



Relict sapphirine+kyanite and spinel+kyanite associations in pyropic garnet from the eastern Sør Rondane Mountains, East Antarctica

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Abstract

Sapphirine, spinel, orthoamphibole±quartz and kyanite are included in porphyroblastic garnet in biotitic gneiss enclosed in a lens of metamorphosed ultramafic rocks in the Cambrian granulite-facies metamorphic complex of the eastern Sør Rondane Mountains, Queen Maud Land, East Antarctica. A bulk analysis of the biotitic gneiss reveals features characteristic both of ultramafic rocks, e.g., high contents of Cr and Ni, and of metasomatism associated with fluids having a crustal source, e.g., relatively elevated contents of Li, Rb, Mo, Cs, Ba, Tl, and Pb. This trace element signature is consistent with the biotitic gneiss being a slice of blackwall skarn that developed between harzburgite and the enclosing biotite–hornblende±garnet±orthopyroxene±clinopyroxene gneiss and was subsequently infolded or inserted by faulting. The matrix assemblage of the biotitic gneiss is garnet+corundum+hercynite+biotite+plagioclase+allanite+zircon. The included associations (all with biotite and rutile) are (1) sapphirine+kyanite, (2) spinel+kyanite, (3) sapphirine+spinel, (4) kyanite, and (5) orthoamphibole+plagioclase±quartz. The garnet porphyroblasts are compositionally zoned with broad pyropic cores ($X_{Mg} (=Mg/(total\ Fe + Mg)) = 0.45–0.55$) surrounded by Fe-rich rims ($X_{Mg} \approx 0.3$ at the outermost part). The garnet cores preserve compositions homogenized under peak conditions of the granulite-facies metamorphism (760–800 °C and 7–8 kb), whereas the Fe-enriched rims are attributed to an amphibolite-facies overprint at 500–600 °C. Theoretical calculations of garnet+corundum+spinel±sapphirine+kyanite equilibria in the FMAS system constrain possible P–T conditions for a sapphirine+spinel+kyanite+garnet ($X_{Mg} \approx 0.55$) assemblage to form near 450 °C and 4 kb on the prograde path. In contrast, a modified calibration of the Das et al. (Das, K., Fujino, K., Tomioka, N., Miura, H., 2006. Experimental data on Fe and Mg partitioning between coexisting sapphirine and spinel: an empirical geothermometer and its application. *Eur. J. Mineral.*, 18, 49–58). sapphirine–spinel thermometer gives 860–895 °C for the included associations; pressures would have to be at least 12 kb to stabilize kyanite at these temperatures. Neither estimate is satisfactory and the stability range of kyanite+spinel–hercynite±sapphirine assemblages remains an unresolved question. The Sør Rondane Mountains constitute the third region for kyanite, sapphirine and spinel–hercynite inclusions in garnet in granulite-facies rocks of the Neoproterozoic–Cambrian orogen extending from the Sør Rondane Mountains to Lützow–Holm Bay and onward to Sri Lanka, southern India and southern Madagascar, and thus determining the stability range of kyanite+spinel–hercynite±sapphirine is critical for deducing the tectonic evolution of this orogen.

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1. Introduction

Sapphirine is found most typically in silica-undersaturated Al- and Mg-rich rocks metamorphosed under granulite-facies conditions (Deer et al., 1978); at the highest temperatures it also appears in silica-saturated rocks (Harley and Hensen, 1990; Harley, 1998). Silimanite is the most common Al_2SiO_5 phase associated with sapphirine. Nonetheless, sapphirine is also found with kyanite as inclusions in garnet (Motoyoshi et al., 1989; Ogo et al., 1992; Hiroi et al., 1994), though not

always in equilibrium (Simon and Chopin, 2001). Another sapphirine + kyanite paragenesis involves sapphirine formation as breakdown product of kyanite-bearing assemblages during decompression (e.g., Schreyer and Abraham, 1975; Grew, 1986; Johansson and Möller, 1986; Carswell et al., 1989; Möller, 1999; Baba, 1999; Straume and Austrheim, 1999; Baba, 2003), but these occurrences have a very different origin from the included assemblages of interest here. Spinel–hercynite solid solution is also most commonly found with sillimanite, but occurrences with kyanite ± spinel–hercynite

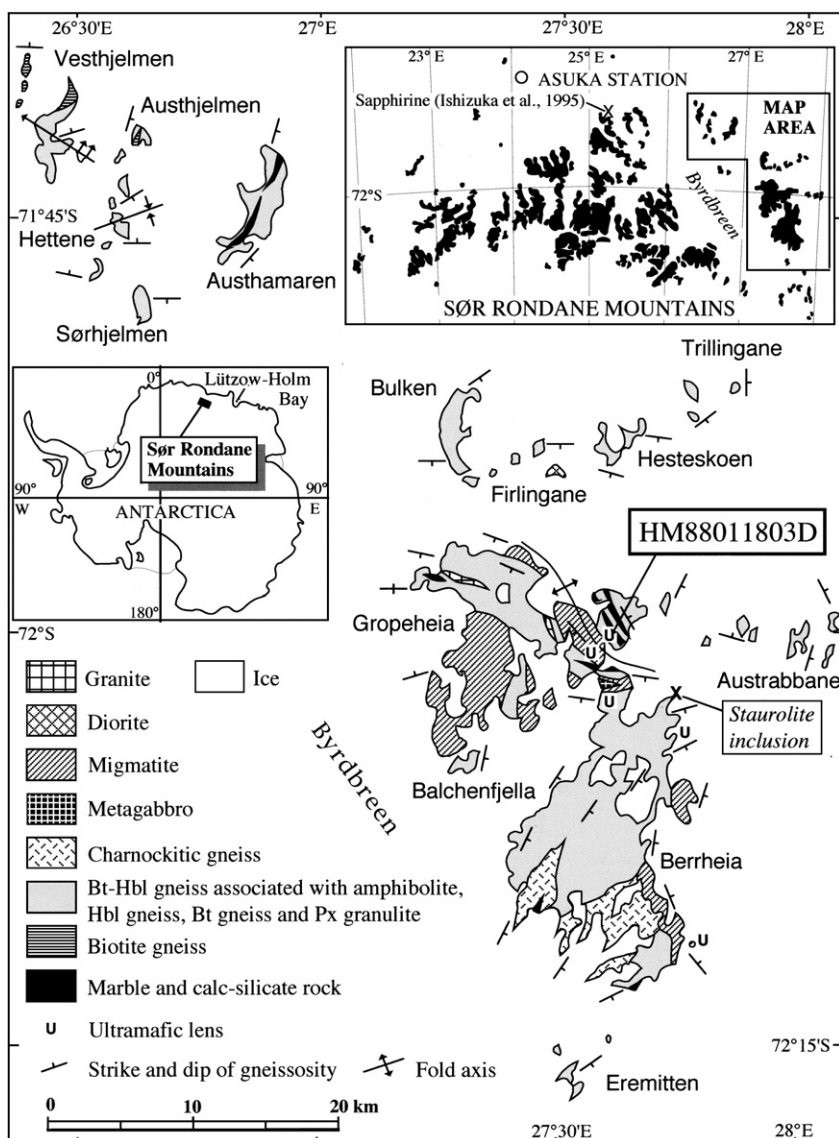


Fig. 1. Geologic map of the eastern Sør Rondane Mountains (modified from Asami et al., 1991, and Ishizuka et al., 1993) showing the localities for the sapphirine-bearing biotitic gneiss (sample HM88011803D, Makimoto et al., 1990; this paper), sapphirine-bearing meta-troctolite from Austkampane west of Byrdreen (Ishizuka et al., 1995), and for a staurolite-bearing corundum–garnet gneiss (Asami et al., 1990).

have also been reported as inclusions in garnet (e.g., Hiroi et al., 1983; Motoyoshi et al., 1985; Ogo et al., 1992; Hiroi et al., 1994). Kyanite + spinel – hercynite $\pm$ sapphirine assemblages are thought to have formed from breakdown of staurolite on the prograde path, e.g., at $T \approx 900$ °C and $P \approx 11$ kb in Sri Lanka (Hiroi et al., 1994). Stabilities of kyanite + sapphirine + spinel have not been constrained experimentally although it has been shown that sapphirine stability overlaps with kyanite stability in the MgO–Al₂O₃–SiO₂ system (Ackermann et al., 1975).

We report here sapphirine, spinel and kyanite as inclusions in garnet associated with corundum and hercynite in a rock intimately associated with an ultramafic lens at Gropeheia (Fig. 1) in the eastern Sør Rondane Mountains, East Antarctica (Asami et al., 1992, 1994). This is only one of two known sapphirine occurrences in the Sør Rondane Mountains overall; Ishizuka et al. (1995) reported sapphirine with orthopyroxene and cordierite in a meta-troctolite from Austkampane west of Byrdreen. In order to draw attention to the significance of the sapphirine + spinel + kyanite assemblage and its implications for inferring prograde paths in granulite-facies terranes, we report here detailed textural and compositional relationships of minerals in the Gropeheia rock, and compare the Gropeheia sapphirine + spinel + kyanite assemblage with similar assemblages in the Neoproterozoic–Cambrian orogen extending from the Sør Rondane Mountains to Lützow–Holm Bay and onward to Sri Lanka, southern India and southern Madagascar.

2. Geologic setting

The crystalline basement exposed in the eastern Sør Rondane Mountains (Fig. 1) is composed of high-grade gneissic rocks accompanied by migmatite and small bodies of intrusive rocks (Asami et al., 1989; Grew et al., 1989; Makimoto et al., 1990; Asami et al., 1990, 1991, 1992; Tainosho et al., 1992; Ishizuka et al., 1993). The metamorphic rocks are metasedimentary, metavolcanogenic and metaigneous. The majority of them are intermediate in composition, represented by biotite–hornblende gneiss, with subordinate charnockitic gneiss, mafic granulite, amphibolite, cummingtonite–orthopyroxene orthogneiss, garnet–biotite gneiss, marble, quartzite and ultramafic rock.

Regional metamorphism in the granulite-facies (760–800 °C and 7–8 kb) is indicated by the common occurrence of orthopyroxene- and two-pyroxene-bearing assemblages. The amphibolite-facies overprint (500–600 °C) is closely related to regional migmatization and has been recognized as a discrete event on the basis of geologic and petrologic features. According to geochro-

nologic studies by Shiraishi and Kagami (1992) and Grew et al. (1992), the granulite-facies event took place about 1000 Ma ago and the retrograde event about 500 Ma ago. However, recent CHIME (chemical Th–U–total Pb isochron method) monazite dating gives an early Paleozoic age for the granulite-facies event: ~ 540 Ma (e.g., Asami et al., 1996, 2005).

3. Field occurrence

Ultramafic lenses up to several meters in size occur at four localities in Balchenfjella (Fig. 1), where they are surrounded by the biotite–hornblende gneiss, probably of sedimentary origin, or by migmatite (Makimoto et al., 1990). Foliation in the host rocks is mostly concordant with the margin of the included ultramafic lenses. The sapphirine-bearing biotitic gneiss is found in an ultramafic lens surrounded by well-layered biotite–hornblende gneiss containing garnet, orthopyroxene and clinopyroxene at Gropeheia (Figs. 1 and 2). This lens is about 3 $\times$ 5 m in size and is composed of harzburgite, orthopyroxenite and garnet amphibolite, of which harzburgite is dominant (Fig. 2). Harzburgite consists dominantly of olivine and orthopyroxene; clinopyroxene is minor or absent. Spinel and hornblende are minor constituents. Secondary talc and calcite are present, but olivine is remarkably free of serpentinization. Boundaries between the different ultramafic rock types are sharp, and foliation in each rock type is approximately concordant with layering of the host gneiss. These rock types were metamorphosed under granulite-facies conditions together with the host gneiss (Makimoto et al., 1990). Pegmatite veins cut both the host gneiss and the ultramafic lens.

The sapphirine-bearing biotitic gneiss from which the studied sample (HM88011803D) was collected forms a concordant lenticular body 10–20 cm thick, about 2 m long and black in color (Fig. 2). The body is surrounded by harzburgite except at the right end, where it appears to be truncated by the garnet amphibolite: the boundary between the harzburgite and garnet amphibolite (and the pegmatite vein emplaced along this boundary) is oblique to the foliation of the harzburgite. The biotitic gneiss has a distinct foliation, in part gneissose banding, concordant with the foliation of the harzburgite.

4. Petrography

The sapphirine-bearing biotitic gneiss (“biotite–plagioclase–garnet schist” of Grew et al., 1989) is medium-grained, schistose rock consisting of 70–80 modal

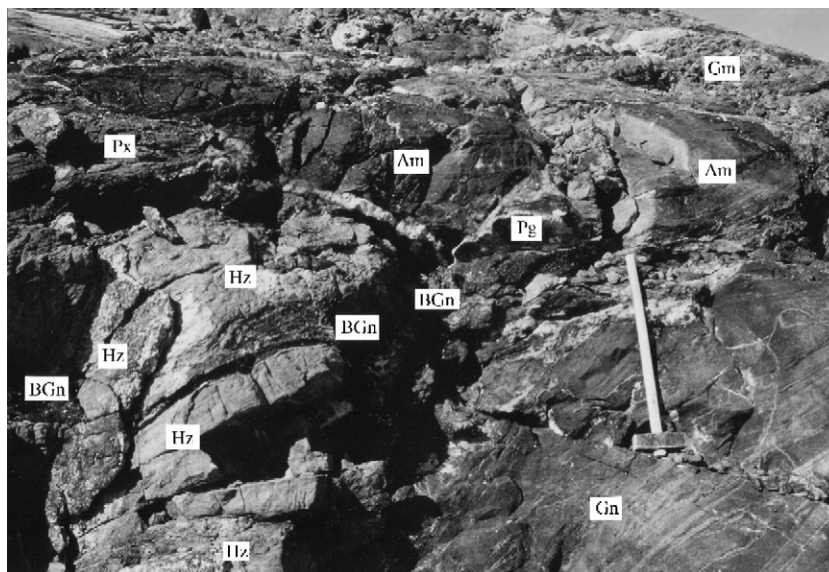


Fig. 2. Field occurrence of the sapphirine-bearing biotitic gneiss (BGN). The gneiss forms a roughly tabular, concordant mass in harzburgite (Hz), which is one component of an ultramafic lens enclosed by hornblende–biotite gneiss (Gn); other components are orthopyroxenite (Px) and garnet amphibolite (Am). Pegmatite veins (Pg) cut the biotitic gneiss, ultramafic rocks and host gneiss. The shaft of the hammer is about 70 cm long.

% black biotite having a pronounced preferred orientation and of pink garnet in porphyroblasts up to 6 mm in diameter (Fig. 3a, b; mineral abbreviations based on Kretz (1983) are given in Table 1). In addition to porphyroblasts, garnet forms small grains enclosed in plagioclase. Plagioclase, spinel, and corundum are subordinate constituents of the matrix. Grew et al. (1989) reported rare sillimanite, but subsequent study showed the one occurrence of sillimanite to be orthoamphibole that had been included in garnet and released by garnet breakdown. Zircon (identification confirmed by electron microprobe) grains are dispersed throughout the rock as inclusions in biotite, plagioclase and garnet. A brown, weakly pleochroic mineral found sparingly in biotite has been tentatively identified as allanite because it is surrounded by pleochroic haloes. Garnet and the matrix minerals except the biotite–plagioclase aggregates described below are considered to represent an assemblage originally formed under granulite-facies metamorphic conditions: garnet + corundum + spinel + biotite + plagioclase + allanite + zircon.

The garnet encloses minerals in grains less than 0.2 mm long; these include not only the matrix minerals biotite, spinel and plagioclase, but also sapphirine, kyanite, orthoamphibole, quartz and rutile, which are absent in the matrix (except rare orthoamphibole as noted above). The inclusions are considered to be relict minerals crystallized prior to the garnet porphyroblasts and the matrix minerals. No single garnet porphyroblast

encloses all the listed minerals, instead only the following associations were found.

- (A) Associations involving sapphirine, kyanite and spinel: direct contacts are commonly observed between sapphirine and kyanite, less commonly between spinel and kyanite or between sapphirine and spinel (Fig. 3c, d). However, all three minerals have never been found together.
- (B) Kyanite only.
- (C) Orthoamphibole + plagioclase ± quartz aggregate (Fig. 3a, e, f).

In addition, biotite and rutile are commonly present in small amounts, the former as rounded grains and the latter as euhedral to subhedral prisms or grains.

Relatively large sapphirine inclusions (0.1 mm in maximum length) show pleochroism such as X: colorless, Y: light lavender blue and Z: light greenish blue. Orthoamphibole is pale yellowish and indistinctly pleochroic. The following optical properties obtained with a 5-axis universal stage using hemisphere of $n=1.649$ confirm the identification of kyanite: (1) presence of two cleavages intersecting at an angle of 103° , (2) $2V_X=80-83^\circ$, corrected for $\beta=1.720$ with a weak dispersion of $r>v$, and (3) if the two observed cleavages are $\{100\}$ and $\{010\}$, the extinction angle of 32° between their intersection and Z is consistent with the optical properties of kyanite.

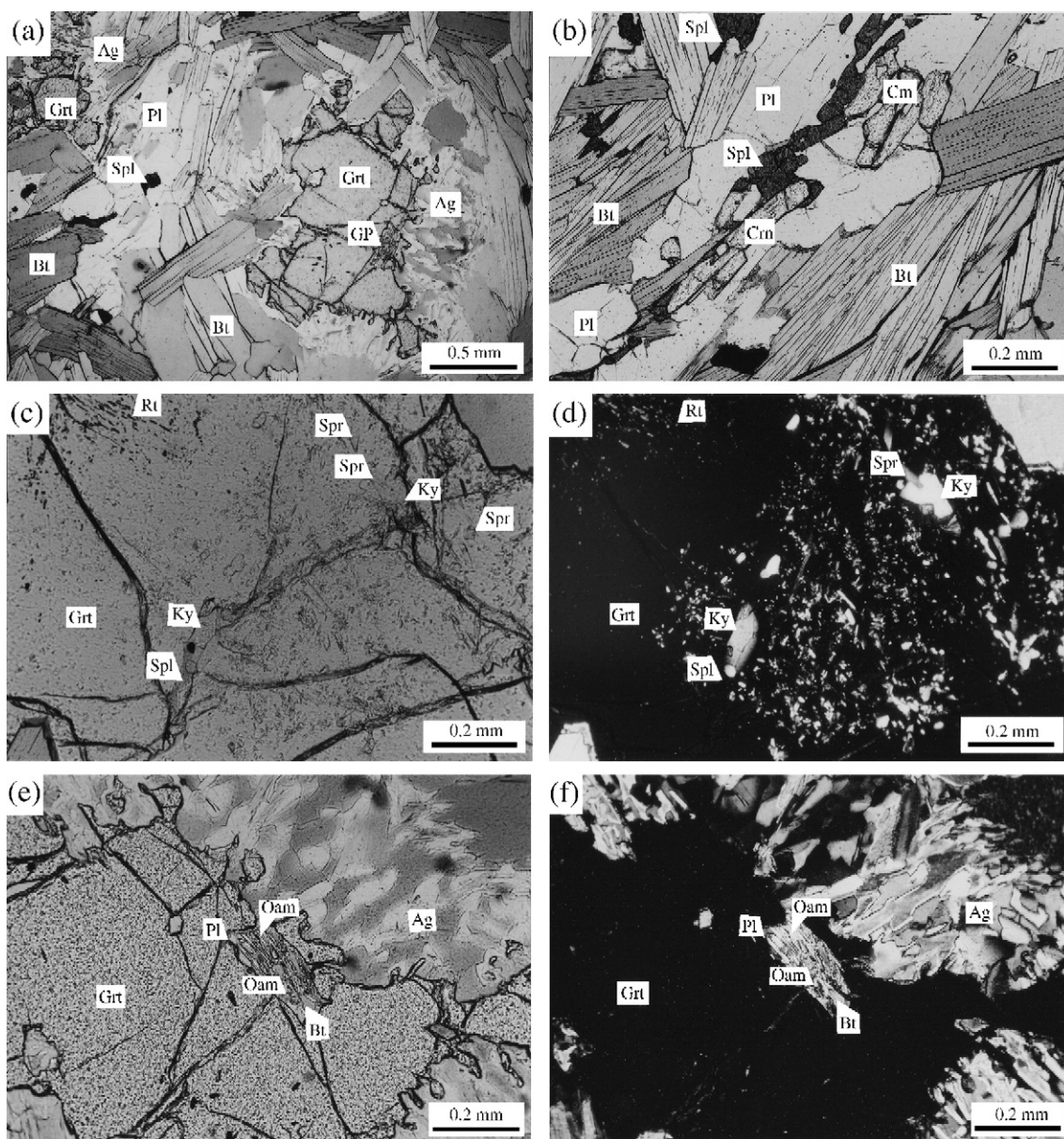


Fig. 3. Photomicrographs of the sapphirine-bearing biotitic gneiss. (a) Two garnet porphyroblasts (Grt) and surrounding matrix minerals biotite (Bt), plagioclase (Pl) and spinel (Spl). An inclusion consisting of orthoamphibole and plagioclase (GP) is present in the larger garnet (right), which also has minute prismatic inclusions of rutile. The margins of both garnets are embayed by biotite–plagioclase aggregates (Ag); breakdown of garnet was so extensive that orthoamphibole-bearing inclusion is no longer fully isolated from the matrix. One polar. (b) Typical mineral association of the matrix: biotite (Bt), plagioclase (Pl), corundum (Crn) and spinel (Spl). Corundum and spinel are aligned parallel to the gneissosity represented by oriented biotite flakes. One polar. (c) Inclusions of sapphirine (Spr), kyanite (Ky), spinel (Spl) and rutile (Rt) in a garnet porphyroblast (Grt). One polar. (d) Ditto. Crossed polars. Note contact relations of sapphirine-kyanite and spinel-kyanite. (e) The orthoamphibole (Oam)–plagioclase (Pl) inclusion (enlargement of GP in Fig. 3a), in which biotite (Bt) is also found. The selvage of garnet (Grt) between the inclusion and aggregate (Ag) has been breached. One polar. (f) Ditto. Crossed polars.

Spinel is green and where included in garnet, it is paler in color than matrix spinel. Biotite inclusions have a Z light reddish brown, whereas matrix biotite is light yellowish brown. Such differences in color reflect compositional differences (see below).

In many cases, margins of garnet porphyroblasts are irregularly embayed by aggregates of fine-grained biotite and plagioclase (Fig. 3a, e, f). Such a textural feature, along with compositional characteristics of garnet and biotite mentioned below, suggests that the biotite–plagioclase

Table 1

Selected microprobe analyses of minerals in the sapphirine-bearing biotitic gneiss

Mineral	Grt _C	Grt _R	Bt _I	Bt _M	Bt _A	Ged	Spr _{GC}	Spr _{GR}	Spl _{GC}	Spl _M	Pl _I	Pl _{R/M}	Pl _A	Ky	Cm
Grain #	Ga62	Ga72	Bi56	Bi222	Bi127	Gd42	Sa91	Sa118	Sp168	Sp233	Pl120	Pl223	Pl129	Ky96	Cm2
Wt. %															
SiO ₂	40.03	38.65	36.80	35.95	37.45	50.16	11.77	11.55	0.00	0.00	45.03	46.27	48.35	36.52	0.01
TiO ₂	0.02	0.06	3.95	1.31	0.63	0.15	0.02	0.06	0.11	0.01	0.00	0.00	0.01	0.02	0.00
Al ₂ O ₃	22.52	21.70	18.47	19.15	18.01	9.94	65.99	64.14	64.51	56.12	35.12	33.92	32.25	62.72	99.00
Cr ₂ O ₃	0.02	0.00	0.82	0.22	0.10	0.02	0.31	0.08	0.20	3.25	0.02	0.00	0.00	0.06	0.27
FeO ^a	20.04	26.91	6.21	11.62	10.44	13.19	5.62	8.41	15.20	29.35	0.54	0.02	0.00	0.87	0.59
MnO	0.33	2.95	0.00	0.12	0.18	0.23	0.10	0.21	0.00	0.24	0.00	0.04	0.01	0.00	0.06
MgO	13.60	7.16	19.05	16.94	17.69	21.85	16.64	15.05	16.93	7.41	0.03	0.01	0.00	0.02	0.02
ZnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.85	3.12	0.00	0.02	0.00	0.00	0.00
CaO	3.86	3.48	0.02	0.04	0.03	0.56	0.00	0.00	0.03	0.00	18.76	17.74	16.11	0.00	0.02
Na ₂ O	0.01	0.00	0.75	0.70	0.73	0.93	0.00	0.00	0.01	0.00	1.21	1.63	3.02	0.03	0.00
K ₂ O	0.00	0.00	8.61	8.62	8.38	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.05	0.00	0.01
Total	100.43	100.91	94.68	94.67	93.64	97.03	100.45	99.50	98.85	99.51	100.71	99.65	99.80	100.24	99.98
Formulae per given oxygen/cations (anhydrous O for Bt)															
O/cat	24	24	22	22	22	23	20/14	20/14	8/6	8/6	32	32	32	20	6
Si	5.953	5.978	5.292	5.298	5.524	7.059	1.380	1.383	0.000	0.000	8.284	8.550	8.894	3.947	0.000
Al	3.948	3.956	3.131	3.327	3.131	1.649	9.120	9.054	3.945	3.715	7.615	7.388	6.992	7.989	3.975
Ti	0.002	0.007	0.427	0.145	0.070	0.016	0.002	0.005	0.004	0.000	0.000	0.000	0.001	0.002	0.000
Cr	0.002	0.000	0.093	0.026	0.012	0.002	0.029	0.008	0.008	0.144	0.003	0.000	0.000	0.006	0.007
Fe ³⁺	—	—	—	—	—	—	0.087	0.161	0.040	0.141	—	—	—	0.070	0.015
Fe ²⁺	2.492	3.481	0.747	1.432	1.288	1.552	0.464	0.681	0.619	1.238	0.083	0.000	0.000	—	—
Mn	0.042	0.387	0.000	0.015	0.022	0.027	0.010	0.021	0.000	0.011	0.000	0.006	0.002	0.000	0.002
Mg	3.014	1.651	4.082	3.721	3.889	4.583	2.908	2.686	1.309	0.620	0.008	0.003	0.000	0.003	0.001
Zn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.071	0.129	0.000	0.003	0.000	0.000	0.000
Ca	0.615	0.577	0.003	0.006	0.005	0.084	0.000	0.000	0.002	0.000	3.698	3.512	3.175	0.000	0.001
Na	0.003	0.000	0.209	0.200	0.209	0.254	0.000	0.000	0.001	0.000	0.432	0.584	1.077	0.006	0.000
K	0.000	0.000	1.580	1.621	1.577	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.012	0.000	0.000
X _{Mg}	0.547	0.322	0.845	0.722	0.751	0.747	0.862	0.798	0.679	0.334					
An%											89.5	85.7	74.5		

Abbreviations: Bt — biotite, Cm — corundum, Ged — orthoamphibole, Grt — garnet, Ky — kyanite, Pl — plagioclase, Spl — spinel, Spr — sapphirine; C — core, R — rim, I — inclusion, M — matrix, A — aggregate embaying garnet, GC — in garnet core, GR — in garnet rim, R/M — rim of matrix grain.

^a Total iron as FeO. X_{Mg} indicates Mg/(total Fe+Mg) for garnet, biotite and orthoamphibole, and Mg/(Fe²⁺+Mg) for sapphirine and spinel.

aggregates are of retrograde origin, although biotite in the aggregates is similar in color to the larger matrix biotite.

5. Mineral chemistry

Minerals in the sapphirine-bearing rock were analyzed with a JEOL JXA-733 electron microprobe using a 15 kV accelerating voltage and a 0.012 μ A specimen current. The Bence–Albee correction method was used. Two or more grains of each mineral were examined. Selected analyses are listed in Table 1. Throughout the paper, X_{Mg} indicates Mg/(total Fe+Mg) for garnet, biotite and orthoamphibole, and Mg/(Fe²⁺+Mg) for sapphirine and spinel.

5.1. Garnet

Of the five garnet porphyroblasts examined for compositional zoning, three enclose rutile and biotite with

sapphirine, kyanite, or spinel but never all three together (e.g., Grt_S A, Fig. 4a), one encloses an orthoamphibole + plagioclase + quartz + biotite + rutile association (Grt_G A, Fig. 4b), and one has no inclusions (Grt_{NI} A, Fig. 4c). Grt_S A and Grt_G A are weakly embayed by the biotite–plagioclase aggregates along the margins, whereas Grt_{NI} A is intensely embayed. All three garnet porphyroblasts have the same type of chemical zoning: a broad Mg-rich core (X_{Mg}=0.45–0.55) surrounded by a rim richer in Fe (X_{Mg}≈0.3 at the outermost part) with an abrupt outward increase of Fe and Mn contents and a decrease of Mg content. The core in each garnet porphyroblast is approximately homogeneous, but the X_{Mg} values differ: the sapphirine-bearing porphyroblast is the most magnesian, and the orthoamphibole-bearing one is the least. Mn contents are extremely low except in the rims. These garnets are nearly homogeneous in Ca content with about 10 at.%. X_{Mg} values are close to 0.3 in rims in contact with

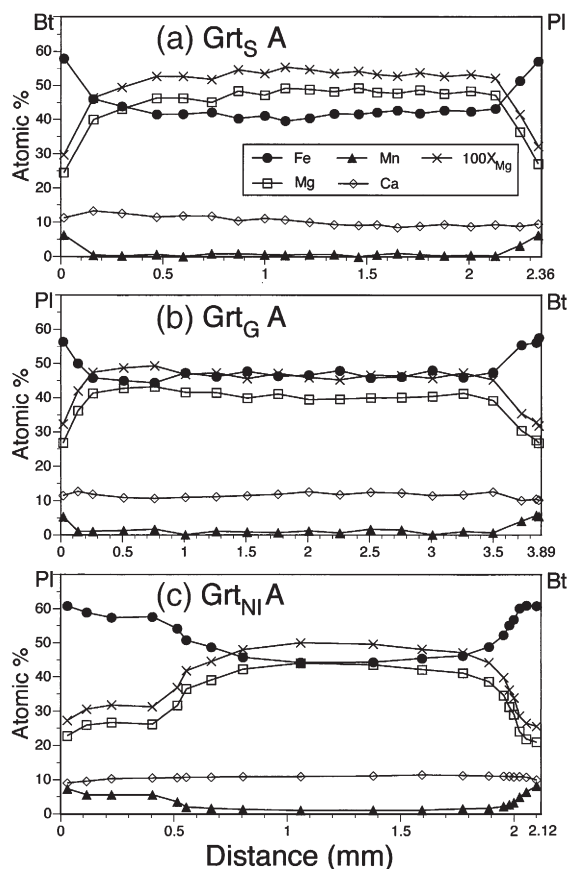


Fig. 4. Compositional profiles of three garnet porphyroblasts in the sapphirine-bearing biotitic gneiss. Grt_S: garnet with sapphirine inclusions, Grt_G: garnet with orthoamphibole–plagioclase inclusions, Grt_{NI}: garnet with no inclusion. Bt, Pl: biotite and plagioclase, respectively, being in contact with each edge. All distances of the horizontal axes are in millimeters.

the fine-grained biotite–plagioclase aggregates whether the mineral contiguous to the analyzed garnet rim is biotite or plagioclase. The zoning suggests that the Mg-rich cores have preserved compositions homogenized under peak conditions of the granulite-facies metamorphism, whereas Fe-enrichment in the rims is due to reactions during retrograde metamorphism.

5.2. Biotite

The three texturally distinct types of biotite, viz. (I) inclusions in sapphirine- and orthoamphibole-bearing garnets (Grt_S A, B and Grt_G A), (II) matrix, and (III) aggregate, differ in composition; particularly in X_{Mg} and Ti content (Fig. 5). Type I biotite is highest in both X_{Mg} (0.85–0.86) and Ti (0.32–0.43 per formula unit of 22 oxygens or $TiO_2 = 2.95$ – 3.95 wt.%). Type II biotite

has slightly lower X_{Mg} values (0.70–0.73) and slightly higher Ti contents (0.12–0.16 p.f.u. or $TiO_2 = 1.06$ – 1.44 wt.%) than Type III biotite ($X_{Mg} = 0.71$ – 0.75 and $Ti = 0.07$ – 0.13 p.f.u., $TiO_2 = 0.63$ – 1.18 wt.%). The compositions suggest that Type I biotites could have formed at higher temperatures than the other two types. In quartz-bearing rocks the Ti content of biotite associated with Ti- and Al-saturating phases such as rutile and sillimanite increases with increasing temperature even if biotite X_{Mg} is relatively high (Guidotti, 1984; Henry et al., 2005).

5.3. Orthoamphibole

Grains in three aggregates enclosed near the center of garnet Grt_G A were analyzed: viz orthoamphibole+ biotite+plagioclase aggregate (Inclusion 1), orthoamphibole+ biotite+plagioclase+quartz aggregate (Inclusion 2), and orthoamphibole+plagioclase aggregate (Inclusion 3). These data are supplemented by analyses reported by Grew et al. (1989) from an orthoamphibole+ biotite+ quartz aggregate (Inclusion 4) enclosed in another garnet (Grt_G B) in the same rock sample.

According to accepted nomenclature (e.g., Leake et al., 1997), both anthophyllite ($Si > 7$) and gedrite ($Si < 7$) are present. TiO_2 (0.04–0.49 wt.%), Cr_2O_3 (0.01–0.17 wt.%), MnO (0.00–0.47 wt.%) and CaO (0.21–0.56 wt.%) are low; K_2O is below detection. X_{Mg} ranges only from 0.74 to 0.78, but Si, Al, total R^{2+} and Na per formula units of 23 oxygens vary considerably, with evidence for both the edenite-type substitution

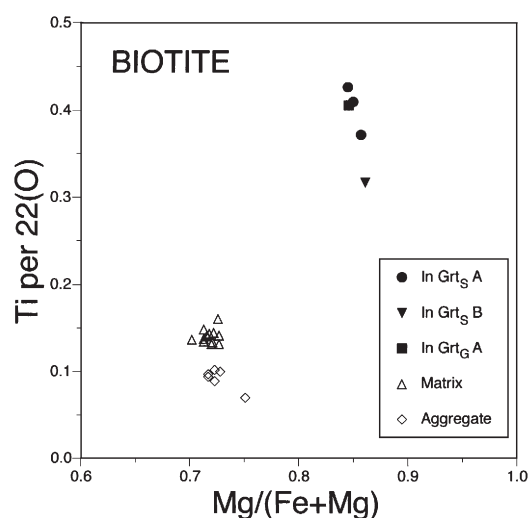


Fig. 5. $Mg/(Mg+Fe)$ –Ti plot of analyzed biotite in the sapphirine-bearing biotitic gneiss. Grt_S: garnet with sapphirine inclusions, Grt_G: garnet with orthoamphibole–plagioclase inclusions.

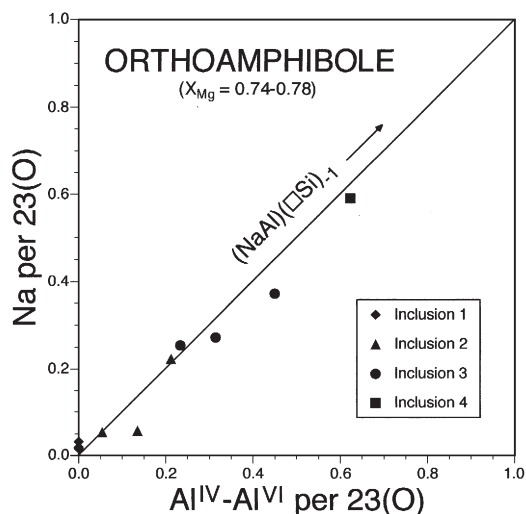


Fig. 6. $[\text{Al}^{\text{IV}}-\text{Al}^{\text{VI}}]-\text{Na}$ relation for analyzed orthoamphibole inclusions in garnet from the sapphirine-bearing biotitic gneiss.

vacancy + $\text{Si} = \text{Na} + \text{Al}^{\text{IV}}$ (Fig. 6) and the Tschermak substitution $\text{Si} + \text{R}^{2+} = \text{Al}^{\text{IV}} + \text{Al}^{\text{VI}}$, which is operating in tandem with the edenite substitution in a 2:1 ratio (Fig. 7). That is, $\text{Na}:\text{Al}^{\text{IV}}$ ratios range from 1:3 to 1:4 (Fig. 8) and the amphibole compositions plot close to the join $\text{R}^{2+}_7\text{Si}_8\text{O}_{22}(\text{OH})_2-\text{NaR}^{2+}_5\text{Al}_2\text{Si}_5\text{Al}_3\text{O}_{22}(\text{OH})_2$. The latter composition was supposed to be the gedrite “ideal end composition” (J. Schumacher in Robinson et al., 1982, p. 177; cf. sodicgedrite, Leake et al., 1997), but Hawthorne and Oberti (2006) suggested that it be given a new rootname.

It has been known that a miscibility gap exists with respect to A-site occupancy and Al contents in the anthophyllite–gedrite series (e.g. Robinson et al., 1971; Spear, 1980). Spear (1980) estimated a temperature of the crest of the solvus to be about 600 °C in samples with X_{Mg} of approximately 0.6. The orthoamphibole Na and Al^{IV} contents in our sample (Figs. 6–7) span the miscibility gap, suggesting the formation of the orthoamphiboles under supersolvus conditions, i.e., above 600 °C. However, our orthoamphiboles are more magnesian than those Spear (1980) used to construct the solvus, and given the narrowing of the solvus with X_{Mg} that Spear (1980) reported, this minimum temperature could be less than 600 °C.

5.4. Sapphirine

Sapphirine inclusions in three garnet porphyroblasts Grt_S A, Grt_S B and Grt_S C were analyzed, all analyzed grains are from the magnesian cores except for a few inclusions from the Fe-rich rim of Grt_S A. Stoichio-

metric calculation assuming 20 oxygens and 14 cations gives Fe^{3+} contents ranging from 0.014 to 0.143 for grains in the core and 0.108–0.214 for those in the rim, which correspond to 3–26% and 13–25% of total Fe, respectively. Sapphirine is somewhat more aluminous than $\text{R}^{2+}\text{O}:\text{R}^{3+}_2\text{O}_3:\text{SiO}_2$ (M:A:S)=7:9:3 (Fig. 9). The compositions plot below the line for $\text{R}^{2+} + \text{Si} = (\text{R}^{3+})^{\text{VI}} + \text{Al}^{\text{IV}}$ because Fe^{3+} was not included in R^{3+} . X_{Mg} values calculated for Fe^{2+} range 0.78–0.88 overall: inclusions in the garnet rim are richer in Fe ($X_{\text{Mg}}=0.78-0.81$) than those in the cores ($X_{\text{Mg}}=0.85-0.88$). Nonetheless, $K_{\text{D}}^{\text{Grt/Spr}}=(\text{total Fe/Mg})_{\text{Grt}}/(\text{Fe}^{2+}/\text{Mg})_{\text{Spr}}$ increases from 6 in the cores to 10.53 in the rim (Fig. 10). This increase results from exchange of Fe and Mg between the sapphirine inclusions and surrounding garnet as temperature decreased on the retrograde path. Increasing fractionation of Fe into garnet relative to sapphirine is to be expected because K_{D} normally varies inversely with temperature. Such a retrograde exchange also implies that sapphirine in the core did not retain the compositions of primary sapphirine, but represent those re-equilibrated with the magnesian garnet core during the granulite-facies metamorphism. $K_{\text{D}} \approx 6$ for the garnet core-sapphirine pairs is higher than the $K_{\text{D}} \approx 3.5$ for garnet-sapphirine pairs from the Napier Complex, Antarctica (Grew, 1983), a relationship consistent with the metamorphic temperatures estimated for the Napier Complex being higher than those estimated for the Sør Rondane Mountains.

5.5. Spinel

Both spinel included in garnet (Grt_S A) and matrix spinel were analyzed. Fe^{2+} and Fe^{3+} contents were

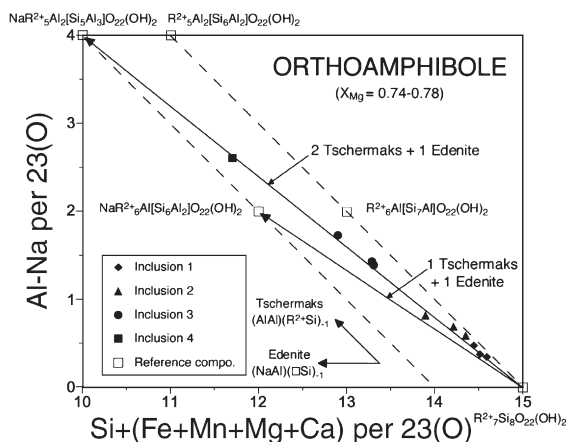


Fig. 7. $[\text{Si}+(\text{Fe}+\text{Mn}+\text{Mg}+\text{Ca})]-[\text{Al}-\text{Na}]$ relation for analyzed orthoamphibole inclusions in garnet from the sapphirine-bearing biotitic gneiss.

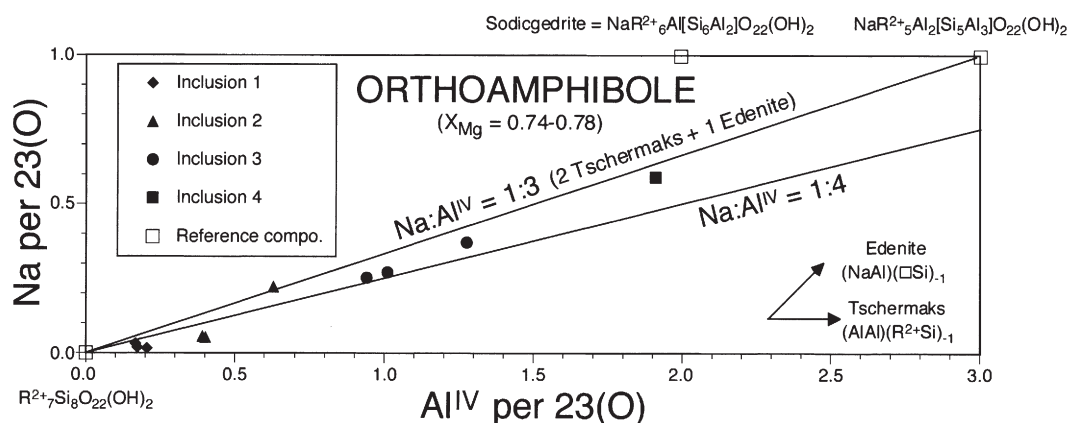


Fig. 8. Al^{IV} –Na diagram for analyzed orthoamphibole inclusions in garnet from the sapphirine-bearing biotitic gneiss. In the reference compositions for end-member anthophyllite and possible gedrite end members, R^{2+} is dominantly Mg, with Fe^{2+} subordinate.

estimated stoichiometrically on the basis of 8 oxygens and 6 cations; the inclusions give Fe^{3+} proportions of 0.037–0.086, which correspond to 6–8% of total Fe, and the matrix grains give larger proportions of 0.084–0.176, 6–12% of total Fe (Fig. 11a). Both types of spinel contain ZnO, with a larger variation for the inclusions (1.9–5.6 wt.%) than for the matrix (2.7–3.6 wt.%) (Fig. 11b). There are other substantial compositional differences between included and matrix spinel (Fig. 11): the inclusions are relatively Cr-poor and Mg-rich and variable in X_{Mg} ($\text{Cr}=0.002$ – 0.023 per 8 oxygens; $\text{Cr}_2\text{O}_3=0.1$ – 0.5 wt.%, $X_{\text{Mg}}=0.36$ – 0.68), whereas the matrix grains are relatively Cr- and Fe-rich (hercynite)

and uniform in composition ($\text{Cr}=0.125$ – 0.195 ; $\text{Cr}_2\text{O}_3=2.8$ – 4.4 wt.%, $X_{\text{Mg}}=0.26$ – 0.34).

Fe/Mg ratios of the included spinel tend to increase with increasing Fe/Mg ratios of adjacent garnet, but unlike $K_{\text{D Grt/Spr}}$, $K_{\text{D Grt/Spl}}$ ($=(\text{total Fe/Mg})_{\text{Grt}}/(\text{Fe}^{2+}/\text{Mg})_{\text{Spl}}$) decreases from garnet core to rim, i.e., from 1.92 to 1.12 (Fig. 12). This decrease with decreasing temperature is anomalous, as is the relatively high $K_{\text{D Grt/Spl}}$ in the garnet core. In contrast, K_{D} for garnet core and matrix spinel gives an extremely low average value of 0.39. $K_{\text{D Grt/Spl}}$ is typically close to unity (e.g., Hensen and Green, 1972), but significant deviations have been reported (e.g., $K_{\text{D Grt/Spl}} < 1$, Ouzegane et al., 2003). If there had

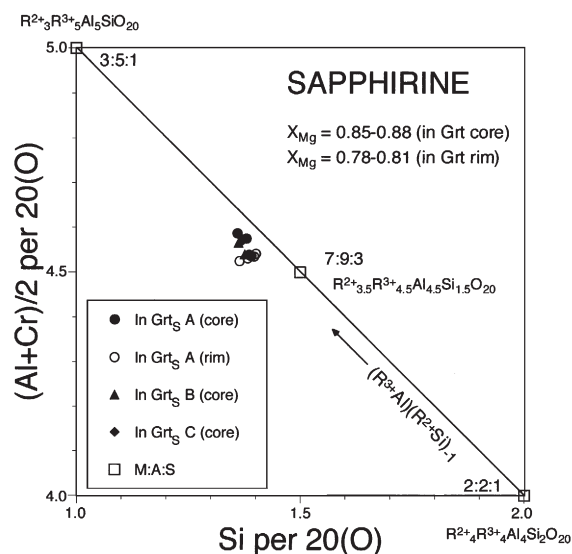


Fig. 9. Si–(Al+Cr)/2 plot of analyzed sapphirine inclusions in garnet from the sapphirine-bearing biotitic gneiss. Grt_S: garnet with sapphirine inclusions.

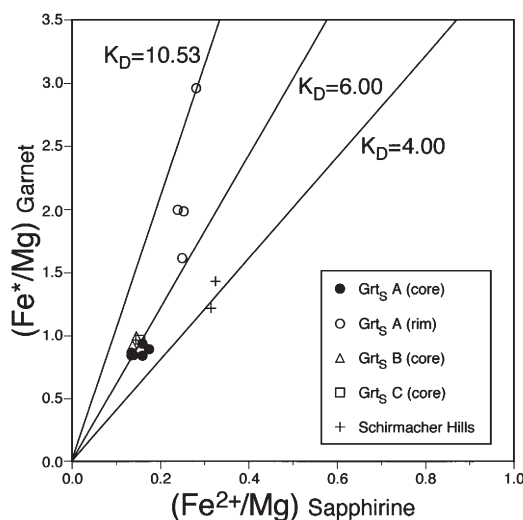


Fig. 10. Fe–Mg distributions between sapphirine and garnet from this sample and the Schirmacher Hills granulites (Grew, 1983). Grt_S: garnet with sapphirine inclusions. Fe*: total Fe. $K_{\text{D}}=(\text{Fe}^*/\text{Mg})_{\text{Grt}}/(\text{Fe}^{2+}/\text{Mg})_{\text{Spr}}$.

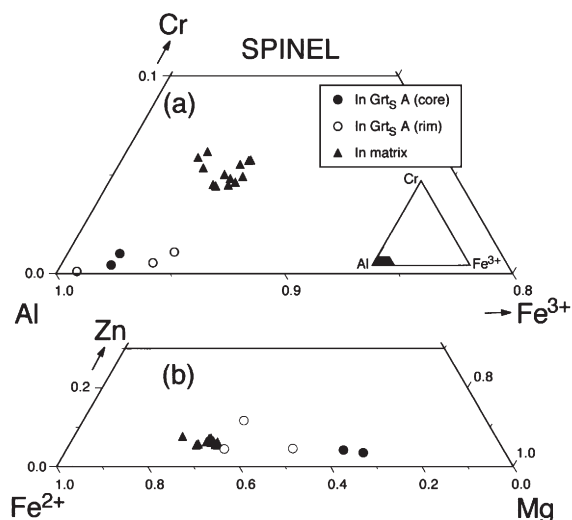


Fig. 11. Compositions of analyzed spinel in the sapphirine-bearing biotitic gneiss. (a) Cr–Al–Fe³⁺. (b) Zn–Fe²⁺–Mg. Grt_s: garnet with sapphirine inclusions.

been an exchange of Fe and Mg between the spinel inclusions and surrounding garnet during the granulite-facies metamorphism and subsequent retrogression, either an equilibrium distribution was not attained or

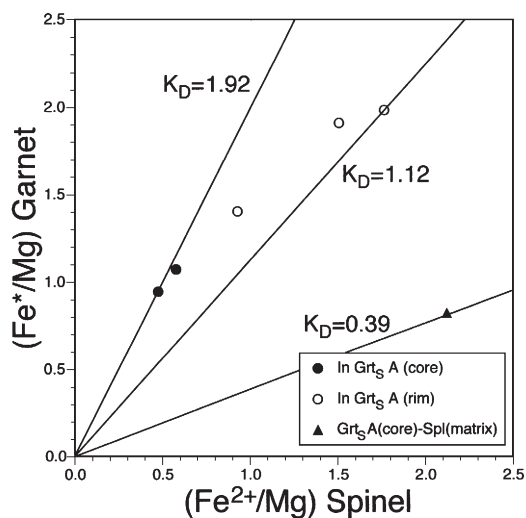


Fig. 12. Fe–Mg distribution between spinel and garnet in the sapphirine-bearing biotitic gneiss. Grt_s: garnet with sapphirine inclusions. Fe*: total Fe. $K_D = (Fe^*/Mg)_{Grt} / (Fe^{2+}/Mg)_{Spl}$. Filled circles indicate individual (Fe*/Mg) determinations for Grt_s A (core) in direct contact with an analyzed spinel inclusion and the Fe²⁺/Mg value for the spinel inclusion. Unfilled circles indicate corresponding values in Grt_s A rims. Solid triangle indicates the average Fe*/Mg value for all the analyzed points of Grt_s A (core) and the average Fe²⁺/Mg value for all the analyzed matrix spinel grains.

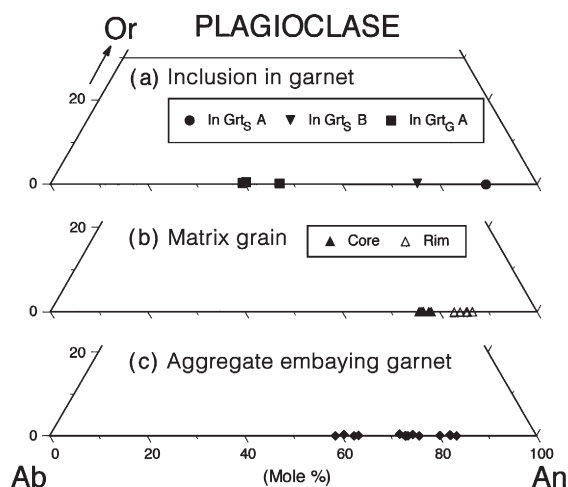


Fig. 13. Ab–An–Or compositions of analyzed plagioclase in the sapphirine-bearing biotitic gneiss. Grt_s: garnet with sapphirine inclusions, Grt_G: garnet with orthoamphibole–plagioclase inclusions.

the distribution was affected by the presence of Zn and Cr in spinel.

5.6. Plagioclase

Anorthite contents of plagioclase included in garnet, in the matrix and in the fine-grained aggregates with biotite aggregates embaying garnet differ markedly (Fig. 13). Plagioclase in the sapphirine-bearing garnets (Grt_s A and B) is bytownite–anorthite (e.g., An₉₀ for a grain enclosed together with sapphirine), whereas

Table 2

Bulk analysis of sample HM88011803D: major constituents in wt.%

SiO ₂	37.06
TiO ₂	1.03
Al ₂ O ₃	21.70
Cr ₂ O ₃	0.21
Fe ₂ O ₃	2.49
FeO*	9.27
MnO	0.114
MgO	14.33
CaO	2.16
Na ₂ O	0.84
K ₂ O	7.00
P ₂ O ₅	0.02
F [†]	0.15
Cl [§]	0.05
S [‡]	0.03
LOI2	3.00
O=F, Cl	−0.07
Total	99.38

Note: By FUS-XRF unless otherwise noted: *Titration, [†]FUS-ISE, [§]INAA, [‡]TD-ICP. Explanation of LOI2 and abbreviations are given in the text.

Table 3

Bulk analysis of sample HM88011803D: trace constituents in ppm

	MULT	MULT INAA	MULT INAA	MULT INAA	INAA	TD- MS	TD- ICP
	TD-ICP	TD- ICP	TD-ICP- MS	TD- ICP			
	TD-ICP- MS			TD- MS			
Li						83.2	
Be	0.1						
Sc					39		
V							220
Cr			1480				
Co			73.6				
Ni				665			
Cu	56.4						
Zn				202			
Ga						22.3	
Ge						0.2	
As					<0.5		
Se			0.4				
Br					<0.5		
Rb			75.1				
Sr						45.3	
Y						4.1	
Zr						30	
Nb						7.9	
Mo		5					
Ag				<0.05			
Cd	<0.1						
In						<0.1	
Sn						2	
Sb					<0.1		
Te						0.8	
Cs			2.45				
Ba			1270				
La					9.7	2.5	
Ce					17	4.8	
Pr						0.6	
Nd					<5	2.5	
Sm					1.5	0.6	
Eu					0.6	0.28	
Gd						1.5	
Tb					<0.5	0.2	
Dy						1.2	
Ho						0.3	
Er						1.1	
Tm						0.2	
Yb					3.5	1.6	
Lu					0.57	0.2	
Hf					4	1.1	
Ta			2.3				
W					<1		
Re						0.002	
Ir					<0.005		
Au					<0.002		
Hg					<1		
Tl						1.92	
Pb	8.6						
Bi	0.2						

Table 3 (continued)

	MULT	MULT INAA	MULT INAA	MULT INAA	INAA	TD- MS	TD- ICP
	TD-ICP	TD- ICP	TD-ICP- MS	TD- ICP			
	TD-ICP- MS			TD- MS			
Th			0.8				
U			0.3				

Note: Abbreviations given in the text.

plagioclase in the orthoamphibole-bearing garnet (Grt_G A) is andesine (An₃₉₋₄₇). Matrix plagioclase grains are zoned bytownite with cores more sodic (An₇₆₋₇₈) than rims (An₈₃₋₈₇). Plagioclase in the aggregates is labradorite (An₅₉₋₆₃) and bytownite (An₇₂₋₈₄). Orthoclase contents do not exceed 0.6 mol %.

5.7. Kyanite

Kyanite included in Grt_S A, Grt_S B and Grt_S C contains minor Fe₂O₃ (0.6–1.5 wt.%), MnO (0.0–0.3 wt.%) and MgO (0.0–0.3 wt.%).

5.8. Corundum

An analyzed corundum grain associated with spinel, biotite and plagioclase in the matrix contains 99.0 wt.% Al₂O₃ with minor Cr₂O₃ (0.3 wt.%) and Fe₂O₃ (0.6 wt.%).

6. Whole-rock chemistry

Sample HM88011803D was analyzed at the Activation Laboratories Ltd, Canada by the following methods (Tables 2 and 3): X-Ray fluorescence of sample fused in lithium metaborate/tetraborate (FUS-XRF); titration, fusion ion specific electrode (FUS-ISE), instrumental neutron activation analysis (INAA), and by inductively coupled plasma mass spectrometry (ICP-MS) of material “totally” digested (TD) in a mix of hydrochloric, nitric, perchloric and hydrofluoric acids (TD-MS). Loss on ignition (LOI) was determined by weight loss before and after ignition at 1050 °C. This measures the total content of volatile species, not only CO₂, S, H₂O⁺ and H₂O[−], but also F and Cl if these had been driven out from biotite at 1050 °C. Thus, there could be duplication between LOI, F and Cl. LOI₂ is LOI adjusted for the difference in O between FeO and Fe₂O₃.

The TD acid treatment does not dissolve zircon, which would be present in the untreated material used

for INAA. Thus, INAA of elements concentrated in zircon would be higher than ICP-MS analyses of these elements in the soluble material extracted by TD. This is clearly evident in the case of REE and Hf, for which the INAA values are greater than the corresponding TD-MS values (Table 3). MULT means that more than one method was applied, and the best result reported. In most cases, this means that the ICP will be reported for lower levels and INAA for higher levels for some elements where INAA becomes more reliable than the TD ICP process. Th and U, two other elements concentrated in zircon, were determined by MULT INAA/TD-ICP-MS, and we considered the reported values sufficiently reliable to be plotted in Fig. 14.

Analysis of Cr gave nearly identical values by XRF after fusion (1437 ppm Cr, Table 2) and by MULT INAA/TD-ICP-MS (1480 ppm Cr, Table 3). Contents of other elements expected to be concentrated in spinel, such as V, Ni, and Co, should also be suitable for inclusion in Fig. 15. We expect that the other elements plotted in Figs. 14 and 15 are contained in minerals soluble by TD rather than in zircon.

The trace element signature of the biotitic gneiss has features characteristic of ultramafic rocks, i.e., contents of the transition metals are comparable to those in primitive mantle (Fig. 15). However, the rock is enriched by 2 orders of magnitude in Li, Rb, Mo, Cs, Ba, Tl and Pb, and by a lesser extent in Sn, La, Ce, Yb, Lu, U, and Th, all elements indicative of metasomatism associated with fluids having a crustal source. Li, Sn, Rb, Cs, and Tl are elements concentrated in biotite relative to feldspars (Hall et al., 1993) as well to the other minerals in the biotitic gneiss; Pb and Ba are expected to substitute for K in biotite in the absence of another K-rich phase. Thus, a significant portion of the trace-element signature not attributable to the ultramafic

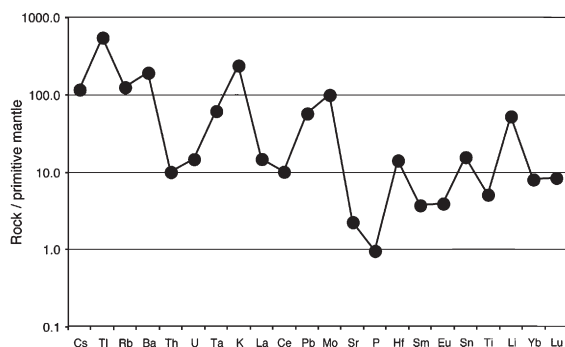


Fig. 14. Primitive-mantle normalized diagram of incompatible elements following the sequence of Sun and McDonough (1989). Source of primitive-mantle data: pyrolite composition of McDonough and Sun (1995).

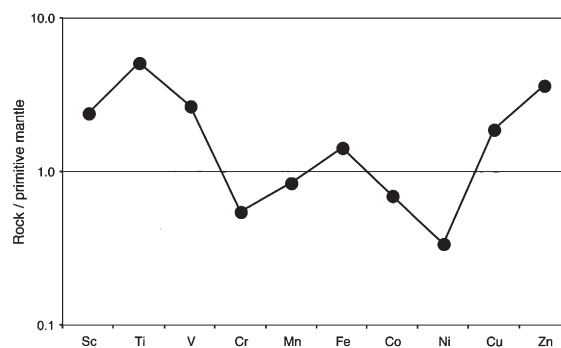


Fig. 15. Primitive-mantle normalized diagram of transition elements. Source of primitive-mantle data: pyrolite composition of McDonough and Sun (1995).

precursor can be linked to biotitization. It is more likely that the biotitization resulted from interaction between the harzburgite and precursor to the host gneiss, and that a slice of such blackwall skarn was subsequently infolded or faulted into the harzburgite. However, we cannot exclude the possibility that crustal fluids locally metasomatized the ultramafic rocks prior to their insertion into the gneiss presently hosting it. Biotite inclusions in garnet imply that the biotitization of the ultramafic rock preceded the formation of garnet in the biotitic gneiss, but compositional relationships between the inclusion assemblages and the matrix assemblage imply that metasomatism overlapped with granulite-facies metamorphism (introduction of Fe^{2+} , see below).

7. P–T estimates

Textural and compositional relations suggest a three stage evolution of the biotitic gneiss: (1) assemblages with sapphirine, spinel, kyanite and orthoamphibole on the prograde path, (2) a peak granulite-facies assemblage garnet + corundum + hercynite + biotite + plagioclase, and (3) retrogression under amphibolite-facies conditions that resulted in Fe-enrichment in the rims of the garnet porphyroblasts and crystallization of fine-grained biotite–plagioclase aggregates at the expense of garnet. Fine-grained garnet enclosed in plagioclase could be a relic of this retrogression. We attempted to estimate P and T for each stage using both cation exchange thermometry (garnet–biotite, sapphirine–spinel,) and petrogenetic grids.

7.1. Garnet–biotite thermometry

The Kleemann and Reinhardt (1994) thermometer gives equilibrium temperatures of 750–780 °C for garnet core-matrix biotite pairs (Table 4), i.e., the Mg-rich

Table 4

Temperatures estimated using Kleemann and Reinhardt's (1994) garnet–biotite thermometer (sample HM88011803D)

Temperatures estimated using Al content and formulae of (1979) garnet-clinopyroxene thermometer (sample FMS01-10002)																		
No.	(1a)			(1b)			(2a)			(2b)			(3a)			(3b)		
Mineral pair	Grt _S A	(c)	Bt _M	Grt _S A	(r)	Bt _A	Grt _S B	(c)	Bt _M	Grt _S B	(r)	Bt _A	Grt _G A	(c)	Bt _M	Grt _G A	(r)	Bt _A
Grain No.	Ga63		Bi229	Ga49		Bi47	Ga184		Bi200	Ga196		Bi197	Ga10		Bi1	Ga6		Bi4
Mg	2.922		3.697	1.461		3.717	2.802		3.638	1.560		3.756	2.592		3.646	1.607		3.768
Fe*	2.528		1.391	3.457		1.424	2.709		1.443	3.585		1.367	2.661		1.469	3.376		1.410
Mn	0.041		0.005	0.379		0.004	0.053		0.009	0.417		0.006	0.103		0.028	0.321		0.000
Ca	0.566			0.677			0.545			0.584			0.640			0.690		
Al ^{VI}			0.670			0.674			0.641			0.634			0.624			0.610
Ti			0.132			0.102			0.141			0.131			0.138			0.126
Mg/Fe*	1.156		2.658	0.423		2.610	1.034		2.521	0.435		2.748	0.974		2.482	0.476		2.672
T (°C) at 7 kb	777						762						751					
T (°C) at 4 kb			531						526						548			

* Total Fe. Grt_S: sapphirine-bearing garnet, Grt_G: orthoamphibole-bearing garnet. Bt_M: matrix biotite, Bt_A: biotite in aggregate embaying garnet. c: core, r: rim. Mineral pairs used here are garnet core and nearby matrix biotite, and garnet rim and adjacent embaying biotite. Atomic proportions listed above are based on 24(O) for garnet and 22(O) anhydrous for biotite.

cores of the porphyroblasts preserve compositions homogenized under the granulite-facies conditions. Garnet–biotite thermometry gives 530–550 °C for garnet rim–secondary biotite pairs (Table 4), values in good agreement with the temperatures estimated for amphibolite-facies overprint in the Sør Rondane Mountains.

7.2. Sapphirine–spinel thermometry

A thermometer based on Fe²⁺–Mg distribution between co-existing sapphirine and spinel could potentially provide a temperature estimate for minerals formed on the prograde path. Direct application of two published calibrations (Owen and Greenough, 1991; Das et al., 2006) gives temperatures ranging from 767 to 929 °C (Table 5). We devised a modified version of the Owen

and Greenough (1991) thermometer by plotting compositions of their 8 pairs of natural sapphirine and spinel in terms of inverse temperature (Fig. 16). The resulting least-squares fit gives lower temperatures (Table 5) than the $\ln K_D$ vs. T relation on which Owen and Greenough (1991) based their calibration. Neither treatment is satisfactory because of the scatter in the calibrant data and because the input temperatures are estimates of uncertain precision. The Das et al. (2006) calibration is also not entirely satisfactory. It is based on 22 synthetic pairs including several synthesized under oxidizing conditions (Das et al., 2001) and sapphirine compositions having anomalous stoichiometry (Das et al., 2003). The 6 pairs synthesized in specially designed experiments reported in the 2006 paper constitute an internally consistent data set giving a relatively tight fit (Fig. 16). This

Table 5

Temperatures estimated from sapphirine–spinel thermometers (sample HM88011803D)

No.	(1)		(2)		(3)	
Mineral pair	Spr	Spl	Spr	Spl	Spr	Spl
Grain no.	Sa87	Sp152	Sa91	Sp168	Sa98	Sp152
Fe ²⁺	0.568	0.701	0.463	0.622	0.503	0.701
Mg	2.824	1.214	2.909	1.309	2.887	1.214
ln <i>K</i> _D	1.0539		1.0934		1.1975	
<i>Temperature (°C)</i>						
Owen and Greenough (1991)	767		776		800	
Ditto, modified ^a	736		748		780	
Das et al. (2006)	897		905		929	
Ditto, modified ^a	860		869		895	

Mineral pairs were taken for nearby sapphirine and spinel in the magnesian core of garnet (Grt_S A). Atomic proportions of Fe²⁺ and Mg are based on 20(O) and 14 cations for sapphirine (Spr) and 8(O) and 6 cations for spinel (Spl).

^a From Fig. 17.

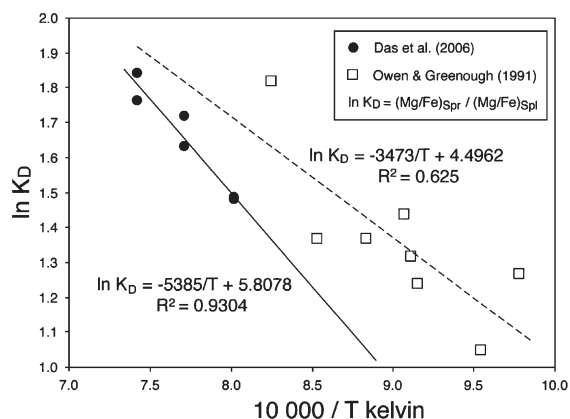


Fig. 16. Temperature dependence of the distribution coefficient $K_D = (\text{Mg/Fe})_{\text{Spr}} / (\text{Mg/Fe})_{\text{Spl}}$ for the six sapphirine–spinel pairs synthesized by Das et al. (2006) and for the eight pairs of natural sapphirine and spinel used by Owen and Greenough (1991) for their geothermometer. The lines are least-square regressions of the data points.

calibration gives lower temperatures than the Das et al. (2006) version based on the 22 pairs (Table 5).

Owen and Greenough (1991) and Das et al. (2006) reviewed the pitfalls of this thermometer, e.g., the effects of oxygen fugacity, cation disorder and variations in Tschermak-type substitution. Because significant Fe^{3+} can be present in both minerals, even the method of calculating their formulae has an effect. For example, sapphirine and spinel formulae calculated using, respectively, 20 O/14 and 4/3 cations give temperatures 14 °C lower than those based on the formula calculation of Higgins et al. (1979) for sapphirine and “charge balance” for spinel as Das et al. (2006) did for the 6 pairs.

7.3. Petrogenetic grids

Theoretical calculations of garnet+corundum+spinel+sapphirine+kyanite and garnet+corundum+spinel+kyanite equilibria in the FMAS system using the GIBBS program (Spear and Menard, 1989) constrain possible P–T conditions for a sapphirine+spinel+kyanite+garnet ($X_{\text{Mg}} \approx 0.55$) assemblage to near 450 °C and 4 kb (Fig. 17), well within the stability field of chlorite and muscovite. Although this estimate is consistent with the calculation by Simon and Chopin (2001) that sapphirine could appear at such low temperatures if water activities were sufficiently low, we doubt that this temperature is valid for the Sør Rondane metamorphism because of the assumptions involved and the contradictory evidence. Firstly, the garnet composition used in calculating the estimate records the granulite-facies event and spinel cation ordering assumed in the calculations may differ from that in the natural spinel at

ambient P–T. Secondly, the presence of FeO , ZnO and Cr_2O_3 would shift the $\text{En} + \text{Crn} + \text{Spl} = \text{Spr}$ reaction to higher temperatures because these constituents are preferentially incorporated in enstatite and spinel relative to sapphirine. Thirdly, the presence of hypersolvus orthoamphibole implies a minimum temperature possibly as high as 600 °C (see above). The stability limits of Na-free gedrite $\square\text{Mg}_6\text{Al}[\text{AlSi}_7\text{O}_{22}](\text{OH})_2$ (Fischer et al., 1999) provide no constraints on the P–T estimates for the included assemblages (Fig. 17); evidently the presence of Na and Fe in the natural material extends the stability of gedrite not only to pressures above 12 kb as shown by Fischer et al. (1999), but also to pressures below 9 kb.

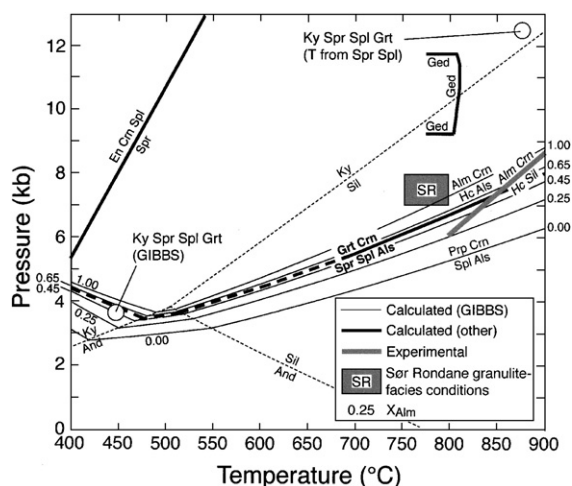


Fig. 17. P–T diagram showing phase relations for the reactions garnet+corundum= Al_2SiO_5 +spinel and garnet+corundum= Al_2SiO_5 +spinel+sapphirine in the system FeO – MgO – Al_2O_3 – SiO_2 (FMAS). The end-member univariant reactions in the subsystems FAS and MAS and isopleths in FMAS (light black lines) were calculated using the Gibbs program (Spear and Menard, 1989) and Holland and Powell (1998). The univariant FMAS reaction garnet+corundum= Al_2SiO_5 +spinel+sapphirine is taken from Ouzegane et al. (2003) and extrapolated to lower temperatures (heavy black line, dashed where extrapolated). The calculated stability limit of $\square\text{Mg}_6\text{Al}[\text{AlSi}_7\text{O}_{22}](\text{OH})_2$ gedrite is taken from Fischer et al. (1999). The lower temperature limit of sapphirine in the MAS+ H_2O system at low H_2O activity was taken from Simon and Chopin (2001). Other sources of information are: experimental Alm+Crn=Hc+Sil curve (Shulters and Bohlen, 1989), Al_2SiO_5 phase diagram (Holdaway and Mukhopadhyay, 1993), and P–T estimates for granulite-facies metamorphism in the Sør Rondane Mountains (Asami et al., 1992). There are two P–T estimates for the Ky+Spr+Spl+Grt assemblage in which $X_{\text{Alm}}=0.45$: (1) 4 kb, 450 °C based on isopleths calculated from GIBBS and (2) ≥ 12 kb, 860–895 °C based on a modification of the sapphirine–spinel thermometer. Abbreviations: And — andalusite, Als — Al_2SiO_5 , Crn — corundum, En — enstatite, Ged — gedrite, Grt — garnet, Hc — hercynite, Ky — kyanite, Prp — pyrope, Sil — sillimanite, Spl — spinel, Spr — sapphirine, X_{Alm} — mole proportion of almandine in binary garnet solid solution.

As an alternative to the above approach, Ian Buick attempted to calculate a pseudosection in the Na_2O – CaO – K_2O – FeO – MgO – Al_2O_3 – SiO_2 – H_2O system using the whole rock analysis (Table 2), an unpublished 2002 update of the Holland and Powell (1998) dataset and Perplex 05 (Connolly and Pettrini, 2002); biotite, chlorite, cordierite, staurolite, garnet, orthopyroxene, sapphirine, spinel, plagioclase, K-feldspar, muscovite, hornblende, and clinopyroxene were considered as potentially stable solid solutions. However, a stability field for sapphirine+spinel+kyanite+garnet was not found. Possible explanations include the effect of components that could not be considered in calculating the pseudosection (TiO_2 , Cr_2O_3 , Fe_2O_3) and a difference between the bulk composition of the rock as a whole and the bulk composition of the volume in which the sapphirine+spinel+kyanite+garnet assemblage crystallized, a difference in the part resulting from metasomatism.

7.4. Summary

Our garnet–biotite temperatures are consistent with previous estimates for peak granulite-facies conditions and retrograde amphibolite-facies conditions in the eastern Sør Rondane Mountains; additionally, the estimate peak conditions lie within the stability field for the garnet–corundum association in the model FeO – MgO – Al_2O_3 – SiO_2 (FMAS) system (Fig. 17). However, we were not successful in obtaining a satisfactory P–T es-

timate for the inclusion (prograde) sapphirine+spinel+kyanite+garnet assemblage. Temperatures estimated from a grid are unreasonably low and inconsistent with other evidence. In contrast, temperatures based on our modified calibration of the Das et al. (2006) sapphirine–spinel thermometer, 860–895 °C (Table 5) are higher than the temperature estimates for the granulite-facies event. Pressures should have been at least 12 kbar to stabilize kyanite at these temperatures (Fig. 17). Such extreme conditions have not been previously reported for Sør Rondane metamorphism, although comparable conditions have been reported in related complexes (see below).

8. Chemical evolution and reactions

Distribution of the minerals included in garnet suggests that the precursor to the corundum+hercynite+plagioclase+biotite+garnet matrix assemblage was heterogeneous on a millimeter scale, i.e., some parts of the rock were constituted by sapphirine+spinel+kyanite, others by orthoamphibole+plagioclase±quartz. The two assemblages differ in bulk composition: the former assemblage is richer in Al_2O_3 , poorer in SiO_2 and ($\text{MgO} + \text{FeO}$), and has a higher Mg/Fe ratio (Fig. 18a). In addition, the garnet core enclosing the former is somewhat Mg-richer than that enclosing the latter (Fig. 4). Ignoring differences in Fe/Mg ratio, the present bulk composition of the biotitic gneiss plots between the

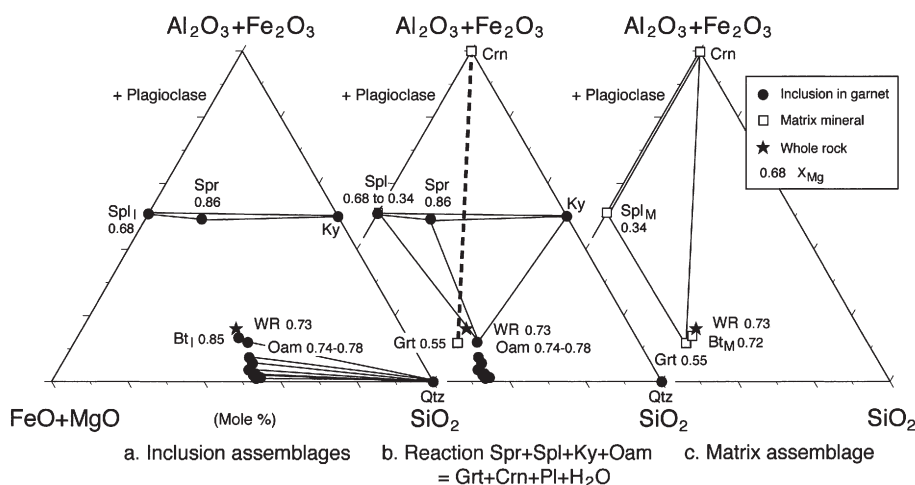


Fig. 18. Projection through plagioclase onto the $(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$ – $(\text{FeO} + \text{MgO})$ – SiO_2 plane of minerals in the sapphirine-bearing biotitic gneiss. Filled circles indicate a representative analysis of each mineral except orthoamphibole, for which individual analyses are plotted to show its compositional range. Garnet composition is projected through An_{100} , orthoamphibole compositions, through An_{40} , which is the average $\text{Ca}/(\text{Ca} + \text{Na})$ ratio for orthoamphibole. Matrix biotite and whole-rock compositions are also projected from K_2O onto the $(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$ – $(\text{FeO} + \text{MgO})$ – (SiO_2) plane. Tie lines to biotite are not shown. The Grt–Crn tie line is shown thick and dashed in (b) to emphasize the reaction relationship with the inclusion assemblages. Abbreviations: Bt_I — biotite inclusion, Bt_M — matrix biotite, Crn — corundum, Grt — garnet, Ky — kyanite, Oam — orthoamphibole, Qtz — quartz, Spl_I — spinel inclusion, Spl_M — matrix spinel, Spr — sapphirine; WR — whole-rock.

inferred bulk compositions of the included assemblages, that is, the precursor to the biotite gneiss was a mixture of the two assemblages on a fine scale prior to the growth of garnet. These millimeter scale compositional heterogeneities were not entirely homogenized during the growth of garnet, but are preserved as two distinct mineral assemblages.

The bulk-rock composition plots close to the compositions of garnet and biotite and slightly on the SiO_2 side of the biotite–corundum join (Fig. 18c). The bulk rock is more magnesian than biotite, probably because X_{Mg} of the whole rock was calculated for Fe^{2+} only, whereas X_{Mg} for biotite was calculated for total Fe.

Prior to the discovery of sapphirine and spinel as inclusions in garnet in the biotitic gneiss and ignoring the CaO content of garnet and orthoamphibole, [Grew et al. \(1989\)](#) proposed the following continuous reaction the formation of garnet from the included quartz-bearing assemblage:

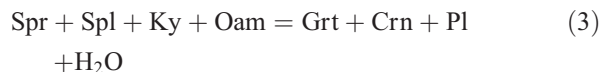


However, the chemographic relationship between grossular-bearing garnet projected through anorthite and the reactant phases (Fig. 18a) is not consistent with reaction (1). This equation can explain the disappearance of quartz only if one assumes that the product Ca-free garnet was incorporated in the dominant grossular-bearing porphyroblasts.

The configuration in Fig. 18b is consistent with the breakdown of the inclusion assemblage sapphirine + spinel + kyanite to the matrix assemblage garnet + corundum by the univariant reaction (in FeO – MgO – Al_2O_3 – SiO_2)



if garnet is assumed to be more magnesian than associated spinel as reported by [Ouzegane et al. \(2003\)](#). Calculations with the GIBBS program imply that this reaction is prograde in the kyanite field, but at 450 °C (Fig. 17), making it highly unlikely that this reaction can explain the relationship between the included and matrix assemblages. If we assume instead that minerals from different domains reacted with one another, the configuration in Fig. 18b is consistent with the following reaction relating all the included phases in the FeO – MgO – Al_2O_3 – SiO_2 – Na_2O – CaO – H_2O system except quartz:



In contrast to reaction (2), which could proceed without a change in bulk Fe^{2+}/Mg ratio, compositions of the ferromagnesian reactants and products require an increase in bulk Fe^{2+}/Mg ratio to produce garnet from the four-phase assemblage.

In summary, inferring changes in pressure and temperature from the reaction relating the inclusion assemblages and matrix assemblage is not possible because pressure and temperature were not the only factors involved in the reaction. Metasomatic introduction of Fe^{2+} played a major role in the breakdown of sapphirine, kyanite and orthoamphibole to form garnet and corundum, that is, this breakdown resulted from the same process that biotitized the precursor of the biotitic gneiss as discussed above.

9. Kyanite + sapphirine + spinel in a Neoproterozoic–Cambrian orogenic belt

The Sør Rondane Mountains constitute the third region for kyanite, sapphirine and spinel–hercynite inclusions in garnet in granulite-facies rocks of the Neoproterozoic–Cambrian orogen extending from the Sør Rondane Mountains to Lützow–Holm Bay and onward to Sri Lanka, southern India and southern Madagascar (Fig. 19). Kyanite + spinel ± staurolite assemblages have been reported from garnet–sillimanite–spinel quartzofeldspathic gneisses at Skallen and Langhovde in Lützow–Holm Bay ([Hiroi et al., 1983](#); [Motoyoshi et al., 1985](#)), and sapphirine + kyanite, from Rundsvågshetta ([Motoyoshi et al., 1989](#); [Motoyoshi and Ishikawa, 1997](#)). A greater variety of included assemblages are found in garnet–sillimanite quartzofeldspathic gneisses over an extended area of the Highland Complex in Sri Lanka, e.g., kyanite + sapphirine + spinel and kyanite + hercynite + staurolite ([Ogo et al., 1992](#); [Hiroi et al., 1994](#)). The widespread occurrence of included staurolite has led [Hiroi et al. \(1994\)](#) to infer a staurolite precursor to the Highland Complex sapphirine-bearing assemblage. They estimated temperatures near 900 °C and pressures between 11 and 12 kb for the sapphirine-bearing assemblage. In making this estimate, [Hiroi et al. \(1994\)](#) assumed that the divariant FMAS reaction corundum + garnet = kyanite + hercynite was stable in a band slightly steeper than the line for the univariant FAS reaction corundum + garnet = sillimanite + hercynite, and displaced 3–4 kb to higher pressure on a P–T diagram. The temperature estimate was constrained by staurolite breakdown to kyanite + garnet + hercynite or corundum in FMAS + H_2O . In contrast, [Motoyoshi and Ishikawa \(1997\)](#) assumed that included sapphirine and kyanite formed within the stability field of staurolite because of

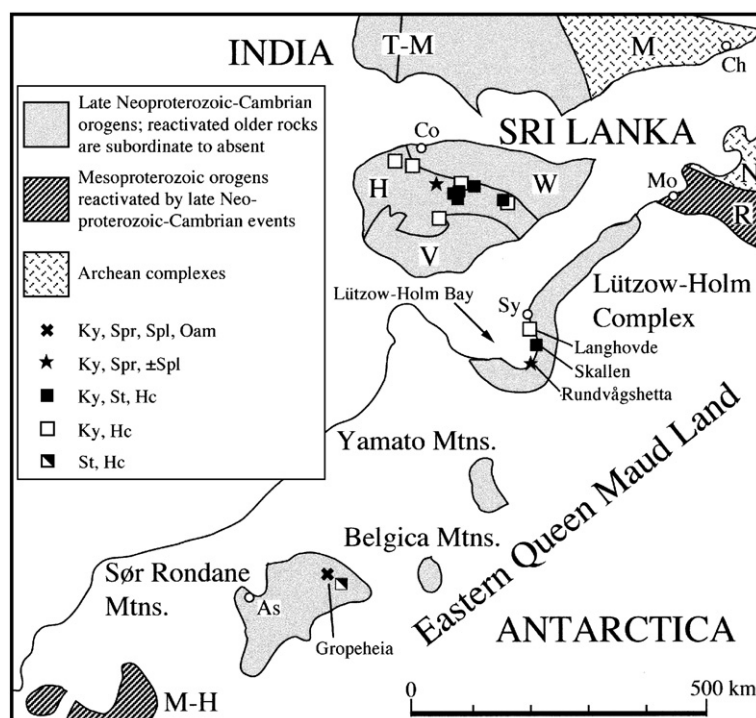


Fig. 19. Map of a portion of the Neoproterozoic–Cambrian orogenic belt in Gondwana (excerpted from Asami et al., 2002, 2005) showing localities in granulite-facies complexes for inclusions in garnet of kyanite with sapphirine or spinel. Sources of information: Sør Rondane Mountains (Asami et al., 1990; this paper); Lützow–Holm Bay (Motoyoshi et al., 1985; Motoyoshi and Ishikawa, 1997), and Sri Lanka (simplified from Hiroi et al., 1994). The spinel series mineral in the Langhovde and Skallen rocks was reported as spinel, but no analyses were given; this mineral could also be hercynite. Abbreviations: As — Asuka Station, Ch — Chennai, Co — Colombo, H — Highland Complex, Hc — hercynite, Ky — kyanite, M — Madras Block, Mo — Molodezhnaya Station, M–T — Mühlig–Hofmann Mountains, N — Napier Complex, Oam — orthoamphibole, R — Rayner Complex, Spl — spinel, Spr — sapphirine, St — staurolite, Sy — Syowa Station, T–M — Trivandrum–Madurai Block, V — Vijayan Complex, W — Wannai Complex.

the presence of staurolite inclusions in garnet elsewhere in Lützow–Holm Bay. Their temperature estimates ranged from 550 to 700 °C at pressures above 9 kb.

The Gropeheia biotitic gneiss differs in several important respects from the rocks from Lützow–Holm Bay and Highland Complex. The gneiss is associated with ultramafic rocks rather than paragneisses and its matrix is silica-undersaturated. Orthoamphibole, rather than staurolite, is the only hydrous phase except for biotite found as inclusions in garnet. Nonetheless, we suspect that despite the differences in geologic association, the similarity of the included assemblages in the Sør Rondane Mountains, Lützow–Holm Bay and the Highland Complex implies a common P–T evolution. Our estimate of the P–T conditions based on a modification of the Das et al. (2006) calibration of the sapphirine–spinel thermometer (Fig. 17) is close to the conditions estimated by Hiroi et al. (1994) sapphirine-bearing inclusion assemblages in Sri Lanka. Staurolite is found as inclusions in garnet in a corundum–garnet gneiss (Asami et al., 1990) 6 km to the southeast of

Gropeheia (Fig. 1), and so the prograde path must have passed through the staurolite stability field in the Sør Rondane Mountains as it had in Lützow–Holm Bay and the Highland Complex. One point of disagreement is whether sapphirine and spinel formed from staurolite breakdown, as Hiroi et al. (1994) suggested, or formed within the stability field of staurolite, as Motoyoshi and Ishikawa (1997) assumed.

An unresolved question is the stability range of the kyanite + spinel–hercynite assemblage. The temperatures implied by the calculated equilibria in Fig. 17 are way too low for formation of the included assemblage from staurolite breakdown, and perhaps too low for formation within the stability field of staurolite, particularly if the staurolite is a high-temperature variety as Hiroi et al. (1994) suggested on the basis of its distinctive composition. More systematic theoretical and experimental study of kyanite + spinel–hercynite ± sapphirine equilibria would clarify the tectonic evolution of the Neoproterozoic–Cambrian belt in eastern Queen Maud Land and Sri Lanka.

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