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METAMORPHIC CONDITIONS OF ULTRAMAFIC LENSES FROM THE EASTERN SØR RONDANE MOUNTAINS, EAST ANTARCTICA

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Abstract: Lenses up to 5 m in size of ultramafic rocks occur in quartzo-feldspathic, locally migmatized, gneisses at four localities of the eastern Sør Rondane Mountains. A composite lens at one locality consists of harzburgite, orthopyroxenite and garnet amphibolite, and a second, consists entirely of harzburgite. Harzburgite contains chromite-poor spinel ($Cr/(Cr+Al) \sim 0.1$), which indicates that it was equilibrated under conditions of the spinel lherzolite facies. Temperature estimates for the ultramafic lenses represent that they preserved at least two stages of metamorphic temperature conditions. The higher temperatures ($\sim$750°C) estimated by the maximum Al-content of orthopyroxene and the pyroxene geothermometers are consistent with those of the early granulite-facies metamorphic event reported in the eastern Sør Rondane Mountains. This indicates that the ultramafic lenses and the surrounding metamorphic rocks recrystallized under the same granulite-facies metamorphic temperature conditions. The lower temperatures (520–670°C) obtained from garnet rim-biotite pairs probably correspond to the later, discrete amphibolite-facies event in the Mountains.

1. Introduction

Petrologic nature of the ultramafic rocks emplaced in high-grade metamorphic terrains is of use in characterization of *P-T* conditions of metamorphism and understanding of the tectonic process in orogenic environments. Consequently, ultramafic rocks have been specially sought in the Sør Rondane Mountains (71°40′–72°20′S; 22°30′–28°E), which are part of the Precambrian shield of East Antarctica. However, during geological surveys by the 25th–29th Japanese Antarctic Research Expeditions (JARE) (1983–1988), few ultramafic rocks have been found in the Mountains (KOJIMA and SHIRAISHI, 1986; ISHIZUKA and KOJIMA, 1987; ASAMI *et al.*, 1989).

The present paper reports petrography and mineral chemistry of the ultramafic lenses collected in Balchenfjella (Balchen Mountain) of the eastern Sør Rondane Mountains during JARE-29. Moreover, metamorphic conditions of the lenses are preliminarily examined, and compared to those estimated for the surrounding metamorphic rocks.

2. Outline of Geology

The geology of the eastern Sør Rondane Mountains and preliminary petrology of the metamorphic rocks have been reported by ASAMI *et al.* (1989) and GERW *et al.* (1989), and are briefly summarized here. The crystalline basement of the Mountains consists largely of metasedimentary and metavolcanogenic rocks with subordinate metaigneous rocks (Fig. 1). The dominant metamorphic rocks are biotite-hornblende quartzo-feldspathic gneisses, in which a wide variety of rock types forms concordant to subconcordant lenses ranging from 1 m to 1 km in extent. Such rock types include mafic granulites, amphibolites, cummingtonite + orthopyroxene orthogneiss, garnet-biotite gneisses, marbles, quartzite and ultramafic rocks. By using field data, petrography and geothermobarometry, at least two metamorphic events can be distinguished in this area: (1) an early upper amphibolite to granulite facies metamorphism ($\geq$7 kbar and 700–750°C) and (2) a late amphibolite facies one (500–600°C) which is closely

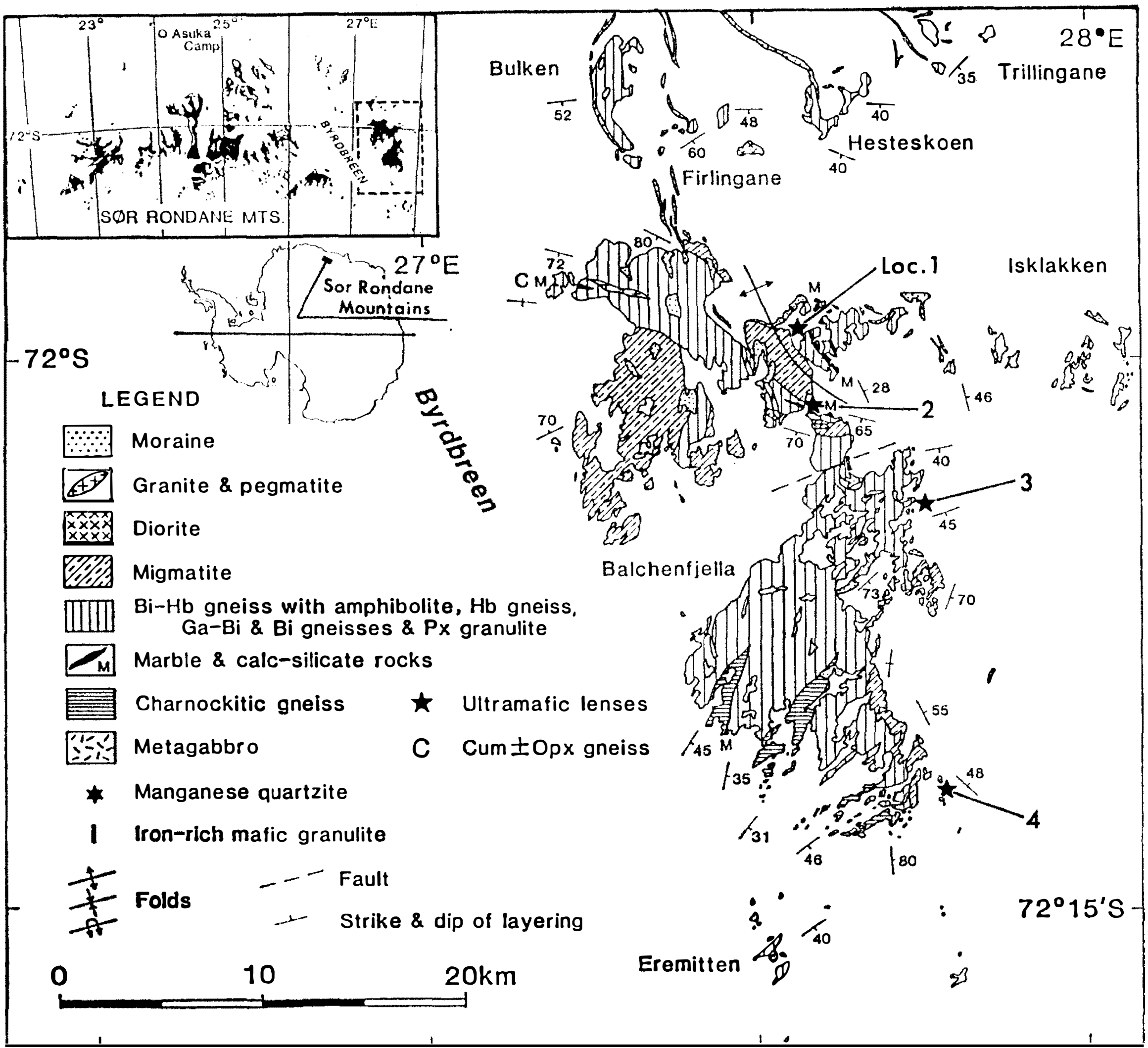

Fig. 1. Geological map of Balchenfjella of the eastern Sør Rondane Mountains including sample Localities 1-4. Modified after Fig. 1 in ASAMI et al. (1989).

related with migmatization. Metadikes intervened between event (1) and (2), indicating that these two events are discrete. Minor unmetamorphosed diorite and granite-pegmatite intrusions are found.

In the Sør Rondane Mountains, radiometric ages of about 500 Ma were previously reported for thermal event associated with plutonic activity (*e.g.* VAN AUTENBOER, 1969). Recently, SHIRAISHI and KAGAMI (1989) gave a whole rock Sm-Nd isochron age of about 1000 Ma which is interpreted to date the granulite-facies metamorphism. A new result of the geochronology on plutonic rocks is shown in TAKAHASHI *et al.* (1990).

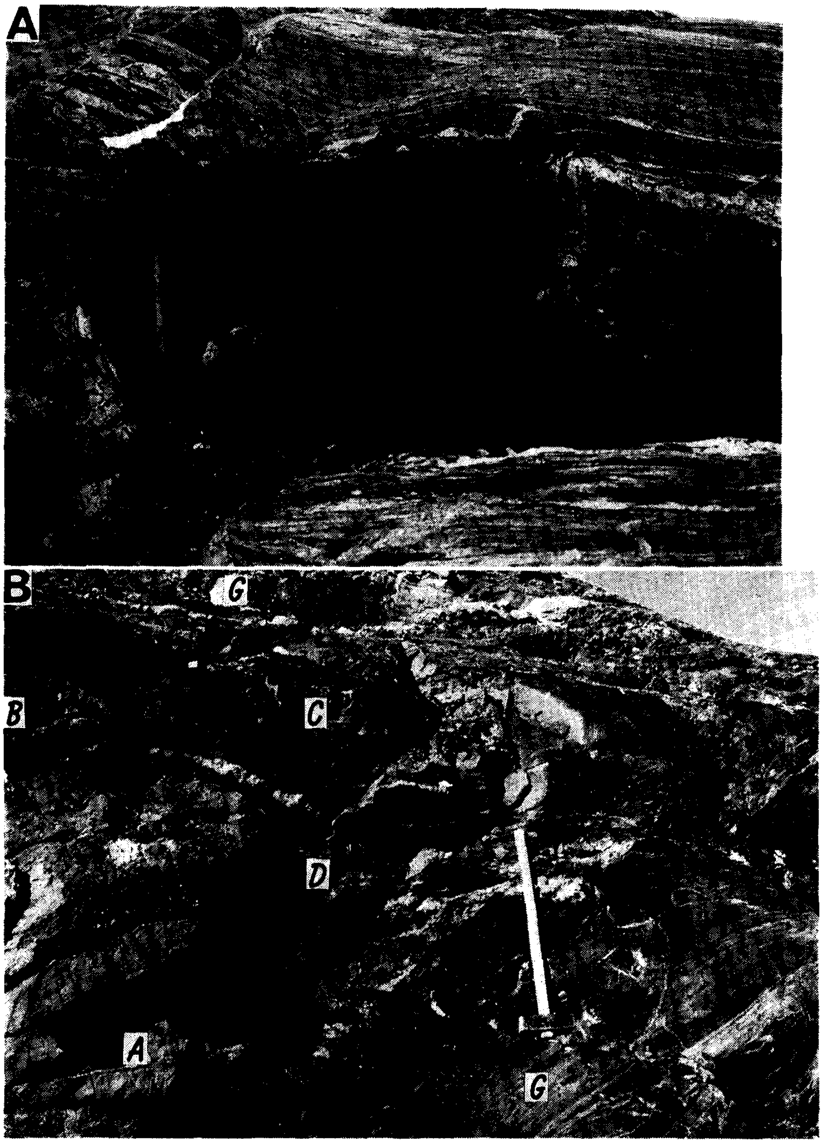

Fig. 2. A: Ultramafic lens at Locality 3. The host rock at this locality is migmatitic quartzo-feldspathic gneiss.
B: Ultramafic composite lens at Locality 1. A: Harzburgite (1803A), B: Orthopyroxenite (1803B), C: Garnet amphibolite (1803C), D: Biotite-plagioclase-garnet schist (1803D), G: Quartzo-feldspathic gneiss.

3. Field Occurrence of the Ultramafic Rocks

The ultramafic rocks occur as lenses or rounded blocks up to several meters in size (Fig. 2A) at four localities in Balchenfjella (Locs. 1 to 4 in Fig. 1). Host rocks for these lenses are metasedimentary quartzo-feldspathic gneisses or migmatite. Foliation in the host rocks is concordant with the margin of the included ultramafic lenses. Between the ultramafic lenses and the host rocks, reaction zones (several centimeters to 20 cm in width) of micas and/or amphiboles are usually developed. At present, the origin of the ultramafic rocks is problematic. We can only say that their occurrence is closely associated with various rock types of oceanic rock assemblages such as marble, Mn-rich quarzite and iron-rich mafic granulite.

At Locality 1, two ultramafic lenses are isolated from each other by about several meters. One lens is composed of several rock types and thus has received special attention in this study. Host rocks for these lenses are well-layered quartzo-feldspathic gneisses containing garnet, orthopyroxene and clinopyroxene.

The composite lens (Fig. 2B) is about 3×5 m in size and consists of harzburgite (Sample HM88011803A abbreviated to 1803A; all sample numbers referred to below have the prefix HM8801–), orthopyroxenite (1803B) and garnet amphibolite (1803C), of which harzburgite is dominant. Each rock types form lenticular bodies, and boundaries between different rock types are lithologically sharp. The garnet amphibolite is separated by a amphibole-rich veinlet from the harzburgite. A biotite-plagioclase-garnet schist (1803D) is part of the reaction zone between the composite lens and the host gneiss (GREW *et al.*, 1989). This schist contains spinel, corundum and sillimanite, but lacks quartz, and was probably derived from a pelitic rock interacted with the ultramafic rocks.

Another lens at Locality 1 is smaller (about 1×3 m in size) and harzburgite (1801B). Reaction zone, up to 3 cm in thickness, of fibrous amphiboles is formed between the lens and the host gneiss.

4. Petrography of the Ultramafic Lenses

Harzburgite (1803A) is fine- to medium-grained (0.2–2 mm), massive and gray with a brown-weathered surface. This rock consists largely of olivine and orthopyroxene with minor spinel, clinopyroxene and pale-green hornblende. Generally these minerals are anhedral and show a granular texture (Fig. 3A). Olivine and spinel are locally interstitial to orthopyroxene. Olivine shows no trace of serpentinization. Spinel is a translucent green to yellow-brown variety and constitutes about 1 modal %. Phlogopite and opaque occur in trace amounts. Talc and calcite are secondary minerals.

Harzburgite (1801B) is petrographically similar to the harzburgite (1803A) of the composite lens, but lacks clinopyroxene. Furthermore, in addition to granular spinel, some finer crystals of pale-green spinel occur as vermicules or elongated blebs in grains of orthopyroxene and along their boundaries (Fig. 3B).

Orthopyroxenite (1803B) consists of coarse orthopyroxene grains (up to 8 mm in diameter) and a fine- to medium-grained (0.2–2 mm) granular matrix of orthopyroxene, clinopyroxene and subordinate pale-brown hornblende (Fig. 3C). Clinopyroxene-rich

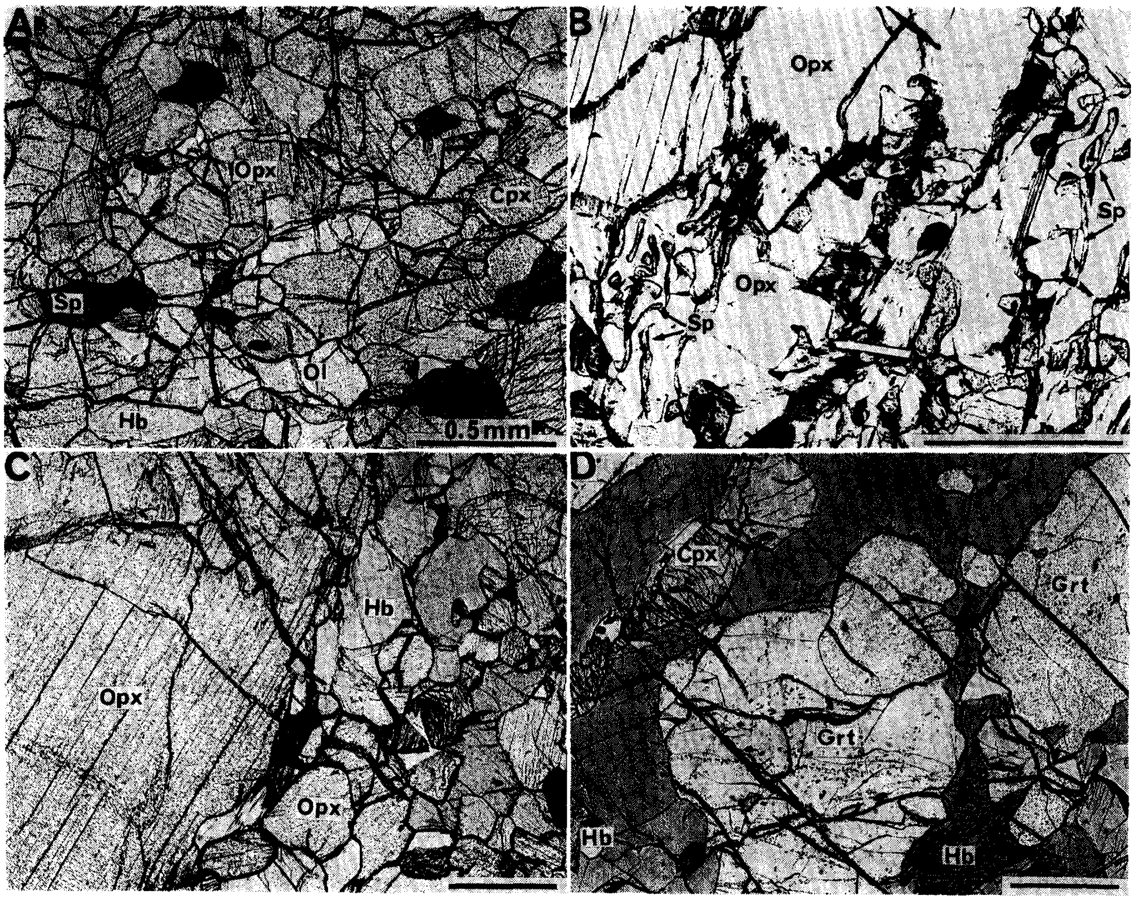

Fig. 3. Photomicrographs of ultramafic rocks. A: Harzburgite (1803A). B: Harzburgite (1801B). Several vermicular spinels are arrowed. C: Orthopyroxenite (1803B). D: Garnet amphibolite (1803C). Plane polarized light. Ol: Olivine, Opx: Orthopyroxene, Cpx: Clinopyroxene, Hb: Hornblende, Grt: Garnet, Sp: Spinel.

patches, up to 2 cm in diameter, are locally developed. The coarse-grained orthopyroxene has thin clinopyroxene exsolution lamellae. Phlogopite is minor, and rutile and opaque occur in trace amounts.

Garnet amphibolite (1803C) is composed of pale-brown hornblende and garnet with minor biotite and clinopyroxene. Rutile and opaque occur in trace amounts. Veinlets of plagioclase ($\sim An_{50}$) are locally developed. Grain-size of hornblende is in the range 0.5–2 mm. Garnet, up to 5 mm in diameter, occurs as subhedral or resorbed anhedral grains in a matrix of hornblende and minor biotite. Garnet is also partly embayed by finer-grained aggregates of biotite and plagioclase with or without green hornblende. Clinopyroxene is fine-grained (<0.2 mm in diameter), anhedral, and always occurs as inclusions in hornblende and garnet (Fig. 3D).

No apparent cumulate textures were observed in any studied ultramafic samples. Rather, the petrographic features mentioned above suggest that these rocks have metamorphic textures.

5. Mineral Chemistry

Minerals from the ultramafic lenses at Locality 1 were analyzed using a JEOL JXA733 electron microprobe at the Geological Survey of Japan. The correction procedures are those by BENCE and ALBEE (1968) with alpha factors by NAKAMURA and KUSHIRO (1970). Selected analyses are listed in Tables 1–3 and plotted in Figs. 4–6.

Compositions of olivine from the harzburgite (1803A, 1801B) are 0.900 in X_{Mg} (=Mg/(Mg+Fe) in atomic ratio), and quite uniform between grains and within individual grains. TiO_2, Al_2O_3 and CaO contents of olivine are very low ($\leq$0.01 wt%). NiO contents are 0.45–0.51 wt% for 1803A and 0.26–0.32 wt% for 1801B.

Granular spinel in the harzburgites has Mg/(Mg+Fe^{2+}) ratios of 0.725–0.746 and Cr/(Cr+Al) ratios of 0.09–0.12. The low chromite contents of spinel indicate that the harzburgite mineral assemblages are characteristic of the spinel lherzolite facies, one of three mineral facies divisions for rocks of peridotitic composition (*e.g.* KUSHIRO and YODER, 1966). Vermicular spinel in 1801B is more Mg-rich (Mg/(Mg+Fe^{2+})=0.780–0.794) and Al-rich (Cr/(Cr+Al)<0.03) than granular spinel (Fig. 5). Judging from

Table 1. Compositions of olivines and spinels.

	1801 B	1803A	1801 B		1803A
	27	26	11	29	17
	Ol	Ol	Sp[1]	Sp[2]	Sp[1]
SiO_2	40.6	40.6	0.02	0.02	<0.01
TiO_2	<0.01	0.01	0.01	<0.01	0.05
Al_2O_3	0.01	<0.01	59.4	66.3	57.8
Cr_2O_3	—	—	8.58	1.47	9.77
FeO	9.80	9.74	12.4	10.4	12.7
MnO	0.16	0.13	0.14	0.11	0.14
NiO	0.32	0.45	—	—	—
MgO	49.7	49.6	19.0	20.7	18.9
CaO	0.01	0.01	0.01	<0.01	0.02
Total	100.6	100.6	99.6	99.0	99.4
		Cations per 4 oxygens			
Si	0.991	0.991	—	—	—
Ti	0	0	0	0	0.001
Al	0	0	1.817	1.971	1.780
Cr	—	—	0.176	0.029	0.202
Fe^{3+}	—	—	0.007	0	0.016
Fe^{2+}	0.200	0.199	0.262	0.219	0.262
Mn	0.003	0.003	0.003	0.003	0.003
Ni	0.006	0.009	—	—	—
Mg	1.808	1.805	0.735	0.778	0.736
Ca	0	0	—	—	—
Total	3.009	3.007	3*	3*	3*
X_{Mg}	0.900	0.901	0.732	0.780	0.726

* Normalized to 3 cations and Fe^{3+} calculated by stoichiometry. Si, Ca contents ignored. X_{Mg} in terms of total Fe.

Ol: Olivine, Sp: Spinel (1: Granular grain, 2: Vermicular grain in orthopyroxene).

the mode of occurrence and chemistry, the vermicular spinel could have been exsolved from orthopyroxene. Both types of spinel are poor in Fe^{3+}; $Fe^{3+}/(Cr+Al+Fe^{3+})$ ratios do not exceed 0.01.

Orthopyroxene in the harzburgites has X_{Mg} ratios of 0.904–0.891, which are similar to those of coexisting olivine. Al_2O_3 contents are low (2.28–3.35 wt%) with somewhat higher concentrations in cores than in rims of grains. Orthopyroxene in the orthopyroxenite (1803B) has X_{Mg} values ranging from 0.773 to 0.756 for matrix grains and from 0.791 to 0.783 for coarse grains. Al_2O_3 contents are low (1.2–2.2 wt%) in both types and Al_2O_3 zoning is weak.

Clinopyroxene in the harzburgite (1803A) has a limited range of compositions approaching diopside ($Wo_{49}En_{47}Fs_4$) with Al_2O_3 content of 3.0–3.2 wt%. Clinopyroxenes in the orthopyroxenite and garnet amphibolite are diopside and salite, respectively, and slightly heterogeneous in Ca-Mg-Fe ratio (Fig. 4) and Al_2O_3 content (2.1–3.8 wt%). Its Na_2O content ranges from 0.44 to 0.75 wt% and 0.39 to 0.60 wt%, respectively, and is higher than that (0.05 wt%) for clinopyroxene in the harzburgite.

Table 2. Compositions of pyroxenes.

	1801B	1803A			1803B			1803C
	33	16	7	12	41	16	6	19
	Opx(C)	Opx(C)	Opx(R)	Cpx(C)	Opx(C)[2]	Opx(C)[1]	Cpx(C)	Cpx
SiO_2	55.7	55.7	55.9	52.7	54.9	53.9	53.0	51.7
TiO_2	0.14	0.15	0.11	0.42	0.05	0.09	0.13	0.23
Al_2O_3	3.13	3.14	2.66	3.01	1.67	2.03	2.95	3.61
Cr_2O_3	0.13	0.26	0.21	0.21	0.07	0.22	0.45	0.03
FeO	6.90	6.45	6.84	2.17	13.7	14.8	5.07	7.31
MnO	0.16	0.17	0.16	0.06	0.29	0.27	0.13	0.25
MgO	33.9	34.1	34.2	17.1	29.1	28.3	15.4	13.8
CaO	0.12	0.41	0.33	24.8	0.22	0.47	22.6	22.2
Na_2O	0.01	<0.01	<0.01	0.04	<0.01	<0.01	0.62	0.45
K_2O	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	0.01
Total	100.2	100.4	100.4	100.5	100.2	100.1	100.4	99.6
			Cations per 6 oxygens					
Si	1.922	1.917	1.926	1.910	1.956	1.936	1.938	1.923
Al^{IV}	0.078	0.083	0.074	0.090	0.044	0.064	0.062	0.077
Al^{VI}	0.049	0.044	0.034	0.039	0.026	0.022	0.065	0.081
Ti	0.004	0.004	0.003	0.011	0.001	9.002	0.004	0.006
Cr	0.004	0.007	0.006	0.006	0.002	0.006	0.013	0.001
Fe	0.199	0.186	0.197	0.066	0.408	0.444	0.155	0.227
Mn	0.004	0.005	0.005	0.002	0.009	0.008	0.004	0.008
Mg	1.744	1.750	1.757	0.924	1.545	1.515	0.840	0.765
Ca	0.004	0.015	0.012	0.963	0.015	0.018	0.888	0.885
Na	0.001	0	0	0.003	0	0	0.044	0.032
K	0	0	0	0	0	0	0	<0.001
Total	4.010	4.011	4.014	0.014	4.006	4.015	4.011	4.005
X_{Mg}	0.898	0.904	0.899	0.933	0.791	0.773	0.844	0.771

Opx: Orthopyroxene, Cpx: Clinopyroxene, C: Core, R: Rim.
1: Matrix Opx, 2: Coarse-grained Opx.

Table 3. Compositions of garnets and micas.

	1803C		1803D		1801B	1803A	1803C	1803D
	30	27	24	5	28	29	25	34
	Grt(C)	Grt(R)	Grt(C)	Grt(R)	Phl	Phl	Bi	Bi
SiO_2	39.6	39.0	40.1	38.1	40.4	41.1	38.2	37.2
TiO_2	0.05	<0.01	<0.01	<0.01	0.71	0.93	3.42	1.10
Al_2O_3	21.7	22.0	22.4	21.4	18.1	15.4	15.8	19.4
Cr_2O_3	0.04	0.04	0.16	0.10	0.07	0.57	0.08	0.28
FeO	21.5	24.1	21.4	27.9	2.81	2.05	11.8	11.8
MnO	0.49	0.59	0.51	3.32	0.04	0.08	0.08	0.03
MgO	9.37	7.60	11.8	5.88	24.8	25.3	16.5	16.8
CaO	6.90	5.79	4.21	3.24	0.02	<0.01	0.04	<0.01
Na_2O	<0.01	<0.01	<0.01	0.02	1.28	0.11	0.22	0.63
K_2O	—	—	—	—	7.69	10.3	9.38	9.13
Total	99.7	99.1	100.6	100.0	95.9	95.8	95.5	96.4
	Cations per 12 oxygens				Cations per 22 oxygens			
Si	3.018	3.017	2.999	2.997	5.573	5.735	5.590	5.382
Al^{IV}	—	—	—	—	2.427	2.265	2.410	2.618
Al^{VI}	1.949	2.006	1.975	1.984	0.516	0.268	0.315	0.690
Ti	0.003	0	0	0	0.074	0.098	0.376	0.120
Cr	0.002	0.002	0.009	0.006	0.008	0.063	0.009	0.032
Fe	1.370	1.559	1.339	1.835	0.324	0.239	1.444	1.428
Mn	0.032	0.039	0.032	0.221	0.005	0.009	0.010	0.004
Mg	1.063	0.876	1.316	0.689	5.100	5.262	3.599	3.623
Ca	0.563	0.480	0.337	0.273	0.003	0	0.006	0
Na	0	0	0	0.003	0.342	0.030	0.062	0.177
K	—	—	—	—	1.353	1.833	1.751	1.685
Total	8.002	7.979	8.007	8.008	15.725	15.802	15.572	15.759
X_{Mg}	0.437	0.360	0.496	0.273	0.940	0.957	0.714	0.717
X_{PY}	0.351	0.297	0.435	0.228				

Grt: Garnet, Phl: Phlogopite, Bi: Biotite, C: Core, R: Rim.

Compositions of garnet in the garnet amphibolite (1803C) are variable (Fig. 4). Figure 6 shows a typical example; X_{PY} (=Mg/(Mg+Ca+Fe+Mn)) ratio ranges from 0.36 to 0.24 in this grain. This compositional variation is due to extensive zoning with pyrope-rich homogeneous core and rim enriched in Fe. Ca contents show the same trend as Mg contents, and Mn are constant in both core and rim. Garnet porphyroblasts from biotite-plagioclase-garnet schist (1803D) are also zoned in composition (Fig. 6). The garnet has a homogeneous core and narrow outer rim, which are separated by an inner rim: the inner rim shows outward increases in Fe. Their garnet cores are pyrope-rich (X_{PY} 0.44 for the grain in Fig. 6). In the garnet cores of the schist (1803D), kyanite, gedrite and quartz occur as minute inclusions, and this relic assemblage suggests pressure above 6 kbar on a prograde path (GREW *et al.*, 1989).

Mica compositions are uniform in each rock type and range in Mg/Fe ratio from phlogopite in the harzburgite and orthopyroxenite to biotite in the garnet amphibolite.

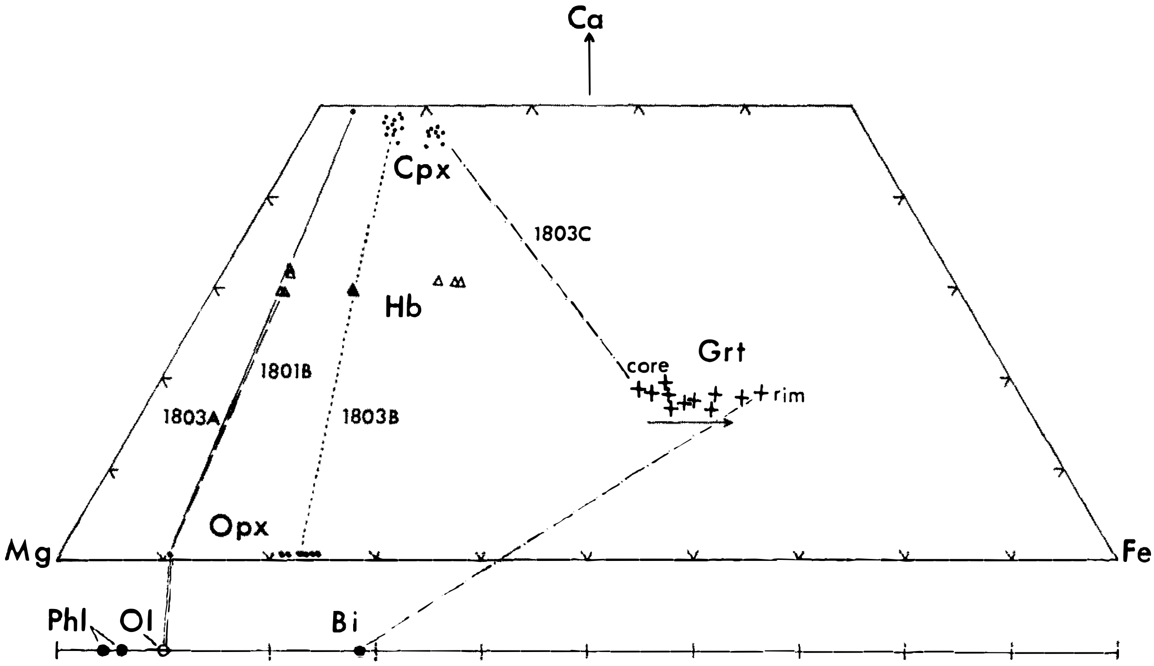

Fig. 4. *Plot of compositions of minerals from the ultramafic lenses in terms of atomic Ca, Mg and Fe. Ol: Olivine, Opx: Orthopyroxene, Cpx: Clinopyroxene, Hb: Hornblende, Grt: Garnet, Phl: Phlogopite, Bi: Biotite.*

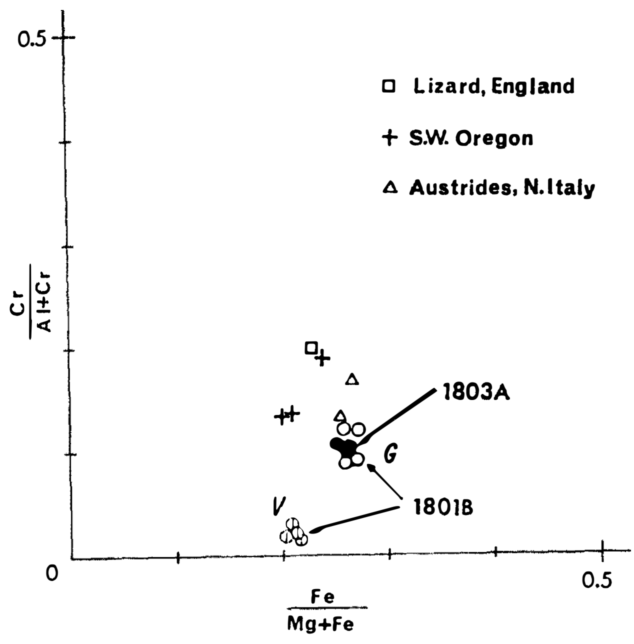

Fig. 5. *Plot of compositions of spinel from the harzburgites. G: Granular grain, V: Vermicular grain. Lizard: GREEN (1964), S. W. Oregon: MEDARIS (1972), Austrides: OBATA and MORTEN (1987).*

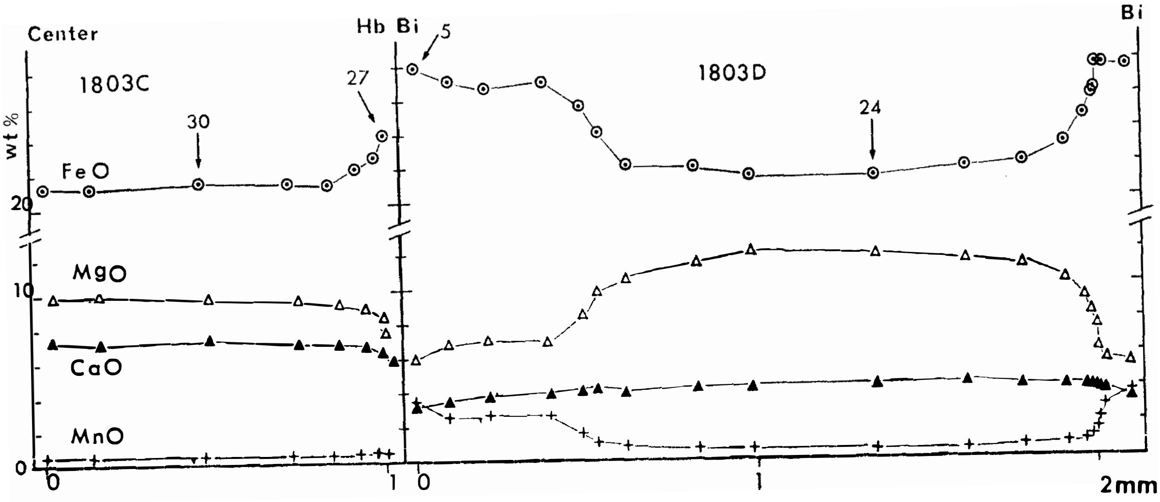

Fig. 6. Compositional profiles for garnets in garnets amphibolite (1803C) and biotite-plagioclase-garnet schist (1803D). Numbers with arrows are the same as those of garnet analyses in Table 3.

6. Temperature Estimates—Metamorphic Conditions—

Temperatures calculated by cation distribution between mineral pairs are summarized in Table 4. The ultramafic rocks of spinel lherzolite facies have no appropriate mineral assemblages for estimating pressure. Based on the result of experimental studies (*e.g.* KUSHIRO and YODER, 1966; GASPARIK and NEWTON, 1984), pressures could lie in the range 6–17 kbar (at 800°C).

For the harzburgites, temperatures of about 760°C and of 650–705°C were obtained using the orthopyroxene-clinopyroxene (WELLS, 1977) and the olivine-spinel (FABRIÈS, 1979) geothermometers, respectively. The temperature discrepancy between both mineral paris is probably due in part to the difference in closure temperatures for cation distribution and in part to discrepancies among the different geothermometers. In addition, maximum and minimum Al_2O_3 contents, 3.35 wt% and 2.28 wt%, of orthopyroxene yield temperatures of about 750°C and 660°C at 7 kbar by using experimental results on Al-solubility of enstatite coexisting with spinel and forsterite (OBATA, 1976; DANCKWERTH and NEWTON, 1978; GASPARIK and NEWTON, 1984). For the orthopyroxenite, matrix orthopyroxene-clinopyroxene pairs give a temperature about 900°C which is higher than those for harzburgites.

The temperatures 705–760°C obtained from the harzburgites are consistent with the 700–780°C temperatures estimated from garnet-pyroxene and clinopyroxene-orthopyroxene geothermometers for an iron-rich mafic granulite (GREW *et al.*, 1989). Such temperatures are "comparable" for granulite-facies metamorphism. However, the estimates based on Fe-Mg exchange thermometers could be spurious (see GREW *et al.*, 1989). Possibly the temperature 750°C calculated from the maximum Al_2O_3 content of orthopyroxene is the most reliable estimate for peak conditions during the granulite-facies event. The temperature of about 900°C for orthopyroxenite may be due to problems in applying the pyroxene geothermometers or to a temperature of ultramafic protolith during the preceding events.

Table 4. Estimated temperatures for ultramafic lenses.

Sample No. HM8801-						Temperature[1] °C (at 7 kbar)[2]		
	Olivine-Spinel							
	Ol X_{Mg}	Sp X_{Mg}	ln K	Y_{Cr}	F			
1801 B	0.897	0.737	1.140	0.088	651			
1803 A	0.900	0.746	1.117	0.106	705			
1803 A	0.900	0.734	1.181	0.118	689			
	Orthopyroxene-Clinopyroxene							
	Opx X_{Mg}	Cpx X_{Mg}	Opx a-$Mg_2Si_2O_6$	Cpx a-$Mg_2Si_2O_6$	W	WB		
1803 A	0.904	0.931	0.769	0.023	760	884		
1803 B	0.770	0.844	0.559	0.047	874	907		
1803 B	0.769	0.854	0.562	0.059	917	940		
	Garnet core-Clinopyroxene							
	Grt X_{Mg}	Grt X_{Ca}	Cpx X_{Mg}	ln K	EG	PN ($X_{Ca}=0.2$)		
1803 C	0.408	0.188	0.795	1.727	743	636		
	Garnet rim-Biotite							
	Grt X_{Mg}	Bi X_{Mg}		ln K	T	FS	PL	IM
1803 C	0.354	0.714		−1.516	618	665	624	672
1803 D	0.273	0.716		−1.905	518	529	551	553

1: Abbreviations; F—Fabriès (1979), W—Wells (1977), WB—Wood and Banno (1973), EG—Ellis and Green (1979), PN—Pattison and Newton (1989), T—Thompson (1976), FS—Ferry and Spear (1978), PL—Perchuk and Lavrent'eva (1983), IM—Indares and Martignole (1985), model B.

2: Pressure estimate from Grew *et al.* (1989).

Temperatures calculated from garnet rim-biotite pairs in the garnet amphibolite and the schist of the reaction zones range from 520°C to 670°C (Table 4), suggesting that they were equilibrated during the later amphibolite-facies event reported by Asami *et al.* (1989) and Grew *et al.* (1989); for this event, Grew *et al.* (1989) estimated the temperature range (550–630°C) from garnet rim-biotite in the garnet-biotite gneiss and calcite-dolomite in the marble. The pyrope-rich cores of garnet in the garnet amphibolite and the reaction zone (Table 3; see also Table 4 in Grew *et al.*, 1989) are most likely relics of the granulite-facies event. During a line-analysis of garnet in the garnet amphibolite with the electron microprobe, clinopyroxene inclusions are found in the zoned rim. A temperature estimated using the Ellis and Green (1979) geothermometer for garnet core-clinopyroxene inclusion pairs is about 740°C, which is consistent with the temperature (~750°C) obtained from the harzburgites. It is likely that the garnet cores were in equilibrium with clinopyroxene under the granulite-facies conditions. From the same mineral pairs, a temperature about 640°C is estimated by the Pattison and Newton (1989) geothermometer, and could be a closure or resetting temperature (see Grew *et al.* 1989).

7. Concluding Remarks

Our temperature estimates for the ultramafic lenses represent that they preserved at least two stages of the metamorphic temperature conditions; higher (~750°C) and lower (520–670°C). The higher temperatures are in good agreement with temperatures (700–750°C) of the early granulite-facies metamorphic event in the Mountains (GREW *et al.*, 1989, Table 14). This indicates that the ultramafic lenses and the surrounding metamorphic rock recrystallized under the same granulite-facies temperature conditions. More restrict evaluate of the metamorphic pressure is hoped for the lenses. The lower temperatures probably correspond to the later, discrete amphibolite-facies event in the Mountains.

The granulite-facies metamorphic temperatures estimated for the eastern part of the Sør Rondane Mountains are somewhat lower than those estimated for the western part (800°C, SHIRAISHI and KOJIMA (1987); 830°C, ASAMI and SHIRAISHI, 1987), and in the range of those estimated for the central part (700–800°C), YAMAZAKI *et al.*, 1986). In the western and central parts, amphibolite-facies metamorphic conditions are also reported (YAMAZAKI *et al.*, 1986; SHIRAISHI and KOJIMA, 1987), but amphibolite-facies metamorphism has not been recognized as a discrete event, and thus amphibolite-facies events are not directly comparable. Correlation of metamorphic history across the Sør Rondane Mountains requires isotopic data as well as more petrologic studies, and is indeed necessary as the next step in our investigation.

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