Proc. NIPR Symp. Antarct. Geosci., 7, 101-114, 1994

REACTION TEXTURES IN GRANULITES FROM FOREFINGER POINT, ENDERBY LAND, EAST ANTARCTICA: AN ALTERNATIVE INTERPRETATION ON THE METAMORPHIC EVOLUTION OF THE RAYNER COMPLEX

Yoichi MOTOYOSHI[1], Masahiro ISHIKAWA[2] and Geoffrey L. FRASER[3]

[1]*National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173*
[2]*Institute of Geology and Paleontology, Faculty of Science, Tohoku University, Sendai 980-77*
[3]*Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia*

Abstract: Aluminous granulites from Forefinger Point in Enderby Land, East Antarctica, preserve a variety of reaction textures which demonstrate a part of the *P-T* evolution. On the basis of the petrographical evidence, the following reactions are inferred:

orthopyroxene + sillimanite + quartz = cordierite,
orthopyroxene + sillimanite = cordierite + sapphirine,
garnet + quartz = orthopyroxene + cordierite,
garnet = orthopyroxene + cordierite + sapphirine.

These reactions are visualized on a simplified (Fe,Mg)O-Al_2O_3-SiO_2 diagram, and are interpreted on *P-T* and P-μ_{FeO} diagrams, respectively. The reactions imply nearly isothermal decompression after the peak metamorphic conditions. The prograde segment of the *P-T* path is inferred by relict spinel and corundum inclusions invariably rimmed by sapphirine in silica-undersaturated granulites. A possible reaction is

spinel + corundum + cordierite = sapphirine.

The petrogenetic grid for a model FMAS system indicates that the decompressional *P-T* path passed between two invariant points; [Spl] 11±1 kbar at 1040±15°C, and [Qtz] 8-9 kbar at 950°C. Assuming a constant temperature, a P-μ_{FeO} diagram is used to demonstrate that the variety of reactions depends on bulk chemical compositions. Several geothermobarometers, including garnet-orthopyroxene, garnet-orthopyroxene-plagioclase-quartz, garnet-plagioclase-sillimanite-quartz, GRAIL, GRIPS and sapphirine-spinel are applied. The garnet-orthopyroxene and sapphirine-spinel geothermometers yield around 700-850°C, and these values are considerably lower than those inferred from the petrogenetic grid mentioned above.

On the basis of the petrographical interpretation and preliminary results of SHRIMP dating (SHIRAISHI, pers. commun.), it is concluded that the Forefinger Point granulites probably do not represent a reworked portion of the Archaean Napier Complex, but rather, they may be the result of Cambrian events in the East Antarctic Shield.

1. Introduction

Forefinger Point in Enderby Land is a small outcrop located close to the boundary between the Archaean Napier Complex and the Proterozoic Rayner Complex (Fig. 1). Therefore this location is appropriate to examine the geological relationships between these distinctive complexes. It is considered that the Rayner Complex has been metamorphosed under lower *P-T* conditions (granulite to upper amphibolite facies) at a relatively higher P_{H_2O} than those of the Napier Complex. Based on relict mineral assemblages from several localities including Forefinger Point, it has been considered that the Rayner Complex is a reworked portion of the Napier Complex (ELLIS, 1983; SHERATON *et al*., 1980, 1987) at 1000±50 Ma (GREW, 1978; BLACK *et al*., 1983, 1987). CLARKE (1988) insisted that the boundary between the complexes is a fault zone reactivated at *c*. 500 Ma. The basement rocks at Forefinger Point consist of metapelitic and metabasic rocks with subordinate granite and pegmatite veins. Undeformed pegmatite at Forefinger Point has been dated to be 500 Ma by GREW and MANTON (1979). HARLEY *et al*. (1990) proposed two-stage decompression for the Forefinger Point orthopyroxene- and sillimanite-bearing granulites, and they considered that the initial high *P-T* assemblage including orthopyroxene+sillimanite±garnet are "relics" from the Napier metamorphism. Moreover, they speculated that the first-stage of nearly isothermal decompression occurred in the Archaean followed by subsequent overprinting by the Proterozoic Rayner metamorphism.

The aim of this paper is to reexamine the reaction textures in the rocks from Forefinger Point, and to discuss the *P-T* evolution combining recent preliminary SHRIMP dating on one of the samples from Forefinger Point. The aluminous rocks described in this paper occur as boudinaged layers or pods in the basement, and they preserve a variety of reaction textures which were used to assess the metamorphic *P-T* evolution. Because distinctive decompressional textures have been reported from Proterozoic or younger metamorphic terranes in East Antarctic Shield (*e.g*. HARLEY, 1988; HARLEY and FITZSIMONS, 1991;

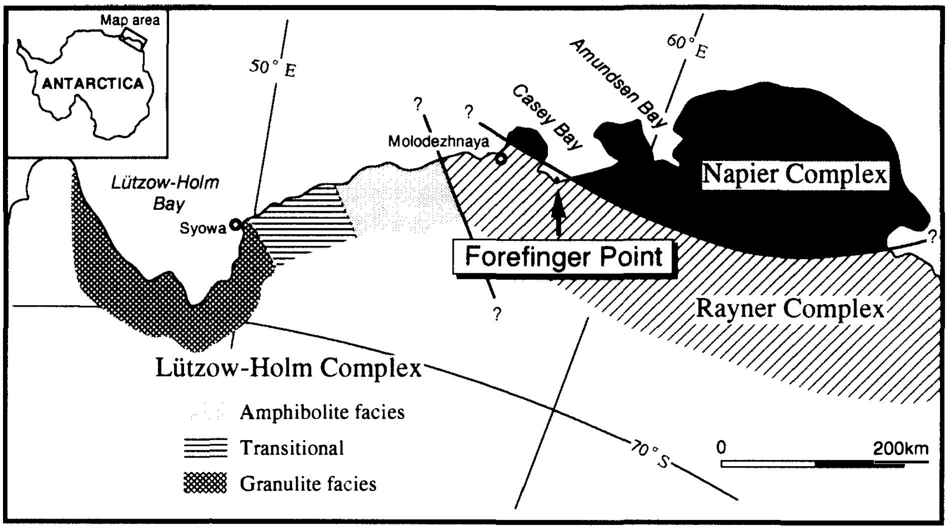

Fig. 1. Locality map of Forefinger Point. The boundary between the Napier and Rayner Complexes is after SHERATON et al. (1987). Metamorphic zonation of the Lützow-Holm Complex is after HIROI et al. (1991).

THOST *et al.*, 1991 ; KAWASAKI *et al.*, 1993), it is important to reconsider the geological framework of these terranes. The rocks described in this paper were collected in February 1993 by the JARE-33 and -34 teams.

2. Petrography, Mineral Chemistry and Interpretation of the Textures

The mineral assemblages and the chemical analyses of the constituent minerals are summarized in Tables 1 and 2. Mineral abbreviations used in this paper are after KRETZ (1983).

The aluminous metapelitic rocks are generally coarse-grained and the textures are quite heterogeneous. In general, ferromagnesian minerals such as Opx and Crd have characteristically high X_{Mg}, and compositional zoning can be detected in Grt and Opx (Table 2). The mineral associations in Table 2 denote local mineral assemblages occurring in a small domain in a single thin section.

In Opx- and Sil-bearing assemblages (Sp. 2206, 2208, 2209, FP1A), Opx+Sil±Grt association is probably an initial mineral paragenesis in relatively magnesian and aluminous metapelites. In these rocks, Opx and Sil are never in direct contact with each other and are separated by Crd moats (Fig. 2A) or Crd+Spr symplectites. The textures suggest the following reactions (HARLEY *et al.*, 1990):

$$\mathrm{Opx+Sil+Qtz=Crd}, \qquad (1)$$

in a Qtz-present domain, and

$$\mathrm{Opx+Sil=Crd+Spr}, \qquad (2)$$

in a Qtz-absent domain, respectively. In Grt-bearing assemblages, Grt preserves Opx and Sil as inclusions, and Grt is occasionally rimmed by symplectitic intergrowth of Opx+Crd±Spr (Fig. 2B). The inferred reactions are

$$\mathrm{Grt=Opx+Crd\pm Spr}, \qquad (3)$$

$$\mathrm{Grt+Qtz=Opx+Crd}. \qquad (4)$$

These reactions are visualized on a simplified (Fe, Mg)O-Al_2O_3-SiO_2 diagram (Fig. 3), in which we can see that the appearance of Spr-bearing assemblages probably depends on

Table 1. Mineral assemblages in the Forefinger Point granulites for microprobe analyses.

Sample No.	Opx	Sil	Grt	Crd	Spr	Spl	Crn	Bt	Ged	Pl	Kfs	Qtz	others
2203	+		+	+	i			+		+	+		xenotime
2206	+	+		+				+		+	+		Rt, Zrn
2208	+	+		+		i		+			+	+	
2209	+	+	+	+	i	i		+		+	+		
2212	+			+	+	i	i	+			+		Zrn
2220	+		+	+	i			+				i	
2223	+		+	+	i	i		+		+		+	
2225		+	+			+		+		+		+	Ilm, Rt, Zrn
2231	+		+	+				+	+	+		+	Mag
FP1A	+	+		+	i			+			+		

+Present ; i as inclusions in other phases. Mineral abbreviations are after KRETZ (1983).

Table 2. Mineral chemistry of the Forefinger Point granulites.

Sp. No.	Association	Opx		Grt			Crd	Spr		Spl	Bt		Ged	Pl
		X_{Mg}	Al_2O_3#	X_{Mg}	X_{Grs}	X_{Sps}	X_{Mg}	X_{Mg}	Si	X_{Mg}	X_{Mg}	TiO_2#	X_{Mg}	X_{Ca}
2203	Opx-Grt in Kfs	0.720	6.62	0.502	0.041	0.010	—	—	—	—	—	—	—	—
	Opx-Grt-Crd-Spr	0.678	8.12	0.449	0.024	0.013	0.853	0.765	0.800	—	0.785	1.98	—	—
	Opx-Grt-Bt-Pl	0.704	7.51	0.479	0.021	0.012	—	—	—	—	0.797	1.39	—	0.282
2206	Opx-Sil-Crd-Bt	0.822	5.31	—	—	—	—	—	—	—	—	—	—	—
		0.803*	3.92*	—	—	—	0.910	—	—	—	0.870	3.07	—	—
	Opx-Bt-Pl	0.845	7.35	—	—	—	—	—	—	—	0.890	3.89	—	—
		0.847*	2.75*	—	—	—	—	—	—	—	—	—	—	0.207
2208	Opx-Crd-Sil-Bt	0.770	4.84	—	—	—	0.889	—	—	n.a.	0.817	3.36	—	—
2209	Opx-Grt-Sil-Crd-Bt	0.726	8.40	0.485	0.020	0.035	—	n.a.	n.a.	n.a.	—	—	—	—
		—	—	0.462*	0.023*	0.036*	0.865	—	—	—	0.797	3.19	—	—
	Grt-Opx-Pl	0.732	5.42	0.502	0.020	0.027	—	—	—	—	—	—	—	0.276
		—	—	0.458*	0.024*	0.025*	—	—	—	—	—	—	—	—
2212	Opx-Spr-Crd-Bt	0.766	7.58	—	—	—	0.887	0.828	0.787	—	0.828	1.27	—	—
	Spr-Spl-Crn-Bt	—	—	—	—	—	—	0.865	0.721	0.600	0.826	1.20	—	—
2220	Grt-Opx-Bt	0.808	9.03	0.606	0.039	0.009	—	—	—	—	0.808	5.12	—	—
	Grt-Opx-Crd-Spr-Bt	0.750	7.75	0.606	0.037	0.007	—	—	—	—	—	—	—	—
		—	—	0.489*	0.042*	0.017*	0.894	0.820	0.786	—	0.893	3.68	—	—
2223	Grt-Crd-Spr-Bt	—	—	0.451	0.041	0.013	0.867	—	—	—	0.748	5.56	—	—
	Grt-Opx-Crd-Bt	0.757	6.15	0.496	0.032	0.013	0.877	—	—	—	0.787	4.46	—	—
	Opx-Grt-Spr-Spl-Crd-Pl	0.761	9.06	0.494	0.036	0.011	0.882	0.817	0.756	0.490	—	—	—	0.410
2225	Grt-Spl-Sil	—	—	0.454	0.056	0.009	—	—	—	0.501	—	—	—	—
		—	—	0.392*	0.035*	0.012*	—	—	—	—	—	—	—	0.406
	Grt-Spl-Sil	—	—	0.407	0.040	0.013	—	—	—	0.437	—	—	—	—
	Spl-Pl-Bt	—	—	—	—	—	—	—	—	0.421	0.752	4.07	—	0.596
2231	Grt-Opx-Crd-Ged	0.669	7.84	0.341	0.029	0.020	—	—	—	—	—	—	—	—
		0.620*	4.90*	0.320*	0.031*	0.017*	0.836	—	—	—	—	—	0.631	0.248
FP1A	Opx-Crd-Spr-Sil-Bt	0.820	8.58	—	—	—	—	—	—	—	—	—	—	—
		0.736*	6.14*	—	—	—	0.862	0.807	0.730	—	0.810	2.91	—	—

$X_{Mg}=Mg/(Fe^{2+}+Mg)$, Fe^{3+} recalculated. #wt%. *rim composition of the same mineral. n.a. not analyzed.
$X_{Grs}=Ca/(Fe^{2+}+Mg+Ca+Mn)$, $X_{Sps}=Mn/(Fe^{2+}+Mg+Ca+Mn)$ of Grt, $X_{Ca}=Ca/(Ca+Na+K)$ of Pl.

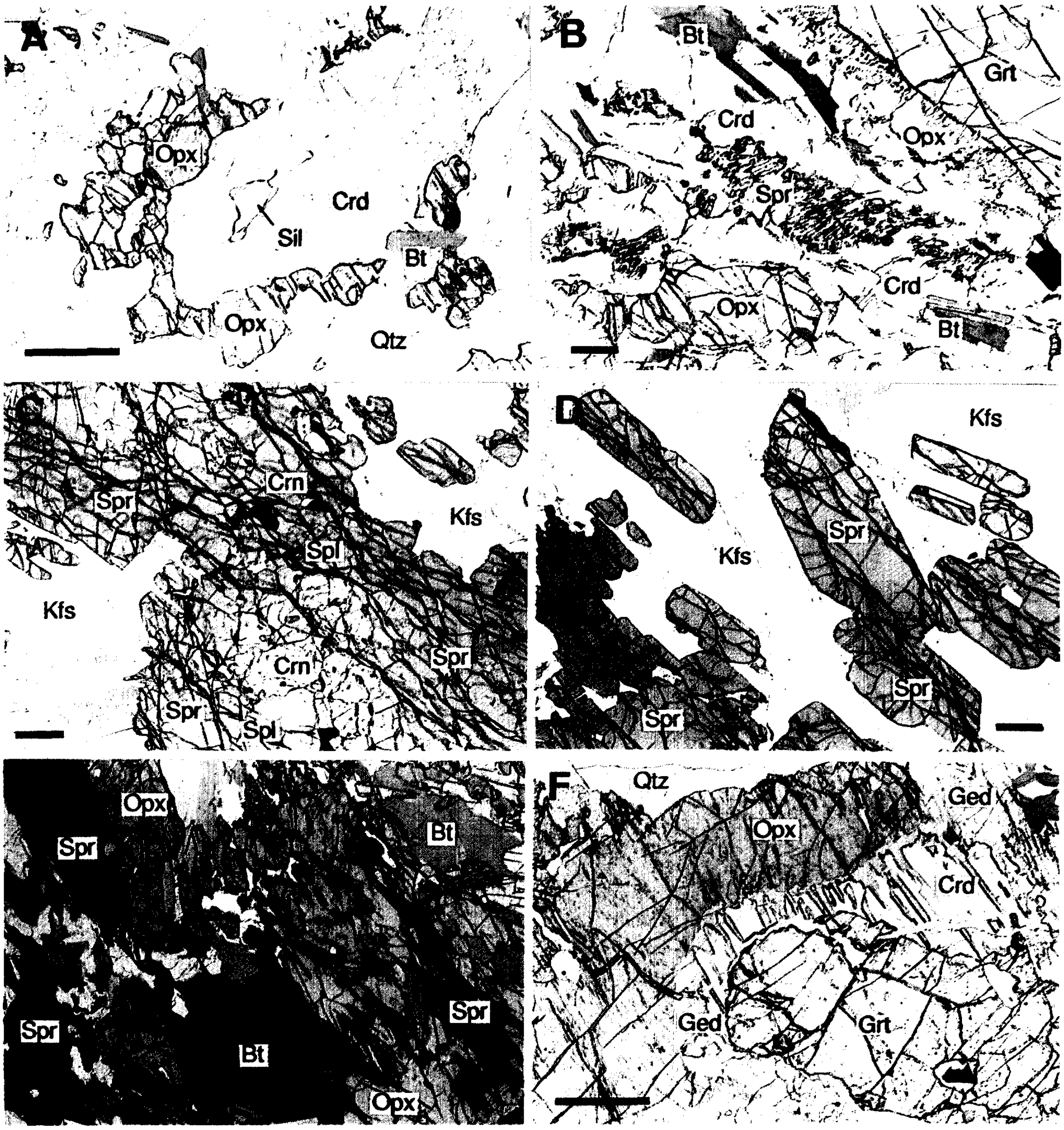

Fig. 2. Photomicrographs of the representative samples from Forefinger Point. A. Secondary Crd separating initial Opx and Sil (Sp. 93022208). B. Symplectitic intergrowth of Spr + Crd + Opx (vermiculated) replacing Grt (Sp. 93022223). C. Spl and Crn inclusions in Spr (Sp. 93022212). D. Euhedral Spr in Kfs (Sp. 93022212). E. Intergrowth of Spr and Opx (Sp. 93022212). F. Secondary Ged + Crd between Opx and Grt (Sp. 93022231). Specimen numbers are abbreviated as last four digits in the text and figures, e.g. as 2208 for 93022208, etc. Scale bars = 0.5 mm.

the bulk chemistry, in particular on a degree of silica saturation. Chemical compositions of the Spr are present in Fig. 4, in which Spr formed through the reactions (2) and (3) plot in Fig. 4A. It is noteworthy that no Spr+Qtz assemblage is observed in these rocks. In general, Opx preserves high Al_2O_3 cores (up to 8.5 wt%) and lower Al_2O_3 rims (~5-6 wt%). Symplectitic Opx around Grt is characterized by relatively low Al_2O_3 around 5-6

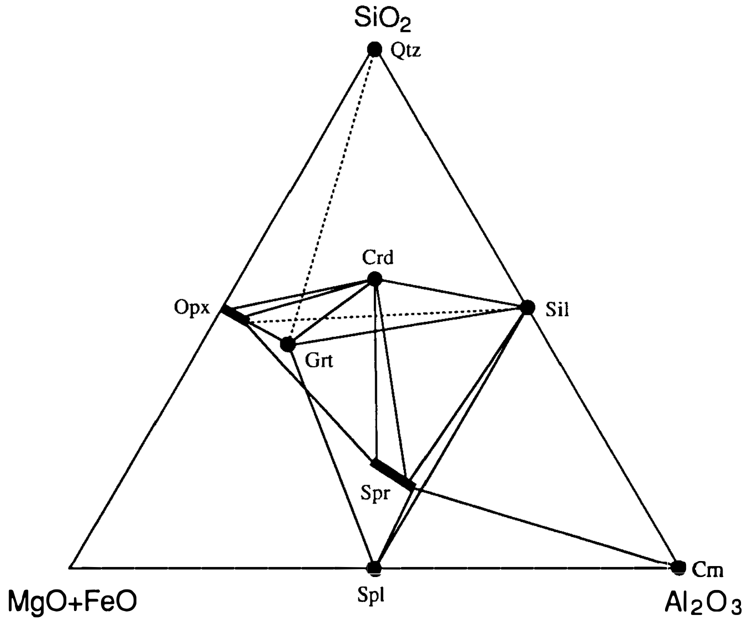

Fig. 3. *(MgO + FeO)-Al_2O_3-SiO_2 diagram illustrating mineral assemblages observed in the Forefinger Point granulites. Dotted tie-lines denote possible initial assemblages at the peak metamorphic conditions.*

wt% (Table 2).

In Opx-absent metapelites (Sp. 2225), Grt+Sil+Spl association without Crd is common, and no distinctive reaction texture is observed. Because no Spl+Qtz association is observed (although both phases are present in the rock), Grt+Sil+Spl association has been stable during the initial isothermal decompression. The reactions mentioned above inevitably suggest decompression at a relatively high-temperature condition.

In Sil- and Qtz-absent assemblages (Sp. 2212), Spr+Spl+Crn+Opx association is observed, in which Spl and Crn occur as inclusions in Spr (Fig. 2C), and they are never present outside Spr. Euhedral Spr crystals are seen in Kfs (Fig. 2D). In a different domain, Spr+Opx intergrowth is observed (Fig. 2F), and a little Crd is rarely seen being associated with Opx. Abundant Bt exist among these anhydrous minerals. The Spr compositions show two distinctive types, namely those including Crn+Spl are more aluminous than those being associated with Opx±Crd (Figs. 3 and 4B). Similar reaction textures, *i.e.* Spl and Crn relics rimmed by Spr, have been reported from the Sipiwesk Lake area in Canada (ARIMA and BARNETT, 1984). HENSEN (1987) reinterpreted this texture as indicative of increasing pressure accompanied by increasing temperature. If this interpretation is reasonable, Sp. 2212 preserves a prograde segment of the *P-T* evolution as represented by the reaction :

$$\text{Spl}+\text{Crn}+\text{Crd}=\text{Spr}, \qquad (5)$$

which has a negative slope in *P-T* domain, with Spr on the high-temperature side (HENSEN, 1987). Combining with the decompressional reactions (1), (2), (3) and (4), the *P-T* evolution of the Forefinger Point granulites is best represented by a clockwise loop.

In addition to the anhydrous mineral assemblages mentioned above, the rocks contain

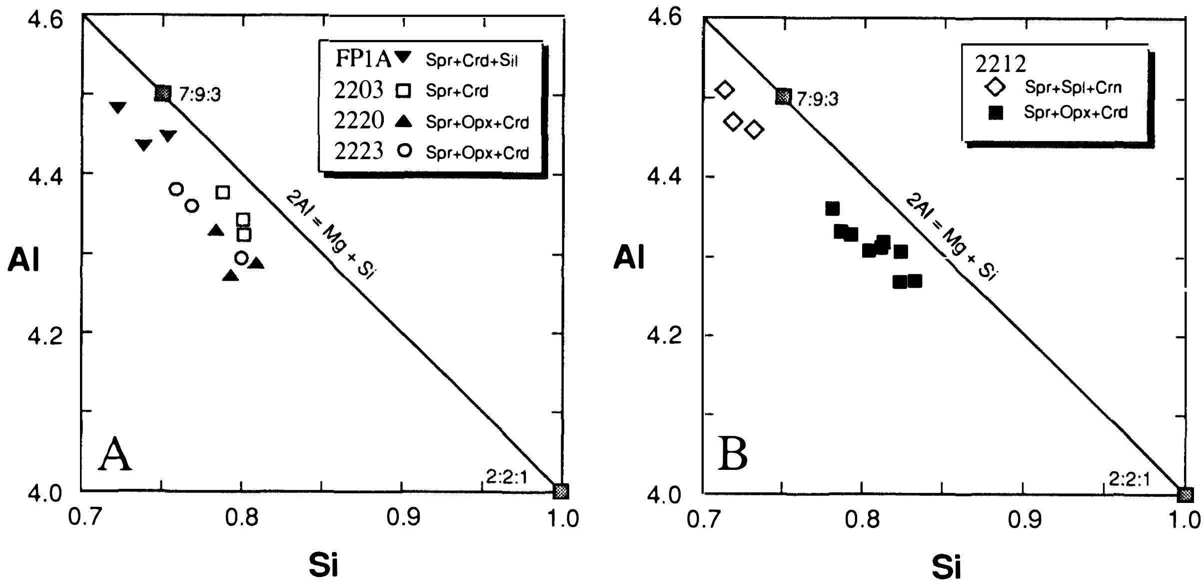

Fig. 4. Chemical compositions of sapphirine on Al-Si cation diagram based on O = 10. 7 : 9 : 3 and 2 : 2 : 1 are molecular ratio of MgO : Al_2O_3 : SiO_2. A. Sapphirine in Opx-Sil-Crd-bearing rock (Sp. FP1A) and Grt-Opx-Crd-bearing but Sil-absent rocks (Sp. 2203, 2220 and 2223). B. Sapphirine in silica-undersaturated rock (Sp. 2212). Note sapphirines containing Spl and Crn inclusions are significantly aluminous than those without inclusions. See Fig. 3 for comparison.

substantial Bt or Ged (Table 1 ; *e.g.* Figs. 2E and F). The significance of these hydrous minerals will be discussed elsewhere.

3. *P-T* Conditions

3.1. Petrogenetic grid

The mineral reactions observed in the Forefinger Point granulites can be interpreted in the model FMAS system (Fig. 5). This grid is for low-fo_2 conditions modified after HENSEN (1971), and reproduced in HENSEN and HARLEY (Fig. 2.5(a), 1990). On the basis of the petrographical evidence, the reactions to produce secondary Crd proceeded between invariant points [Spl] and [Qtz] in Fig. 5. According to HARLEY *et al.* (1990), the invariant points [Spl] and [Qtz] lie approximately at 11 ± 1 kbar and 1040 ± 15°C, and at 8-9 kbar and 950°C, respectively. This implies that the Forefinger Point granulites have certainly undergone very high *P-T* conditions at some stage in the *P-T* evolution. However, there is no evidence that this *P-T* path came down from the Spr-Qtz stability field. The rocks therefore do not appear to have reached the temperatures experienced by those in the neighboring Napier Complex (Fig. 1). The *P-T* path probably suggests nearly isothermal decompression (HARLEY *et al.*, 1990). It is also noteworthy that osumilite or its characteristic breakdown products are absent in these rocks, whereas the peak assemblage Opx+Sil+Kfs+Qtz, which is chemically equivalent to osumilite, is widespread. This probably suggests initial conditions were outside the osumilite stability field, *i.e.* pressure in excess of ~10 kbar (MOTOYOSHI *et al.*, 1993).

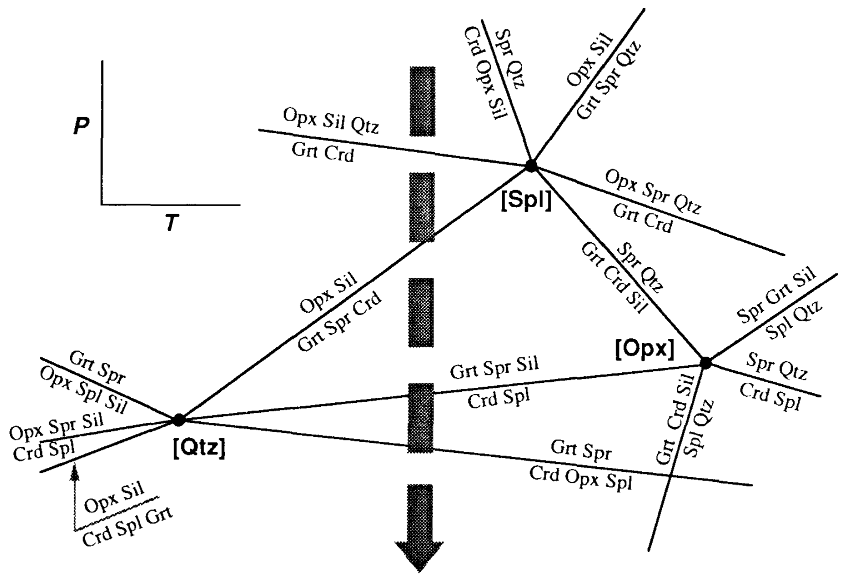

Fig. 5. Model FMAS grid for low-f_{O_2} condition modified after HENSEN (1971) and reproduced in HENSEN and HARLEY (1990). The broken arrow suggests a possible decompressional P-T path on the basis of the reaction textures.

In addition to the *P-T* diagram, we try to interpret the variety of reaction textures as a function of the bulk composition of the rocks. Fig. 6 illustrates P-μ_{FeO} diagram assuming a constant temperature (Fig. 2.6(a) of HENSEN and HARLEY, 1990). If the reactions have proceeded essentially isochemically, we can interpret the variety of reactions, to a first approximation, as due to the differences in μ_{FeO} of the rocks. The difference in this case means local domains of chemical composition within the same rock. On this diagram, the relative order of the reactions along the decompression can be postulated. Moreover, we can see why distinctive reaction textures are lacking in Opx-absent and relatively iron-rich assemblages as in Sp. 2225.

3.2. Grt-Opx geothermobarometry

Grt-Opx geothermometers (SEN and BHATTACHARYA, 1984; HARLEY, 1984a; LEE and GANGULY, 1988) and geobarometers (HARLEY and GREEN, 1982; HARLEY, 1984b) are applied to Grt-Opx bearing assemblages. Mineral analyses used for the calculations are all core of Grt and associated Opx, expecting to obtain the maximum *P-T* conditions. The results are summarized in Fig. 7. For four samples (Sp. 2203, 2209, 2220, 2223), three geothermometers yielded 750–850°C on average, which are considerably lower than the temperatures estimated from the petrogenetic grid (950–1040°C) mentioned above. Moreover, pressures calculated are significantly lower, yielding 2–8 kbar without any confirmative values. A couple of possibilities are postulated to account for this discrepancy; (1) Grt and Opx were not in equilibrium under the maximum *P-T* conditions, (2) Grt and Opx were reequilibrated during the retrograde stage, (3) the rocks have been reheated under such temperatures to attain reequilibrium. For Sp. 2231, Grt-Opx-Pl-Qtz geobarometers (NEWTON and PERKINS, 1982; BOHLEN *et al.*, 1983a; PERKINS and CHIPERA, 1985; POWELL and HOLLAND, 1988; MOECMER *et al.*, 1988) were applied. However, as shown in Fig. 7, the $\ln K_D$ lines are scattered and it is almost impossible to specify which

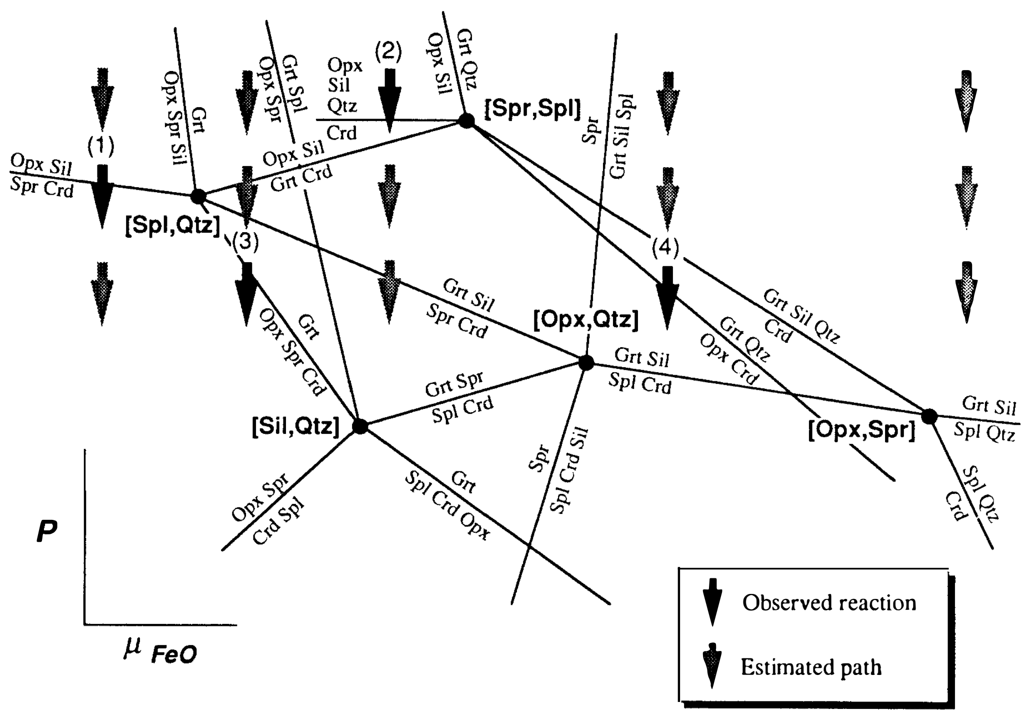

Fig. 6. P-μ_{FeO} section modified after MOHAN *et al. (1986) and* HENSEN *(1988) to explain the variety of reaction textures in terms of the bulk chemical compositions. Numbers in parentheses correspond to reactions described in the text. Shaded arrows under high μ_{FeO} can be applicable to Grt-Sil bearing assemblages free from Crd such as Sp. 2225.*

barometer is reasonable. Moreover, Grt-Opx geothermometers yielded considerably low temperatures around 600–650°C.

3.3 Grt-Pl-Sil-Qtz, GRAIL and GRIPS geobarometry

For Sp. 2225, Grt-Pl-Sil-Qtz geobarometers (NEWTON and HASELTON, 1981 ; HODGES and SPEAR, 1982 ; GANGULY and SAXENA, 1984 ; HODGESS and CROWLY, 1985 ; KOZIOL, 1989), GRAIL (BOHLEN *et al.*, 1983b) and GRIPS (BOHLEN and LIOTTA, 1986) were applied (Fig. 7). These geobarometers, except GRAIL, yielded relatively high-pressure conditions around 8–12 kbar at 900°C, and support the high *P-T* conditions inferred from the petrogenetic grid.

3.4. Spr-Spl geothermometry

An empirical calibration of Fe-Mg exchange reaction between Spr and Spl is proposed as a geothermometer by Owen and GREENOUGH (1991). This geothermometer was applied to Sp. 2212 and 2223. The former carries Spl and Crn as inclusions in Spr (Fig. 2D), suggesting that Spr-Spl pair may have preserved temperature conditions from a relatively early stage of the *P-T* evolution. The latter carries Spr and Spl as inclusions in secondary Crd, suggesting that the pair preserved temperature at some stage on the decompression. The former yielded 832°C in average, and the latter yielded 846–861°C, respectively. These values are similar to, or a little higher than, those obtained by Grt-Opx geothermometers.

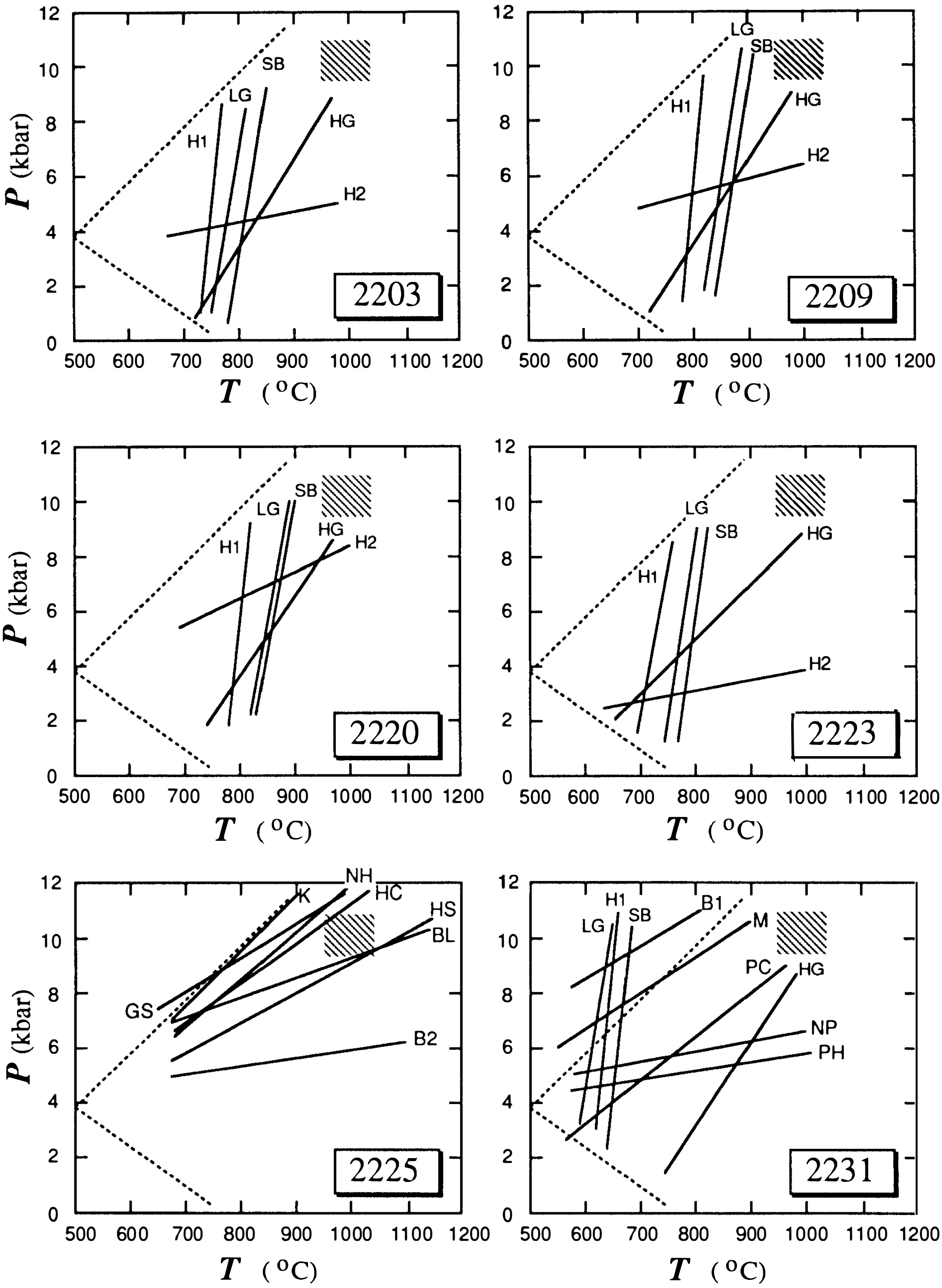

Fig. 7. *Geothermobarometry for selected samples from Forefinger Point. B1-BOHLEN et al. (1983a), B2-BOHLEN et al. (1983b), BL-BOHLEN and LIOTTA (1986), GS-GANGULY and SAXENA (1984), H1-HARLEY (1984a), H2-HARLEY (1984b), HG-HARLEY and GREEN (1982), HS-HODGES and SPEAR (1982), K-KOZIOL (1989), LG-LEE and GANGULY (1988), M-MOECHER et al. (1988), NP-NEWTON and PERKINS (1982), PC-PERKINS and CHIPERA (1985), PH-POWELL and HOLLAND (1988), SB-SEN and BHATTACHARYA (1984). Dotted lines are Al_2SiO_5 boundary after HOLDAWAY (1971). Shaded squares denote the maximum P-T conditions inferred from the petrogenetic grid (Fig. 5).*

In view of the unreasonable variation in *P-T* conditions obtained by geothermometry, we place more confidence in the *P-T* conditions inferred from the petrogenetic grid (Fig. 5).

4. Geological Implication

It is evident that the Forefinger Point granulites have undergone substantial decompression after peak metamorphic conditions of around ~1000°C at ~10 kbar. Such decompressional *P-T* paths have been reported from a number of Proterozoic high-grade terrains in East Antarctica (*e.g.* HARLEY and HENSEN, 1990, and references therein). However, the prograde *P-T* path, suggested by such relict phases as Ky and/or St, has been reported only from the Lützow-Holm Complex (HIROI *et al.*, 1983; MOTOYOSHI *et al.*, 1985, 1989). Recently, similar mineral reactions to those observed in the Forefinger Point granulites have been described from Rundvågshetta, Lützow-Holm Bay (KAWASAKI *et al.*, 1993), and these terrains appear almost identical with respect to the decompressional *P-T* paths.

According to SHIRAISHI (pers. comm.), SHRIMP dating on zircon grains from Forefinger Point and Mt. Vechernaya, both belonging to the Rayner Complex (SHERATON *et al.*, 1987; HARLEY and HENSEN, 1990), invariably preserved 500 Ma rims and no Archaean ages have been detected in zircon cores of those rocks. This suggests that a part of the Rayner Complex has experienced a 500 Ma thermal event simultaneously with the Lützow-Holm Complex (SHIRAISHI *et al.*, 1994). HARLEY *et al.* (1990) speculated that the decompressional *P-T* path obtained from the Forefinger Point granulites represents an Archaean event, but this conclusion is at odds with the new preliminary SHRIMP dating. Hence, it is stressed that the Forefinger Point granulites may not represent a reworked portion of the Archaean Napier Complex, but rather they may have a significant Cambrian history.

Although traces of prograde history have not been confirmed elsewhere in the Rayner Complex, further petrographical work may render an alternative geological framework for this part of the East Antarctic Shield.

Acknowledgments

We express our sincere thanks to members of JARE-33 and -34 and the crew of icebreaker SHIRASE during 92/93 season. The field operation in Forefinger Point was not achieved without their cooperation. Prof. K. SHIRAISHI is acknowledged for his discussion and providing us with the unpublished data on the SHRIMP dating. Drs. K. YANAI and H. KOJIMA are thanked for their assistance in microprobe work. Mr. S. OHNO kindly prepared thin sections for this study. Constructive reviews by Prof. B.J. HENSEN, Drs. H. ISHIZUKA and Y. OSANAI are greatly appreciated. Geothermobarometric calculations were mostly performed using a computer program "Metamorphic *P-T-t* Paths" by F.S. SPEAR and S.M. PEACOCK.

References

ARIMA, M. and BERNETT, R.L. (1984): Sapphirine bearing granulites from the Sipiwesk Lake area of the late Archean Pikwitonei granulite terrain, Manitoba, Canada. Contrib. Mineral. Petrol., **88**, 102–112.

BLACK, L.P., HARLEY, S.L., SUN, S.S. and McCULLOCH, M.T. (1987): The Rayner Complex of East Antarctica: Complex isotopic systematics with a Proterozoic mobile belt. J. Metamorph. Geol., **5**, 1–26.

BLACK, L.P., JAMES, P.R. and HARLEY, S.L. (1983): Geochronology and geological evolution of metamorphic rocks in the Field Islands area, East Antarctica. J. Metamorph. Geol., **1**, 277–303.

BOHLEN, S.R. and LIOTTA, J.J. (1986): A barometer for garnet amphibolites and garnet granulites. J. Petrol., **27**, 1025–1034.

BOHLEN, S.R., WALL, V.J. and BOETTCHER, A.L. (1983a): Experimental investigation and application of garnet granulite equilibria. Contrib. Mineral. Petrol., **83**, 52–61.

BOHLEN, S.R., WALL, V.J. and BOETTCHER, A.L. (1983b): Experimental investigations and geological applications of equilibria in the system FeO-TiO_2-Al_2O_3-SiO_2-H_2O. Am. Mineral., **68**, 1049–1058.

CLARKE, G.L. (1988): Structural constraints on the Proterozoic reworking of Archaean crust in the Rayner Complex, MacRobertson and Kemp Land Coast, East Antarctica. Precamb. Res., **40/41**, 137–156.

ELLIS, D.J. (1983): The Napier and Rayner Complexes of Enderby Land, Antarctica: Contrasting styles of metamorphism and tectonism. Antarctic Earth Science, ed. by R.L. OLIVER *et al*. Canberra, Aust. Acad. Sci., 20–24.

GANGULY, J. and SAXENA, S.K. (1984): Mixing properties of aluminosilicate garnets: Constraints from natural and experimental data, and applications to geothermobarometry. Am. Mineral., **69**, 88–97.

GREW, E.S. (1978): Precambrian basement at Molodezhnaya station, East Antarctica. Bull. Geol. Soc. Am., **89**, 801–813.

GREW, E.S. and MANTON, W.I. (1979): Archean rocks in Antarctica: 2.5-billion-year uranium-lead ages of pegmatites in Enderby Land. Science, **206**, 443–445.

HARLEY, S.L. (1984a): An experimental study of the partitioning of Fe and Mg between garnet and orthopyroxene. Contrib. Mineral. Petrol., **86**, 359–373.

HARLEY, S.L. (1984b): The solubility of alumina in orthopyroxene coexisting with garnet in FeO-MgO-Al_2O_3-SiO_2 and CaO-FeO-MgO-Al_2O_3-SiO_2. J. Petrol., **25**, 665–696.

HARLEY, S.L. (1988): Proterozoic granulites from the Rauer Group, East Antarctica. I. Decompressional pressure-temperature paths deduced from mafic and felsic gneisses. J. Petrol., **29**, 1059–1095.

HARLEY, S.L. and FITZSIMONS, I.C.W. (1991): Pressure-temperature evolution of metapelitic granulites in a polymetamorphic terrane: the Rauer Group, East Antarctica. J. Metamorph. Geol., **9**, 231–243.

HARLEY, S.L. and GREEN, D.H. (1982): Garnet-orthopyroxene barometry for granulites and peridotites. Nature, **300**, 697–701.

HARLEY, S.L. and HENSEN, B.J. (1990): Archaean and Proterozoic high-grade terranes of East Antarctica (40–80°E): a case study of diversity in granulite facies metamorphism. High-temperature Metamorphism and Crustal Anatexis, ed. by J.R. ASHWORTH and M. BROWN. London, Unwin Hyman, 320–370.

HARLEY, S.L., HENSEN, B.J. and SHERATON, J.W. (1990): Two-stage decompression in orthopyroxene-sillimanite granulites from Forefinger Point, Enderby Land, Antarctica: Implications for the evolution of the Archaean Napier Complex. J. Metamorph. Geol., **8**, 591–613.

HENSEN, B.J. (1971): Theoretical phase relations involving cordierite and garnet in the system MgO-FeO-Al_2O_3-SiO_2. Contrib. Mineral. Petrol., **33**, 191–214.

HENSEN, B.J. (1987): *P-T* grids for silica-undersaturated granulites in the systems MAS (n+4) and FMAS (n+3): Tools for the derivation of *P-T* paths of metamorphism. J. Metamorph. Geol., **5**, 255-271.

HENSEN, B.J. (1988): Chemical potential diagrams and chemographic projections: Application to sapphirine granulites from Kiranur and Ganguvarpatti: Evidence for rapid uplift in part of the South Indian Shield. Neus. Jahrb. Mineral. Abhund., **158**, 193-210.

HENSEN, B.J. and HARLEY, S.L. (1990): Graphical analysis of *P-T-X* relations in granulite facies metapelites. High-temperature Metamorphism and Crustal Anatexis, ed. by J.R. ASHWORTH and M. BROWN, London, Unwin Hyman, 19-56.

HIROI, Y., SHIRAISIH, K. and MOTOYOSHI, Y. (1991): Late Proterozoic paired metamorphic complexes in East Antarctica, with special reference to the tectonic significance of ultramafic rocks. Geological Evolution of Antarctica, ed. by M.R.A. THOMSON *et al.* Cambridge, Cambridge Univ. Press, 83-87.

HIROI, Y., SHIRAISHI, K., YANAI, K. and KIZAKI, K. (1983): Aluminum silicates in the Prince Olav and Sôya Coasts, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **28**, 115-131.

HODGES, K.V. and SPEAR, F.S. (1982): Geothermometry, geobarometry and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire. Am. Mineral., **67**, 1118-1134.

HODGES, K.V. and CROWLY, P.D. (1985): Error estimation and empirical geothermobarometry for pelitic systems. Am. Mineral., **70**, 702-709.

HOLDAWAY, M.J. (1971): Stability of andalusite and the aluminum silicate phase diagram. Am. J. Sci., **271**, 97-131.

KAWASAKI, T., ISHIKAWA, M. and MOTOYOSHI, Y. (1993): A preliminary report on cordierite-bearing assemblages from Rundvågshetta, Lützow-Holm Bay, East Antarctica: Evidence for a decompressional *P-T* path? Proc. NIPR Symp. Antarct. Geosci., **6**, 47-56.

KOZIOL, A.M. (1989): Recalibration of the garnet-plagioclase-Al_2SiO_5-quartz (GASP) geobarometer and applications to natural parageneses. EOS, **70**, 493.

KRETZ, R. (1983): Symbols for rock-forming minerals. Am. Mineral., **68**, 277-279.

LEE, H.Y. and GANGULY, J. (1988): Equilibrium compositions of coexisting garnet and orthopyroxene: Experimental determinations in the system FeO-MgO-Al_2O_3-SiO_2, and applications. J. Petrol., **29**, 93-114.

MOECHER, D.P., ESSENE, E.J. and ANOITZ, L.M. (1988): Calculation and application of clinopyroxene-garnet-plagioclase-quartz geobarometers. Contrib. Mineral. Petrol., **100**, 92-106.

MOHAN, A. and ACKERMAND, D. and LAL, R.K. (1986): Reaction textures and *P-T-X* trajectory in the sapphirine-spinel-bearing granulites from Ganguvarpatti, Southern India. Neus. Jahrb. Mineral. Abhund., **154**, 1-19.

MOTOYOSHI, Y., MATSUBARA, S., MATSUEDA, H. and MATSUMOTO, Y. (1985): Garnet-sillimanite gneisses from the Lützow-Holm Bay region, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **37**, 82-94.

MOTOYOSHI, Y., MATSUBARA, S. and MATSUEDA, H. (1989): *P-T* evolution of the granulite-facies rocks of the Lützow-Holm Bay region, East Antarctica. Evolution of Metamorphic Belts, ed. by J.S. DALY *et al.* Oxford, Blackwell, 325-329 (Geol. Soc. Spec. Pub., No. 43).

MOTOYOSHI, Y., HENSEN, B.J. and ARIMA, M. (1993): Experimental study of the high-pressure stability limit of osumilite in the system K_2O-MgO-Al_2O_3-SiO_2: Implications for high-temepratute granulites. Eur. J. Mineral., **5**, 439-445.

NEWTON, R.C. and HASELTON, H.T. (1981): Thermodynamics of the garnet-plagioclase-Al_2SiO_5-quartz geobarometer. Thermodynamics of Minerals and Melts, ed. by R.C. NEWTON *et al.* New York, Springer, 131-147.

NEWTON, R.C. and PERKINS, D. III (1982): Thermodynamics calibration of geobarometers based on the assemblages garnet-plagioclase-orthopyroxene (clinopyroxene)-quartz. Am. Mineral., **67**, 203-222.

OWEN, J.V. and GREENOUGH, J.D. (1991): An empirical sapphirine-spinel Mg-Fe exchange thermometer and its application to high grade xenoliths in the Popes Harbour dyke, Nova Scotia, Canada.

Lithos, **26**, 317–332.

PERKINS, D.III and CHIPERA, S.J. (1985): Garnet-orthopyroxene-plagioclase-quartz barometry: Refinement and application to the English River subprovince and the Minnesota River valley. Contrib. Mineral. Petrol., **89**, 69–80.

POWELL, R. and HOLLAND, T.J.B. (1988): An internally consistent thermodynamic dataset with uncertainties and correlations: 3. Applications to geobarometry, worked examples and a computer program. J. Metamorph. Geol., **6**, 173–204.

SEN, S.K. and BHATTACHARYA, A. (1984): An orthopyroxene-garnet thermometer and its application to the Madras charnockites. Contrib. Mineral. Petrol., **88**, 64–71.

SHERATON, J.W., OFFE, L.A., TINGEY, R.J. and ELLIS, D.J. (1980): Enderby Land, Antarctica: An unusual Precambrian high grade metamorphic terrain. J. Geol. Soc. Aust., **27**, 1–18.

SHERATON, J.W., TINGEY, R.J., BLACK, L.P., OFFE, L.A. and ELLIS, D.J. (1987): Geology of Enderby Land and western Kemp Land, Antarctica. BMR Bull., **223**, 51 p.

SHIRAISHI, K., ELLIS, D.J., HIROI, Y., FANNING, C.M., MOTOYOSHI, Y. and NAKAI, Y. (1994): Cambrian orogenic belt in East Antarctica and Sri Lanka: Implications for Gondwana assembly. J. Geol., **102**, 47–65.

THOST, D.E., HENSEN, B.J. and MOTOYOSHI, Y. (1991): Two-stage decompression in garnet-bearing mafic granulites from Søstrene Island, Prydz Bay, East Antarctica. J. Metamorph. Geol., **9**, 245–256.

(Received April 8, 1994; Revised manuscript received May 29, 1994)