gneiss, calc-silicate rock, granite and diorite occur (ISHIZUKA and KOJIMA, 1987). On the basis of the mineral assemblage of the pelitic gneiss, *e.g.* sillimanite+garnet+biotite+K-feldspar+plagioclase+quartz, the peak metamorphic conditions are estimated to reach the granulite facies of about 750–850°C and 7–8.5 kbar (ASAMI *et al.*, 1992). Furthermore, the appearance of andalusite and muscovite, both of which partially replace the minerals of the granulite facies, is suggestive of retrograde metamorphism of about 530–580°C and 5.5 kbar (YOSHIKURA *et al.*, 1992). From this area, a sapphirine-bearing rock (No. 86010903C) was collected by the summer party of the 27th Japanese Antarctic Research Expedition and has been described briefly (ISHIZUKA and KOJIMA, 1987). This report describes the detailed petrography of this sapphirine-bearing rock, and discusses its significance with respect to the metamorphic evolution of the Sør Rondane Mountains. In general, aluminous rocks as described in this report preserve a variety of reaction textures, so they are commonly used to assess the metamorphic *P-T* evolution (*e.g.*, HARLEY *et al.*, 1990; KAWASAKI *et al.*, 1993; MOTOYOSHI *et al.*, 1994).

2. Mode of Occurrence

The Austkampane area, from which the sapphirine-bearing rock in question was collected, is underlain by various kinds of metamorphic and plutonic rocks (Fig. 1). Among the metamorphic rocks, the garnet-biotite gneiss is the dominant lithology, of which the foliation strikes NE-SW to E-W and gently (25–60°) dips southward. The metamorphosed peridotite and calc-silicate rock occur as small lenses or blocks in the garnet-biotite gneiss. Plutonic rocks such as granite and diorite intrude into the gneisses.

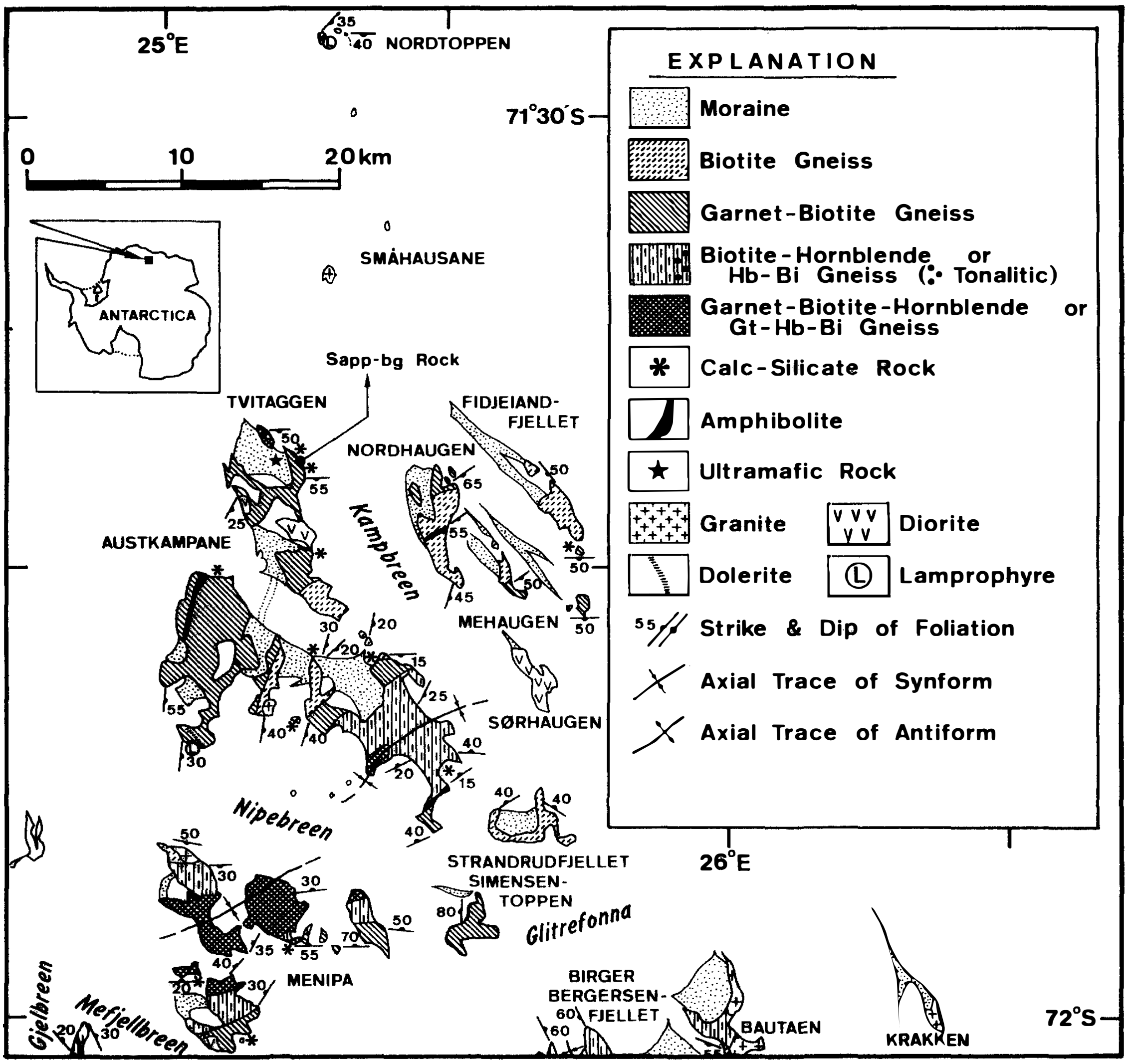

Fig. 1. Geological map of the northern part of the Austkampane area, Sør Rondane Mountains (after ISHIZUKA and KOJIMA, 1987), in which the locality of the sapphirine-bearing rock (Sapp-bg Rock) is shown.

The sapphirine-bearing rock was sampled from the northeastern region of the Austkampane area. The field relationship between the sapphirine-bearing rock and surrounding rock-type is not clear because of the poor exposure. Near the outcrop of the sapphirine-bearing rock, there is a small intrusive body of diorite, in which several kinds of metamorphic rocks are included as small blocks. From these small blocks, OSANAI (1994, oral communication) found the sapphirine-free but gedrite-phlogopite-bearing rock which is similar to the major part of the sapphirine-bearing rock described here. This is reminiscent of the mode of occurrence of the sapphirine-bearing rock, that is, the sapphirine-bearing rock may be a block embedded in the diorite.

3. Petrography

The sapphirine-bearing rock is a medium- to coarse-grained and massive rock with granoblastic texture, and is generally melanocratic, but sometimes it has a leucocratic part. In some portion of the rock, weak metamorphic foliation, defined by prismatic amphibole and mica, develops.

The constituent minerals of the rock include sapphirine (Spr), phlogopite (Phl), cordierite (Crd), plagioclase (Pl), gedrite (Ged), orthopyroxene (Opx), spinel (Spl), corundum (Crn), rutile (Rt) and ilmenite (Ilm). Representative photomicrographs of the rock

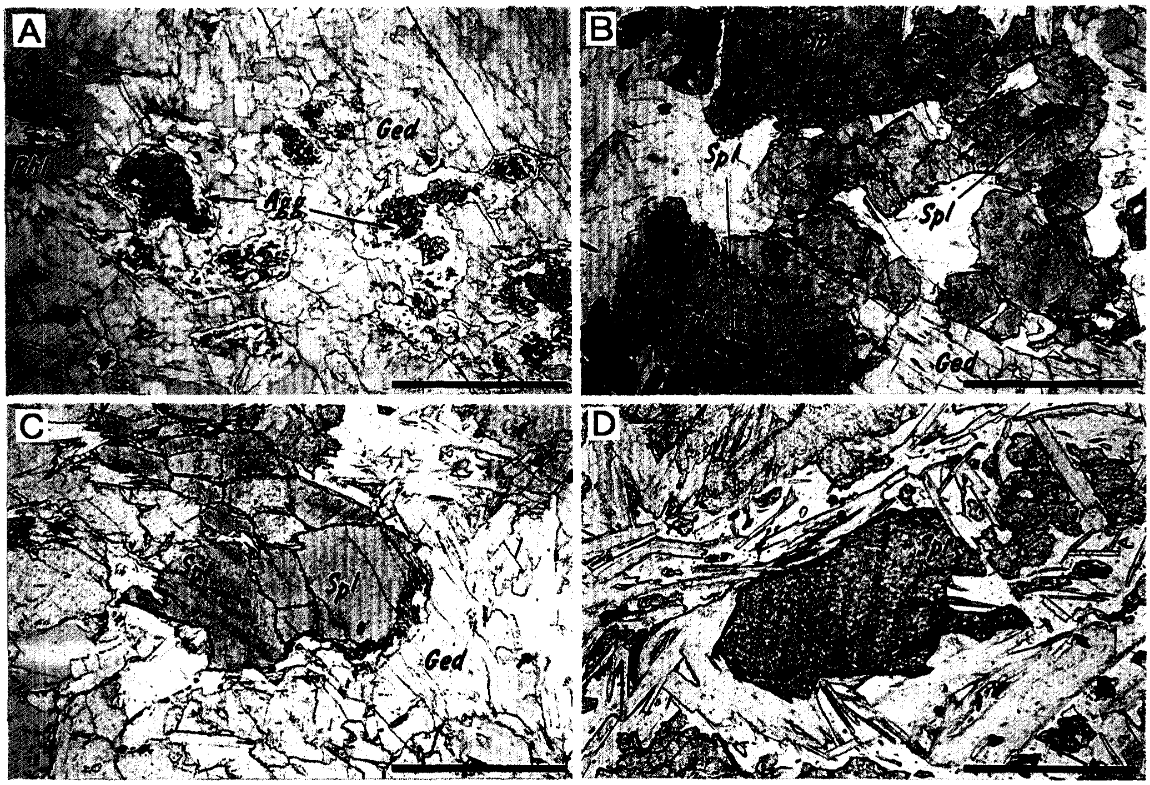

Fig. 2. Photomicrographs of the sapphirine-bearing rock (No. 86010903C). A: Leucocratic part having aggregates (Agg) composed of Spr + Pl + Crd ± Spl ± Crn. Scale bar = 2 mm. B: Idiomorphic Spr enclosing tiny Spl. Scale bar = 1 mm. C: Coexisting idiomorphic Spr and Spl. Scale bar = 1 mm. D: Idiomorphic Spr with lamellae of Ilm. Scale bar = 0.5 mm.

are shown in Fig. 2. X-ray images of several elements obtained by a microstep mapping technique using an electron probe microanalyzer (EPMA, JEOL JXA-8600S/M) at Kochi University are presented in Figs. 3 to 5, which are very useful to study detailed mineral textures.

In the melanocratic part, Phl and Ged are main constituent minerals occupying approximately 70 modal volume % of the rock. Spr, Opx and Spl, occurring as idiomorphic crystals, are minor constituents, of which Spl, pale- to apple-green in color, is sometimes enclosed within Spr.

The leucocratic part is characterized by the presence of aggregates composed of Pl+Spl, Pl+Spl+Spr, Pl+Spl+Crn, and Pl+Spl+Spr+Crd+Opx. These aggregates are generally armored by Crd. Of these minerals, Spr, pale blue in color, is not directly in contact with Opx, and between the two phases the Spl-Crd symplectite develops. Very rarely, Pl in association with Crn exhibits oscillatory zoning.

Rt and Ilm are scattered as accessories, of which Ilm also occurs as tiny crystals or lamellae in Spr.

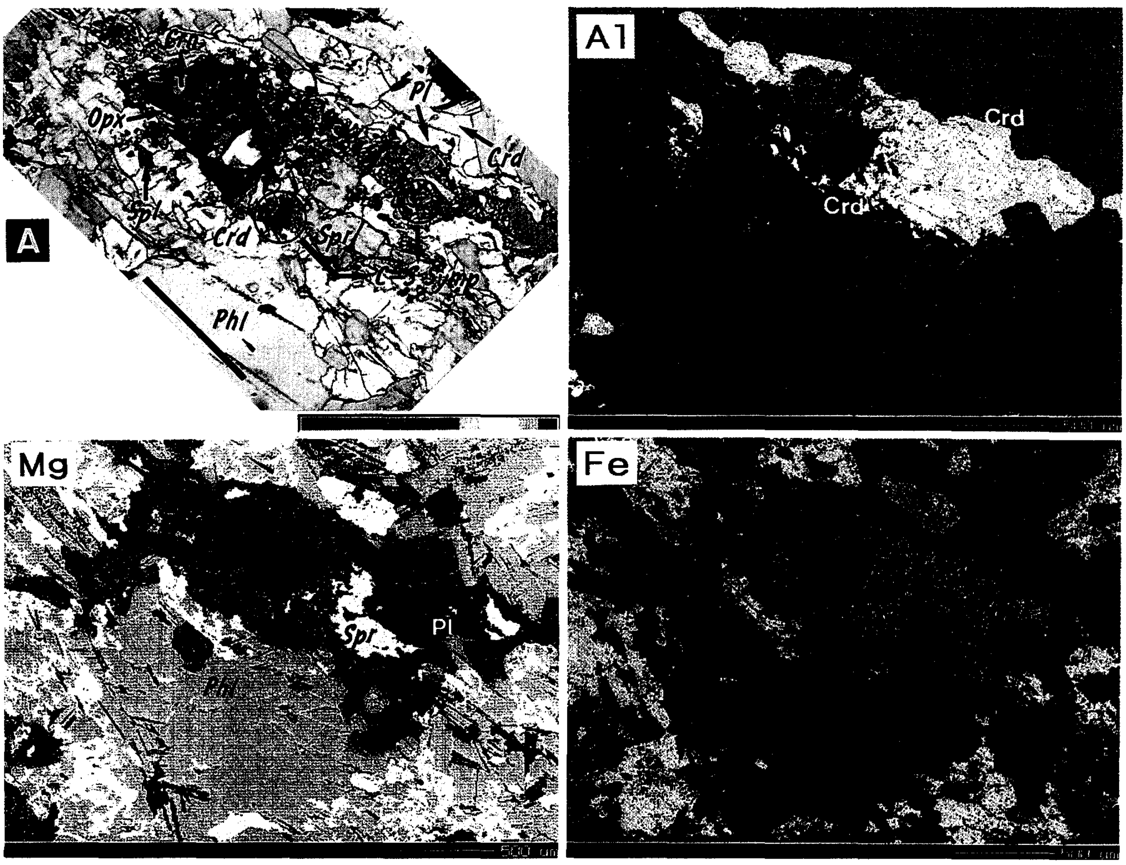

Fig. 3. Photomicrograph (A) and X-ray (Al, Mg, Fe) images of aggregate, showing Crd-Spl symplectite (C-S Symp) set between Spr and Opx. Note that aggregate is further armored by Crd. Scale bar = 0.5 mm in A. Each point of the X-ray images was counted for 80 ms, and 450 × 330 points were measured at 6-μm intervals. Each element is enriched or depleted toward warm or cool color, respectively.

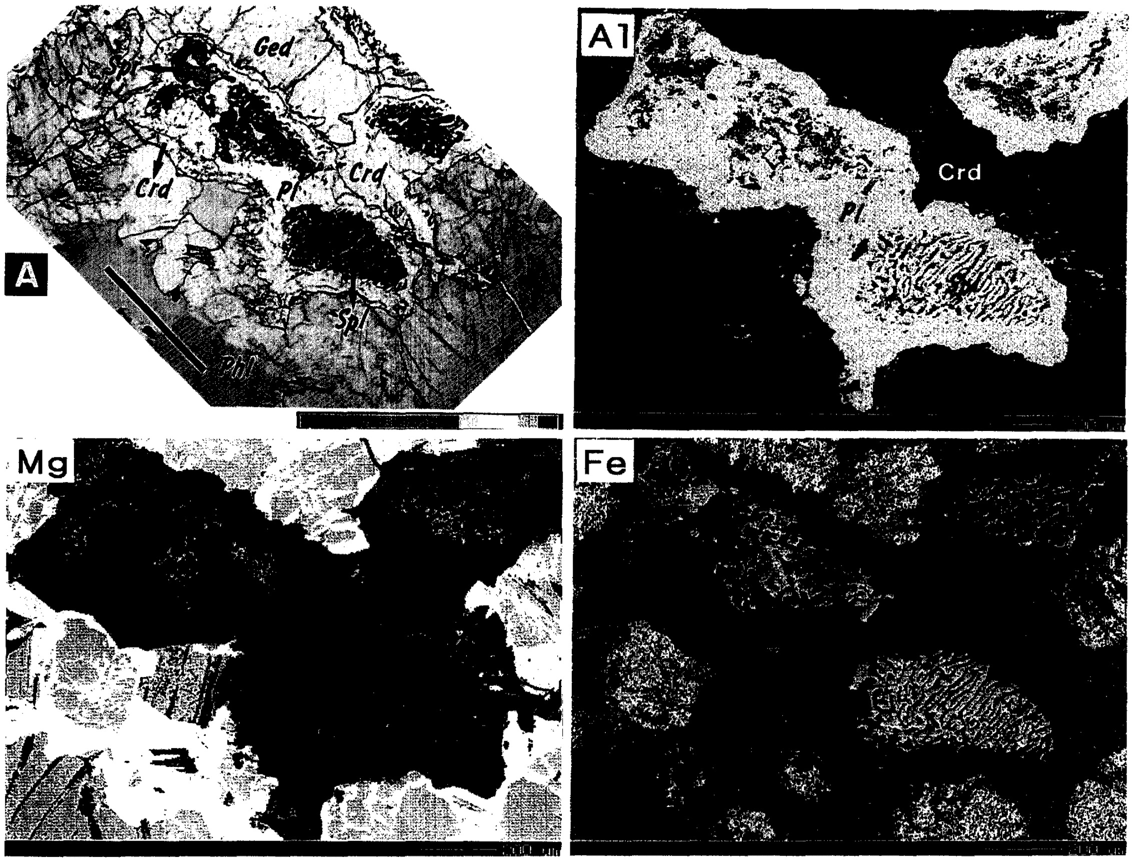

Fig. 4. *Photomicrograph (A) and X-ray (Al, Mg, Fe) images of aggregates, showing tiny Spl and/or Spr set in Pl that is further armored by Crd. Scale bar = 0.5 mm in A. Each point of X-ray images was counted for 60 ms, and 450 × 330 points were measured at 3-μm intervals.*

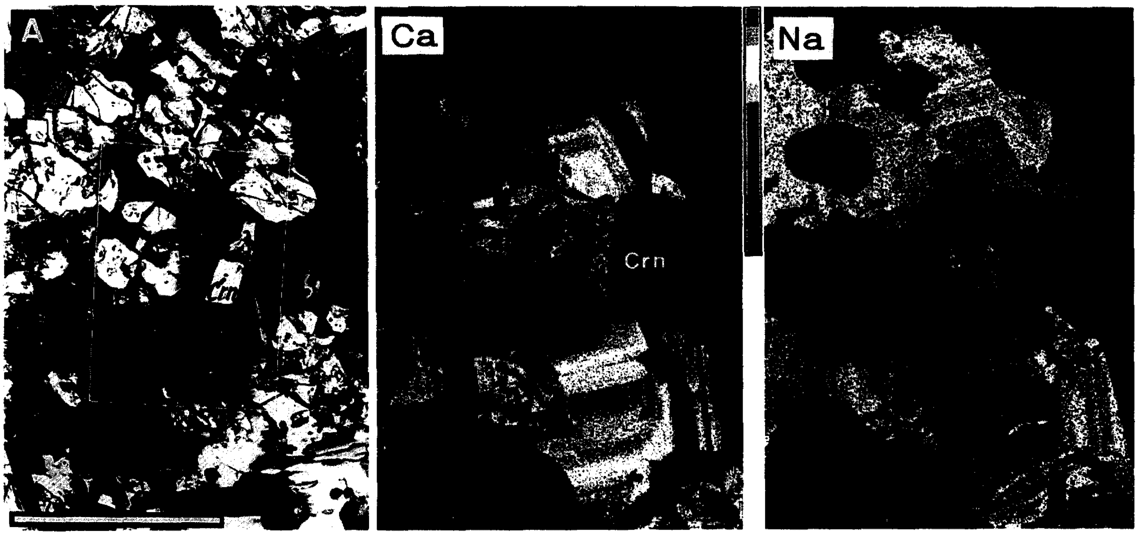

Fig. 5. *Photomicrograph (A) and X-ray (Ca, Na) images of aggregate composed of Pl and Crn. Note that Pl displays oscillatory zoning. Scale bar = 0.25 mm in A. Each point of X-ray images was counted for 100 ms, and 450 × 310 points were measured at 1-μm intervals.*

4. Bulk Rock Chemistry

Bulk rock analyses were performed for two parts of the sapphirine-bearing rock, the melanocratic and leucocratic parts, by using the X-ray fluorescence analyzer (Rigaku, XRF-Model 3080) at Kochi University; and the results are listed in Table 1.

Table 1. Bulk rock compositions of the sapphirine-bearing rock (No. 86010903C).

	Major elements (wt%)			Minor elements (ppm)	
	A	B		A	B
SiO_2	41.38	43.57	Cr	189	125
TiO_2	0.70	0.21	Ni	230	228
Al_2O_3	21.04	22.32	Rb	81	65
FeO*	12.07	19.89	Sr	64	103
MnO	0.15	0.16	V	123	109
MgO	21.05	16.52	Y	20	22
CaO	1.33	5.48	Zr	50	67
Na_2O	1.06	1.12	Ba	19	21
K_2O	1.17	0.66	Nb	8	7
P_2O_5	0.05	0.07			

A: melanocratic part, B: leucocratic part. FeO* means total iron as FeO.

The bulk compositions of the sapphirine-bearing rock are characterized by the high Al_2O_3 and MgO contents as well as the high contents of Cr and Ni. The FeO* and CaO contents are lower in the melanocratic part than that in the leucocratic part, but the MgO content is higher in the former than in the latter. The high Al_2O_3 and MgO contents of the sapphirine-bearing rock as described above are common features of sapphirine-bearing rocks as reviewed by ARIMA and BARNETT (1984). In particular, MIYASHITA *et al.* (1980) have described the sapphirine-bearing rock from Mt. Poroshiri of Hokkaido, northern Japan, and considered its original rock to be an anorthositic troctolite. Compared with the sapphirine-bearing rock of Mt. Poroshiri, the rock in the present study is slightly low in CaO and high in K_2O, but there are some similarities in abundance of other elements. It is, therefore, likely that the sapphirine-bearing rock described here was derived from the aluminous and magnesian mafic rock with troctolitic composition. It is, however, still in dispute whether this precursor represents (1) a plutonic rock (troctolite) crystallized from basaltic melt or (2) a residual phase (restite) during partial melting of the surrounding pelitic gneisses; in this case the neighboring diorite may represent a melt phase, or (3) a rock generated by other processes, which is beyond the scope of this report and will be discussed elsewhere.

5. Mineral Chemistry

Chemical compositions of constituent minerals were analyzed by using EPMA, JEOL JXA-733 at NIPR and JXA-8600S/M at Kochi University. The results are listed in Table 2 and plotted in the system SiO_2-(FeO+MnO+MgO)-Al_2O_3 of Fig. 6. The bulk rock compositions are also plotted in Fig. 6, showing that the data lie nearly on the tie line between Pl and Ol (olivine). This again shows the original rock of the sapphirine-bearing

Table 2. Representative mineral analyses of the sapphirine-bearing rock (No. 86010903C).

Mineral	Spr-1	Spr-2	Phl	Crd-1	Crd-2	Ged	Opx	Spl-1	Spl-2	Spl-3
SiO_2	13.96	13.81	41.66	49.06	50.05	46.05	52.19	0.01	0.02	0.03
TiO_2	0.02	0.04	0.75	0.00	0.00	0.25	0.07	0.01	0.02	0.00
Al_2O_3	62.77	61.36	17.49	33.32	34.32	13.30	7.87	65.62	65.22	63.01
Fe_2O_3	—	—	—	—	—	—	—	0.00	0.00	0.42
Cr_2O_3	0.12	0.19	0.00	0.00	0.00	0.07	0.00	0.50	0.29	0.63
FeO*	6.27	8.49	7.24	2.87	2.56	15.01	14.74	19.99	21.42	23.41
MnO	0.10	0.13	0.03	0.00	0.00	0.26	0.25	0.09	0.08	0.09
MgO	17.59	16.84	20.98	12.14	12.08	20.27	22.64	14.76	13.27	11.67
CaO	0.02	0.04	0.03	0.06	0.05	0.50	0.39	0.00	0.00	0.03
Na_2O	0.00	0.00	0.92	0.17	0.00	1.78	0.91	0.00	0.00	0.11
K_2O	0.00	0.01	7.29	0.00	0.00	0.02	0.00	0.00	0.00	0.00
Total	100.85	100.91	96.39	97.62	99.06	97.51	99.06	100.98	100.32	99.40
*X*Fe*	0.17	0.22	0.16	0.12	0.11	0.29	0.27	0.43	0.48	0.53

Spr-1: idiomorphic crystal, Spr-2: associated with Spl+Pl or Spl+Crd symplectite, Crd-1: associated with Spl symplectite, Crd-2: armouring aggregates of Pl, Spl, Spr, Opx and Crd-1, Spl-1: inclusion in Spr, Spl-2: idiomorphic crystal, Spl-3: symplectite with Pl or Crd, *X*Fe*: Fe*/(Fe*+Mg). FeO* means total iron as FeO, except for Spl for which Fe^{2+} and Fe^{3+} were calculated from total iron assuming ideal spinel formula.

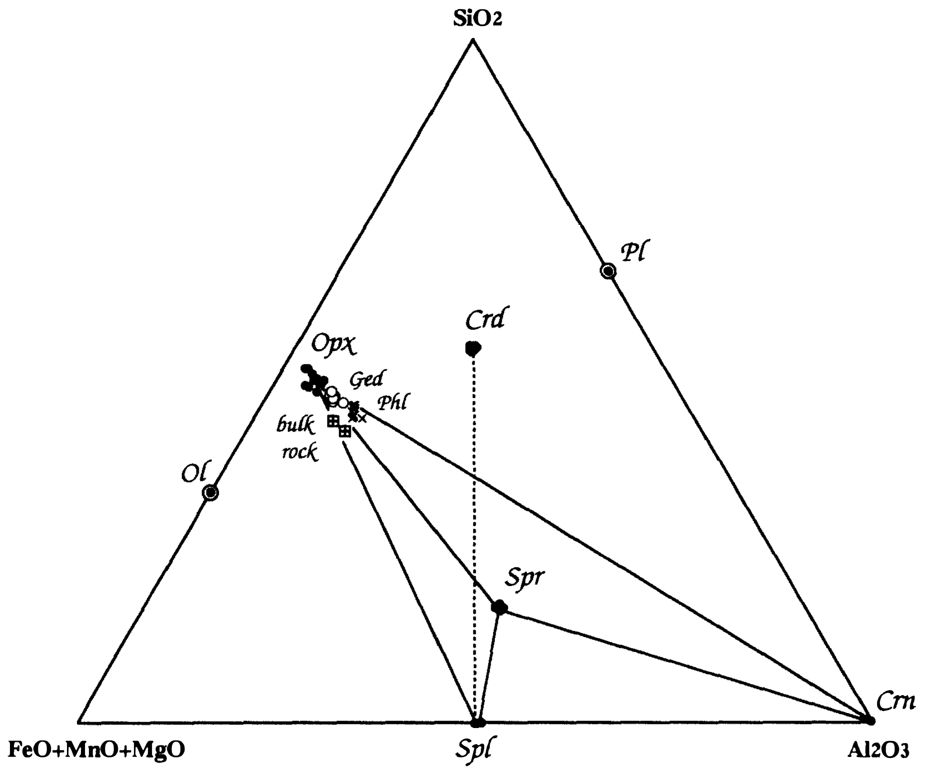

Fig. 6. Mineral and bulk rock compositions plotted in the SiO_2-(FeO + MnO + MgO)-Al_2O_3 diagram, illustrating mineral assemblages (solid lines) prior to the reaction, Opx + Spr = Crd + Spl, and that (dotted line) after the reaction. Ol: olivine.

rock to be an olivine-plagioclase rock such as troctolite. In the following, the ratio of $Fe^*/(Fe^*+Mg)$ is abbreviated to XFe*, in which Fe* means total iron as Fe^{2+}.

Spr analyses are plotted between the 2 : 2 : 1 and 7 : 9 : 3 compositions in the system $(FeO+MnO+MgO)$-Al_2O_3-SiO_2. Spr occurring in aggregates is slightly higher in XFe* than idiomorphic varieties, being in direct contact with Phl and/or Ged. Spr includes up to 0.24 wt% Cr_2O_3.

Phl is relatively homogeneous in composition, ranging from 0.16 to 0.20 in XFe*, from 0.6 to 0.9 wt% in TiO_2, and from 0.7 to 1.0 wt% in Na_2O.

Crd is homogeneous in composition, ranging from 0.10 to 0.13 in XFe*, even though it occurs in two modes as described above. The microprobe analyses of Crd range from 96.5 to 99.5 wt% in total oxide, suggesting the presence of a considerable amount of H_2O and/or CO_2. Crd also contains up to 0.3 wt% Na_2O.

Pl is generally homogeneous, and has an extremely high An-content ranging from 97 to 98, but Pl with oscillatory zoning has the An-rich (An=86–98) core and the An-poor (An=9–27) rim. All analyzed Pl include negligible K_2O up to 0.14 wt%, but contain remarkable Fe_2O_3* up to 0.78 wt%.

Ged ranges from 0.26 to 0.30 in XFe*, but its chemical formula calculated on the basis of O=23 suggests that a considerable amount of ferric iron may be included in Fe*. Ged also contains Na_2O content up to 2.66 wt%. Minor elements include up to 0.75 wt% TiO_2, 0.36 wt% MnO, and 0.70 wt% CaO.

Opx has relatively constant XFe* ranging from 0.25 to 0.29, but its Al_2O_3 content varies from 5.23 to 9.81 wt%. The CaO content ranges from 0.36 to 0.42 wt%.

Spl compositions are highly variable, and especially, XFe* is higher in Spl forming symplectite than that in Spl enclosed within Spr, and it is intermediate in Spl occurring in the matrix. The Cr_2O_3 content ranges from 0.38 to 1.03 wt%.

Crn contains up to 0.29 wt% Fe_2O_3* and 0.34 wt% Cr_2O_3 as its detected impurity.

Rt and Ilm have nearly ideal stoichiometries.

6. Discussion

Most importantly, the presence of the Crd-Spl symplectite as separating Spr from Opx indicates that the assemblage Spr+Opx was replaced by the assemblage Crd+Spl through the reaction Spr+Opx=Crd+Spl.

Prior to this reaction, that is, at the stage of the nearly peak metamorphism, the Spr may have coexisted with the Opx and Spl, of which the latter phase means the Spl occurring as idiomorphic crystal or inclusion enclosed within Spr. The temperature conditions of this stage are estimated by the compositions of Spr, Spl and Opx. An empirical Spr-Spl Mg-Fe exchange thermometer proposed by OWEN and GREENOUGH (1991) was first applied to the Spr-Spl pair, and the calculated temperature ranges from 820 to 870°C. Another estimation of temperature was done by using the Al_2O_3 solubility of Opx coexisting with Crn. It is, however, well known that the solubility of Al_2O_3 in Opx is also a function of its Mg/(Mg+Fe) ratio (HOLDAWAY, 1976). In this connection, GREW (1980) calculated the variation of Al_2O_3 due to the Mg-Fe^{2+} substitution in Opx. Using this calculation and assuming the pressure conditions of 7–8 kbar for the peak metamorphism (ASAMI *et al.*, 1992), the Opx from the sapphirine-bearing rock is estimated to contain 1.9–

3.1 wt% Al_2O_3 at the M1-site in Fe^{2+}-free equivalent compositions, which yields 820–860°C (ANASTASIOU and SEIFERT, 1972). These calculated temperatures are comparable to or slightly higher than those (750–850°C) of the peak metamorphism in the Sør Rondane Mountains as estimated by the mineral assemblage of the pelitic gneisses (ASAMI *et al*., 1992).

The reaction Spr+Opx=Crd+Spl has been studied experimentally by several investigators (NEWTON, 1972; NEWTON *et al*., 1974; SEIFERT, 1974; NEWTON and WOOD, 1979). The results showed that the H_2O and/or CO_2 content of Crd has affected the reaction involving Crd. As described above, the Crd of the sapphirine-bearing rock is a hydrous equivalent. In the system MgO-Al_2O_3-SiO_2-H_2O, an invariant point involving hydrous Crd, Spl, Spr, Opx, chlorite and H_2O is located at about 765°C and 3.7 kbar, of which the higher temperature space is occupied by a univariant reaction Spr+Opx+H_2O=hydrous Crd+Spl with a shallow negative dP/dT slope. GREW (1982) suggested that the introduction of FeO in the system would reduce slightly the pressure condition of the reaction. So, this reaction represents the maximum pressure for the stability of the Spl+hydrous Crd association. In this connection, the Spl-Crd geothermometer proposed by VIELZEUF (1983) was applied to the Spl-Crd symplectite. The results range from 740 to 780°C. It is, therefore, most likely that the reaction may have occurred during the high-temperature decompression of about 4 kbar and 760°C. These conditions, especially calculated temperatures, are apparently different from those (530–580°C) of the retrograde metamorphism mainly due to the intrusion of plutonic rocks as estimated by YOSHIKURA *et al*. (1992).

The nearly isothermal decompression described in this report has recently been proposed from other terrains in East Antarctica such as Forefinger Point, Enderby Land (HARLEY *et al*., 1990; MOTOYOSHI *et al*., 1994) and Rundvågshetta, Lützow-Holm Bay (KAWASAKI *et al*., 1993), although the detailed *P-T* evolution, especially the *P* condition, is different in each terrains. It is, therefore, suggested that such a decompression is a common episode after the peak granulite facies metamorphism, and the comparative study may provide new insight into understanding the geological evolution of East Antarctica.

On the other hand, ASAMI *et al*. (1992, 1994) have also reported a sapphirine-bearing rock from the Balchenfjella area of the eastern Sør Rondane Mountains. This rock is very different in petrography from the sapphirine-bearing rock described here. The sapphirine-bearing rock of Balchenfjella contains the mineral association sapphirine+kyanite with or without spinel as inclusions set in porphyroblastic garnet, and such an association is inferred to be a relict assemblage of the prograde *P-T* path within the kyanite field approaching 700°C and 8 kbar. In contrast, the sapphirine-bearing rock described here has textural evidence indicating the retrograde stage during the nearly isothermal decompression. It follows that there are at least two types of sapphirine-bearing rocks in the Sør Rondane Mountains; a comparative study of these rocks, which may play an important role to evaluate the *P-T* evolution of the Sør Rondane Mountains, is in progress.

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