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A PRELIMINARY REPORT ON CORDIERITE-BEARING ASSEMBLAGES FROM RUNDVÅGSHETTA, LÜTZOW-HOLM BAY, EAST ANTARCTICA: EVIDENCE FOR A DECOMPRESSIONAL *P-T* PATH ?

Toshisuke KAWASAKI[1], Masahiro ISHIKAWA[2] and Yoichi MOTOYOSHI[3]

[1] *Institute of Earth and Planetary Sciences, Faculty of Education, Kochi University, Kochi 780*
[2] *Institute of Geology and Paleontology, Faculty of Science, Tohoku University, Sendai 980*
[3] *National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173*

Abstract: Diagnostic mineral assemblages involving cordierite, sapphirine, orthopyroxene, sillimanite and garnet are newly reported from Rundvågshetta, Lützow-Holm Bay, East Antarctica. Cordierite is probably of secondary origin, because it occurs as symplectitic intergrowth with sapphirine at the expense of initial orthopyroxene + sillimanite. In a different domain, vermiculated orthpyroxene + cordierite ± sapphirine replaces initial garnet locally. On the basis of the textures, the following reactions are inferred:

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

These reactions suggest near isothermal decompression in the model FMAS system, and along with a prograde kyanite from the same locality, the clockwise *P-T* path of the rocks are confirmed. Moreover, the maximum temperature condition of the Lützow-Holm Complex is estimated to be as high as 900°C based on the initial orthopyroxene + sillimanite + garnet assemblage, and this value is apparently higher than those previously estimated.

In high-grade metamorphic terranes of East Antarctica, the similar mineral assemblages and reaction textures have been reported from Forefinger Point in Enderby Land and the Rauer Group in Prydz Bay, respectively. However, it is questionable as to whether these terranes can be corrrelatable to Rundvågshetta, because no evidence of prograde *P-T* paths have been obtained from Forefinger Point and the Rauer Group and there is a lack of relavent geochronological data.

1. Introduction

Rundvågshetta is a small, *c.* 3 km^2 outcrop situated at southern Lützow-Holm Bay (Fig. 1A). The basement rocks are composed essentially of pelitic gneisses and basic to intermediate gneisses, with subordinate pegmatites, ultramafics and calc-silicates. Detailed description of the rocks has been reported by MOTOYOSHI *et al.* (1986) along with a geological map.

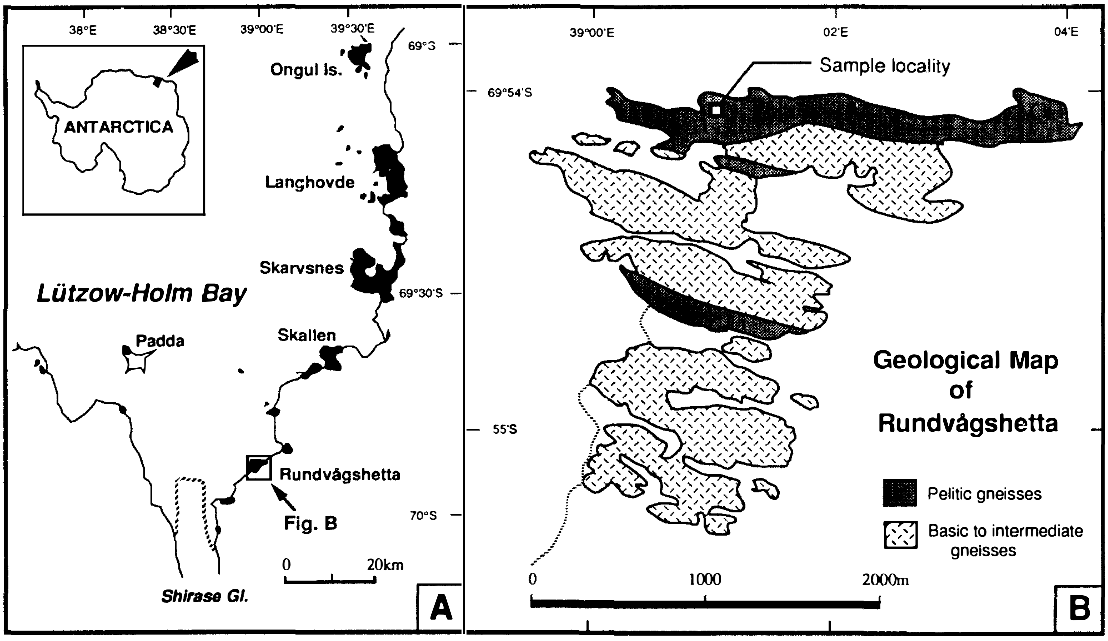

Fig. 1. Location map and geological map of Rundvågshetta. A: Location of Rundvågshetta in Lützow-Holm Bay. B: Locality of the samples described in this paper in Rundvågshetta. The geological map is simplified and modified after MOTOYOSHI *et al. (1986).*

Recent geochronological studies yielded Archaean ages from Rundvågshetta: 3020 Ma by Rb-Sr whole rock isochron method (NAKAJIMA *et al.*, 1988) and 2500-2800 Ma for zircon core by SHRIMP (SHIRAISHI *et al.*, 1994). However, the basement rocks in Rundvågshetta are interpreted to have undergone regional granulite-facies metamorphism, probably in Early Paleozoic, *c.* 520 Ma (SHIRAISHI *et al.*, 1994).

Geothermobarometries yielded the *P-T* conditions to be 760-830°C at 7-8 kbar (MOTOYOSHI *et al.*, 1989), indicating that Rundvågshetta is probably located close to the "thermal axis" defined by HIROI *et al.* (1991). This implies that the basement rocks in Rundvågshetta represent the highest-grade part of the Lützow-Holm Complex.

Diagnostic mineral assemblages including cordierite were newly found from Rundvågshetta. In one of the samples, orthopyroxene and sillimanite coexist but they are separated from each other by "canal" of cordierite and/or symplectitic intergrowth of cordierite+sapphirine. These mineral associations have never been reported from the Lützow-Holm Bay region (MOTOYOSHI, 1986).

The aim of this paper is to give petrographical characteristics of the cordierite-bearing assemblages from Rundvågshetta, and to discuss preliminarily their significance with respect to the *P-T* evolution, combining the petrographical evidence of relict kyanite from the nearby locality.

2. Petrography and Mineral Chemistry

The samples described in this paper (Sp. RVH92011102A and RVH92011102I) both occur at the northern part of Rundvågshetta (Fig. 1B). The rocks occur as thin seams in quartzfeldspathic gneisses in which large crystals of garnet and sillimanite are seen locally (Fig. 2). Cordierite and sapphirine were easily recognized on the surface of the samples. Detailed petrographical descriptions are given below. Mineral abbreviations are after KRETZ (1983).

Chemical analyses of the minerals have been carried out with the JEOL JCXA-733 electron microprobe analyzer at the National Institute of Polar Research. The correction method is Bence-Albee's procedure. Representative analyses of the minerals are given in Tables 1 and 2.

RVH92011102A: The constituent minerals are sapphirine (Spr), cordierite (Crd), garnet (Grt), orthopyroxene (Opx), sillimanite (Sil), spinel (Spl), biotite (Bt), hornblende (Hbl), K-feldspar (Kfs), plagioclase (Pl), quartz (Qtz) and zircon (Zrn). Opaque mineral is rarely seen. All these minerals are not necessarily in equilibrium. In this sample, textural relationships among Opx, Sil, Crd and Spr are particularly characteristic and important, because Opx and Sil are never in direct contact being separated from each other by "canal" of Crd and/or Crd+Spr (Figs. 3A and 3C).

Grt is associated with prismatic Opx and Sil, and is locally replaced by Crd+Opx symplectite (Fig. 3B). Almandine and grossular components slightly increase from core ($Alm_{0.472}$ $Pyp_{0.503}$ $Grs_{0.025}$) to rim ($Alm_{0.477}$ $Pyp_{0.487}$ $Grs_{0.035}$) in contact with vermiculated Opx. Grt contains Kfs as inclusions in which Bt and Qtz are also included in the Kfs. Opx shows two modes of occurrence. One is as large prismatic crystal showing wavy extinction and including round-shaped biotite. The other is as a vermiculated crystal intergrown with Crd, locally developed at the expense of garnet (Fig. 3B). The former has a higher Al_2O_3 content around 7 wt%, whereas the Al_2O_3 content of the vermiculated Opx is ~5.1 wt%. Crd occurs as a reaction product after Opx and Sil assemblage, and as a replacement of Grt. The

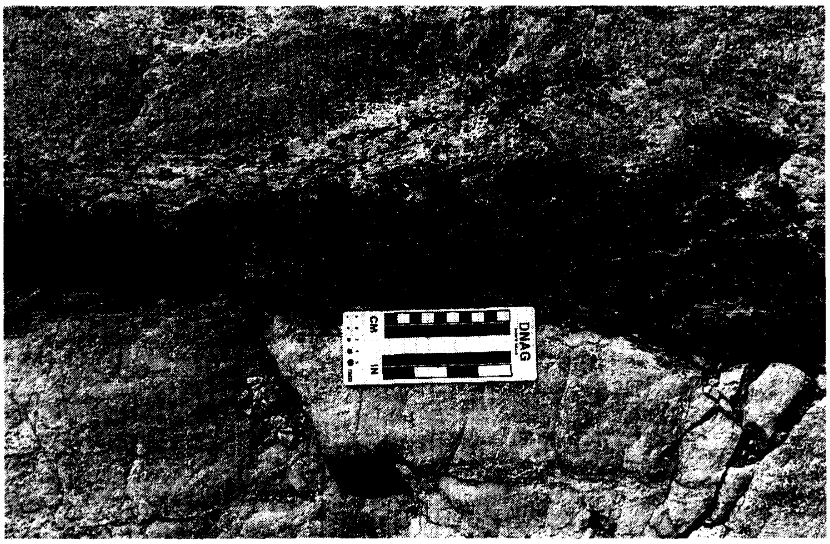

Fig. 2. Field occurrence of Crd-Opx-Sil-Spr-Grt-Bt bearing rock (Sp. RVH92011102A). The rock occurs as thin seams in Grt-bearing quartzfeldspathic gneisses.

Table 1. Representative chemical analyses

	Grt		Opx			Crd		
Anal. No.	1	58	61	23	40	16	32	59
SiO_2	39.99	40.47	51.59	50.54	50.72	50.13	49.41	50.02
TiO_2	.03	.03	.12	.11	.08	.03	.00	.00
Al_2O_3	22.00	22.33	5.17	7.19	6.84	32.74	32.58	33.20
Cr_2O_3	.00	.03	.25	.26	.12	.00	.00	.00
FeO	22.98	22.95	17.04	16.82	17.75	2.66	2.78	2.14
MnO	.75	.66	.11	.15	.07	.00	.06	.00
MgO	13.74	13.14	25.03	24.88	25.00	12.12	12.27	12.29
CaO	.95	1.33	.04	.07	.02	.07	.06	.00
Na_2O	n.d.	n.d.	.01	.00	.00	.00	.09	.09
K_2O	.01	.00	.02	.00	.00	.00	.05	.01
ZnO	n.a.	n.a.	.09	.06	.00	.00	.05	.00
Total	100.46	100.93	100.32	99.71	100.59	97.95	97.36	97.74
O	12	12	6	6	6	18	18	18
Si	2.994	3.011	1.889	1.834	1.834	5.054	5.016	5.032
Ti	.002	.002	.003	.003	.002	.002	.000	.000
Al	1.941	1.958	.222	.307	.291	3.890	3.898	3.937
Cr	.000	.002	.007	.007	.003	.000	.000	.000
Fe	1.439	1.428	.512	.500	.537	.224	.236	.180
Mn	.047	.042	.005	.006	.002	.000	.005	.000
Mg	1.533	1.458	1.349	1.345	1.347	1.821	1.857	1.843
Ca	.076	.106	.003	.001	.001	.008	.007	.000
Na	—	—	.000	.000	.000	.001	.017	.017
K	.001	.000	.001	.000	.000	.000	.007	.002
Zn	—	—	.002	.002	.000	.000	.004	.000
X_{Mg}	0.516	0.505	0.725	0.729	0.715	0.890	0.887	0.911
An	—	—	—	—	—	—	—	—

n.d. not determined; n.a. not analyzed.
X_{Mg} = Mg/(Fe+Mg); An = 100 Ca/(Ca+Na+K).
Anal. No. 1-core; 58-rim in contact with vermiculated Opx; 61-vermiculated Opx; 23-core; 40-rim; 16-symplectitic intergrowth with Opx around Grt; 32-symplectitic intergrowth with Spr; 59-collar around Grt; 54-symplectitic inter-

latter Crd is slightly magnesian (X_{Mg} = 0.91) than the former Crd (X_{Mg} = 0.89). Spr occurs as symplectitic intergrowth with Crd, replacing Sil. The composition is relatively homogeneous with X_{Mg} = 0.2. Spl is locally observed being associated with Spr+Crd symplectite. The ZnO content is around 2 wt%. Pl shows several modes of occurrence, (1) as a product replacing Grt (An_{62}), (2) as an inclusion within Crd (An_{70}), (3) as a phase between Grt and Crd (An_{59}), (4) as a phase intergrown with Crd+Opx symplectite (An_{52}), and (5) as a symplectitic intergrowth with Spr (An_{83}). Bt is generally associated with Opx and Grt, and occurs also as inclusions in them or as overgrowths on Opx. Bt also occurs as inclusions in Crd. Sil is separated from Opx by Crd and is partially replaced by Spr+Crd symplectite within the Crd moats (Fig. 3C). Hbl is locally associated with Sil but its significance is unclear. Fe_2O_3 content of Sil is less than 0.7 wt%. Qtz is present in the matrix locally as well as in Grt, but it is never in direct contact with Spr.

of minerals in Sp. RVH92011102A.

Spr	Spl	Pl					Bt		Sil
54	51	2	8	10	19	28	17	31	47
12.47	0.04	53.39	50.88	54.03	56.26	47.46	37.21	36.53	36.93
.03	.00	.00	.00	.01	.07	.00	5.58	4.75	.05
61.96	60.20	27.37	29.94	28.02	27.25	31.27	15.69	15.27	60.29
.35	.44	.05	.00	.00	.00	.00	.14	.09	.12
7.12	22.45	.30	.00	.02	.05	.12	7.77	9.68	.56
.01	.15	.11	.00	.00	.00	.00	.03	.01	.00
16.36	12.30	.03	.02	.02	.00	.01	17.50	16.61	.00
.00	.00	13.00	14.01	12.28	10.74	16.82	.00	.02	.00
.01	.03	4.32	3.24	4.75	5.45	1.94	.26	.33	.00
.00	.02	.11	.05	.08	.04	.00	9.27	10.32	.00
.13	2.19	.00	.04	.08	.00	.00	.00	.00	.05
98.45	97.82	98.68	98.18	99.28	99.86	97.62	93.45	93.63	98.01
10	4	8	8	8	8	8	22	22	5
.754	.001	2.458	2.354	2.462	2.533	2.231	5.467	5.463	1.019
.001	.000	.000	.000	.001	.002	.000	.618	.534	.001
4.415	1.945	1.485	1.632	1.505	1.446	1.732	2.721	2.692	1.961
.017	.010	.002	.000	.000	.000	.000	.016	.011	.003
.360	.515	.011	.000	.001	.002	.005	.957	1.211	.013
.001	.004	.004	.000	.000	.000	.000	.004	.001	.000
1.474	.503	.002	.002	.001	.000	.000	3.839	3.703	.000
.000	.000	.641	.694	.600	.518	.847	.000	.004	.000
.002	.002	.385	.290	.419	.476	.177	.076	.095	.000
.000	.001	.007	.003	.004	.002	.000	1.739	1.969	.000
.006	.044	.000	.001	.003	.000	.000	.000	.000	.001
0.804	0.494	—	—	—	—	—	0.801	0.745	—
—	—	62.07	70.33	58.59	52.00	82.72	—	—	—

growth with Crd ; 51-symplectitic intergrowth with Crd and Opx.
2-partly replacing Grt ; 8-inclusion in Crd and in contact with Bt ; 10-between Grt and Crd ; 19-intergrowth with Crd + Opx symplectite ; 28-symplectitic intergrowth with Spr ; 17-inclusion in Crd ; 31-in Crd + Spr symplectite ; 47-partly replaced by Crd + Spr symplectite.

RVH92011102I: The constituent minerals are Grt, Opx, Crd, Bt, Pl, Kfs and Qtz. The sample is composed of large grains of these minerals, and their distribution is heterogeneous.

Grt is irregularly eroded along the grain boundary and Opx + Crd symplectite is observed locally (Fig. 3D). Grt rim adjacent to the symplectite has the highest X_{Mg} around 0.49. Opx shows two modes of occurrence. One is as porphyroblastic large crystal, and the other is as a vermiculated crystal intergrown with Crd. The former has a higher Al_2O_3 content ($\sim$7 wt%) than the latter ($\sim$4 wt%). There is no significant difference in X_{Mg} between the two. Bt has a moderate TiO_2 content around 4 wt%, and a similar X_{Mg} to that of Opx. Crd shows two modes of occurrence. One is as independent grain in the matrix, and the other is as in symplectitic intergrowth with Opx. Pl in contact with Grt is more calcic (An_{42}) than in Opx (An_{33}).

Table 2. Representative chemical analyses of minerals in Sp. RVH92011102I.

	Grt		Opx		Bt	Crd	Pl	
Anal. No.	14	23	4	16	21	17	2	15
SiO_2	39.77	39.99	49.94	53.02	37.12	49.89	60.80	59.12
TiO_2	.00	.00	.10	.04	4.55	.00	.00	.00
Al_2O_3	21.30	22.06	7.11	4.26	15.27	33.10	24.52	25.94
Cr_2O_3	.09	.06	.09	.24	.14	.00	.00	.01
FeO	26.10	23.07	18.08	17.88	11.38	2.78	.17	.30
MnO	.69	.77	.17	.23	.00	.05	.00	.03
MgO	11.10	12.58	23.12	24.89	16.10	12.06	.00	.02
CaO	1.36	1.88	.06	.07	.00	.02	6.86	8.88
Na_2O	.04	.00	.00	.00	.10	.03	7.47	6.57
K_2O	.02	.01	.01	.00	10.40	.05	.21	.13
ZnO	.00	.22	.00	.06	.01	.05	.06	.13
Total	100.46	100.64	98.69	100.71	95.08	98.02	100.10	101.13
O	12	12	6	6	22	18	8	8
Si	3.025	3.001	1.844	1.913	5.498	5.024	2.704	2.621
Ti	.000	.000	.003	.001	.507	.000	.000	.000
Al	1.910	1.951	.309	.181	2.666	3.929	1.285	1.355
Cr	.005	.003	.003	.007	.017	.000	.000	.000
Fe	1.661	1.448	.558	.539	1.410	.234	.006	.011
Mn	.044	.049	.005	.007	.000	.004	.000	.001
Mg	1.259	1.407	1.272	1.339	3.556	1.810	.000	.001
Ca	.110	.151	.003	.003	.000	.002	.327	.422
Na	.005	.000	.000	.000	.029	.007	.644	.565
K	.002	.001	.001	.000	1.966	.007	.012	.008
Zn	.000	.012	.000	.002	.001	.003	.002	.004
X_{Mg}	0.432	0.493	0.695	0.713	0.716	0.886	—	—
An	—	—	—	—	—	—	33.26	42.41

$X_{Mg} = Mg/(Fe+Mg)$; $An = 100Ca/(Ca+Na+K)$.
Anal. No. 14-rim in contact with Opx ; 23-rim in contact with Crd+Opx symplectite ; 4-core ; 6-vermiculated Opx in Crd ; 21-in contact with Crd+Opx symplectite ; 17-symplectitic intergrowth with Opx ; 2-in contact with Opx ; 15-in contact with Grt.

3. Discussion

On the basis of the reaction textures, it is interpreted that Crd from Rundvågshetta is probably of secondary origin at the expense of initial Opx+Sil and Grt, respectively. The possible reactions are :

$$\mathrm{Opx + Sil + Qtz = Crd},$$

in a Qtz-present domain, and

$$\mathrm{Opx + Sil = Crd + Spr},$$

in a Qtz-absent domain, respectively. Moreover,

$$\mathrm{Grt = Opx + Crd + Spr},$$
$$\mathrm{Grt + Qtz = Opx + Crd},$$

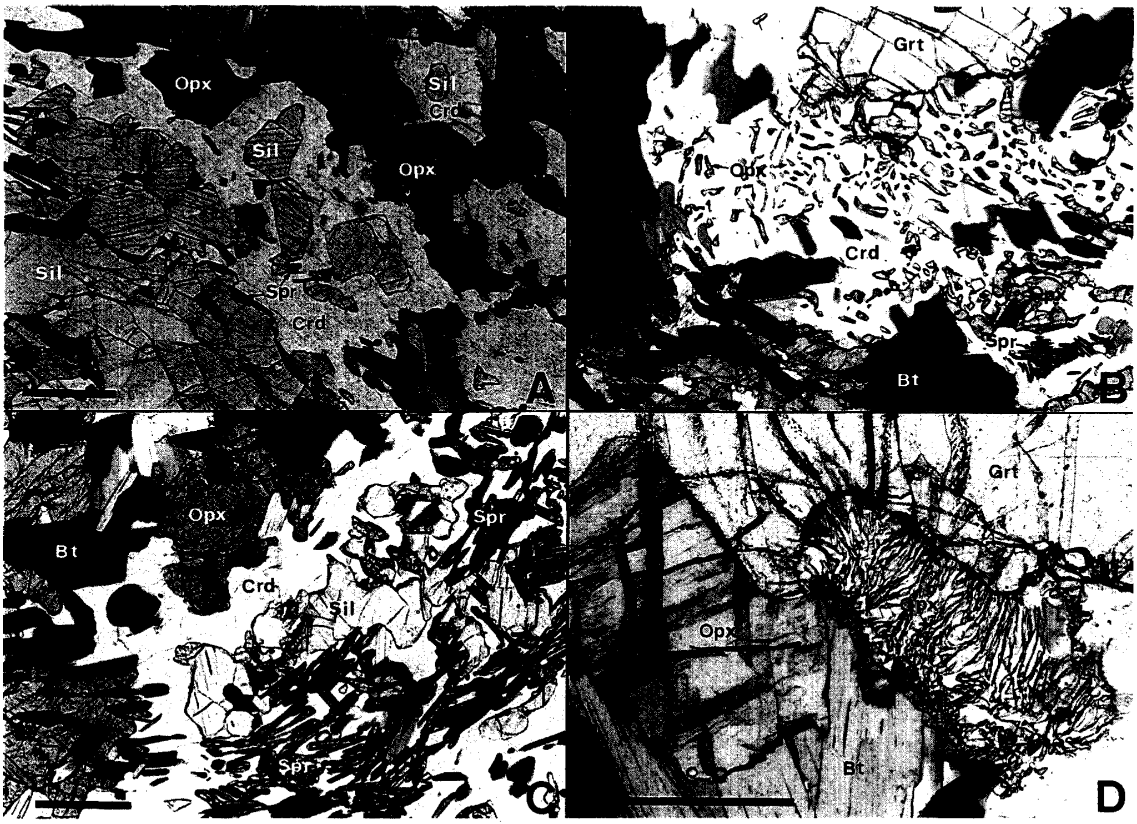

Fig. 3. Photomicrographs of the samples described in this paper (A, B, C —RVH92011102A ; D—RVH92011102I). Scale bar (lower left) is 0.5 mm. Plane polarized light. A : Mode of occurrence of Opx, Sil, Crd and minor Spr, suggesting reaction Opx + Sil = Crd + Spr. Note Opx and Sil are never in direct contact. B : Mode of occurrence of symplectitic intergrowth of Opx + Crd at the expense of Grt. Spr is locally associated with the intergrowth. C : Symplectitic intergrowth of Spr + Crd around Sil. D : Local development of symplectitic intergrowth of Opx + Crd around Grt.

are inferred to explain the symplectitic textures around Grt.

These reactions probably appear to have proceeded locally even in a thin section scale, but inevitably suggest decompression in the model FMAS system proposed by HENSEN (1971, 1986) and WATERS (1986). In the Lützow-Holm Complex, a decompressional *P-T* path has been indirectly obtained on an ultramafic granulite from Akarui Point, in which Grt is rimmed by symplectitic intergrowth of Opx + Pl + Spl (HIROI *et al.*, 1986). Based on an experimental study using this material (T. TATSUMI, pers. comm.), the symplectite crystallized at the expense of Grt with decreasing pressure, lower than 9 kbar at 800°C (HIROI *et al.*, 1991). Hence, it is stressed that the Crd from Rundvågshetta gives further constraints on the decompressional *P-T* path for the Lützow-Holm Complex.

The prograde stage of the rocks in Rundvågshetta is evidenced by relict kyanite (Ky) in Grt porphyroblast in a Grt-Sil gneiss from the nearby locality (MOTOYOSHI *et al.*, 1985, 1986). This prograde *P-T* path from the Ky to Sil field has probably been beyond the stability of Crd in ordinary bulk compositions (MOTOYOSHI, 1986) which may explain the absence of primary Crd in metapelites in the Lützow-Holm Bay region. The peak metamorphic conditions prior to the decompression is represented by Opx+Sil+Grt assemblages, which suggest a very high temperature as high as 900°C or more based on natural occurrence (SHERATON *et al*., 1980; GREW, 1980; ELLIS *et al*., 1980; MOTOYOSHI and MATSUEDA, 1984; ARIMA and BERNETT, 1984; HARLEY, 1985; HARLEY *et al*., 1990; HARLEY and FITZSIMONS, 1991; BERTRAND *et al*., 1992) and on experimental results (HENSEN and GREEN, 1973; BERTRAND *et al*., 1991; ARANOVICH and PODLESSKII, 1989). Quantitative estimation of the peak metamorphic conditions of the Lützow-Holm Complex will be given in elsewhere, but previous geothermobarometric estimation of the *P-T* conditions (760-830°C at 7-8 kbar) will be required modification.

Combining these petrographical data, we can confirm the clockwise *P-T* path for the rocks (MOTOYOSHI *et al*., 1989; HIROI *et al*., 1991), and the prograde segment of this path is unique in high-grade metamorphic terranes of East Antarctica (*e.g.* HARLEY and HENSEN, 1990). In East Antarctica, the similar Opx+Sil+Crd+Spr association has been reported from two Proterozoic terranes, namely Forefinger Point in Enderby Land (HARLEY *et al*., 1990) and the Rauer Group in Prydz Bay (HARLEY and FITZSIMONS, 1991). In both terranes, initial Opx+Sil has been replaced by symplectitic intergrowth involving Crd, Spr and Opx, and they argue that the textures indicate near isothermal decompression at temperatures of higher than 900°C. Moreover, they addressed that the initial decompression probably related to Archaean event, whereas further decompression (under lower temperature) reflected Proterozoic reworking referred to as the Rayner metamorphism. It is questionable as to whether these terranes can be correlatable to Rundvågshetta, not only because no evidence of prograde *P-T* path has been obtained from Forefinger Point and the Rauer Group, but also relevant geochronological data are lacking. In any case, we need further investigation to clarify the tectonic significance of such near isothermal decompression in these terranes.

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References

ARANOVICH, L.Ya. and PODLESSKII, K.K. (1989): Geothermobarometry of high grade metapelites:

Simultaneously operating reaction. Evolution of Metamorphic Belts, ed. by J.S. DALY *et al*. Oxford, Blackwell, 45-61 (Geol. Soc. Spec. Publ., No. 43).

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.

BERTRAND, P., ELLIS, D.J. and GREEN, D.H. (1991): The stability of sapphirine-quartz and hypersthene-sillimanite-quartz assemblages: An experimental investigation in the system FeO-MgO-Al_2O_3-SiO_2 under CO_2 and H_2O conditions. Contrib. Mineral. Petrol., **108**, 55-71.

BERTRAND, P., OUZEGANE, Kh. and KIENAST, J.R. (1992): *P-T-X* relationships in the Precambrian Al-Mg-rich granulites from In Ouzzal, Hogar, Algeria. J. Metamorph. Geol., **10**, 17-31.

ELLIS, D.J., SHERATON, J.W., ENGLAND, R.N. and DALLWITZ, W.B. (1980): Osumilite-sapphirine-quartz granulites from Enderby Land Antarctica: Mineral assemblages and reactions. Contrib. Mineral. Petrol., **72**, 123-143.

GREW, E.S. (1980): Sapphirine+quartz association from Archean rocks in Enderby Land, Antarctica. Am. Mineral., **65**, 821-836.

HARLEY, S.L. (1985): Garnet-orthopyroxene bearing granulites from Enderby Land, Antarctica: Metamorphic pressure-temperature-time evolution of the Archaean Napier Complex. J. Petrol., **26**, 819-856.

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 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 (Mineral. Soc. Ser. 2).

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. (1986): Theoretical phase relations involving cordierite and garnet revisited: The influence of oxygen fugacity on the stability of sapphirine and spinel in the system Mg-Fe-Al-Si-O. Contrib. Mineral. Petrol., **92**, 362-367.

HENSEN, B.J. and GREEN, D.H. (1973): Experimental study of the stability of cordierite and garnet in pelitic compositions at high pressures and temperatures. III. Synthesis of experimental data and geological applications. Contrib. Mineral. Petrol., **38**, 151-166.

HIROI, Y., SHIRAISHI, K., MOTOYOSHI, Y., KANISAWA, S., YANAI, K. and KIZAKI, K. (1986): Mode of occurrence, bulk chemical compositions, and mineral textures of ultramafic rocks in the Lützow-Holm Complex, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **43**, 62-84.

HIROI, Y., SHIRAISHI, 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 University Press, 83-87.

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

MOTOYOSHI, Y. (1986): Prograde and progressive metamorphism of the granulite-facies Lützow-Holm Bay region, East Antarctica. D.Sc. Thesis, Hokkaido University, 238 p. (unpublished).

MOTOYOSHI, Y. and MATSUEDA, H. (1984): Archean granulites from Mt. Riiser-Larsen in Enderby Land, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **33**, 103-125.

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., MATSUEDA, H., MATSUBARA, S., SASAKI, K. and MORIWAKI, K. (1986): Geological map of Rundvågskollane and Rundvågshetta, Antarctica. Antarct. Geol. Map Ser., Sheet 24 (with explanatory text 11 p.). Tokyo, Natl Inst. Polar Res.

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. Publ., No. 43).

NAKAJIMA, T., SHIBATA, K., SHIRAISHI, K., MOTOYOSHI, Y. and HIROI, Y. (1988): Rb-Sr whole-rock ages of metamorphic rocks from Eastern Queen Maud Land, East Antarctica (2): Tenmondai Rock and Rundvågshetta (abstract). Proc. NIPR Symp. Antarct. Geosci., **2**, 172.

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.

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 construction and deep crustal process. J. Geol., **102** (in press).

WATERS, D.J. (1986): Metamorphic history of sapphirine-bearing and related magnesian gneisses from Namaqualand, South Africa. J. Petrol., **27**, 541-565.

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