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Garnet websterites and associated ultramafic inclusions from a nepheline mugearite in the Walcha area, New South Wales, Australia

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ABSTRACT. A nepheline mugearite dyke in the Walcha area, New South Wales, contains xenoliths of Cr-diopside lherzolite, garnet- and spinel websterites, and two-pyroxene-garnet granulites. The Cr-diopside lherzolite xenoliths are regarded as refractory upper mantle which finally equilibrated at *c.* 950-980 °C. The garnet websterites are considered to represent spinel websterite segregations from an Mg-rich olivine tholeiite magma at 14-16 kbar which on isobaric cooling to 1000-1050 °C passed into the garnet pyroxenite stability field. Spinel-amphibole websterites which probably last equilibrated at *c.* 950 °C and pressures of 9-12 kbar have close mineralogical affinites with the Cr-diopside lherzolite xenoliths. The mafic granulites may represent metamorphosed crystal segregates resulting from relatively large degrees of crystallization of tholeiitic basaltic magma which finally equilibrated at *c.* 14 kbar and 1000 °C. Subcalcic clinopyroxene and spinel megacrysts crystallized from the host nepheline mugearite at *c.* 13-20 kbar.

RECENT studies of inclusions in alkaline volcanic rocks have tended to concentrate on the pyroxene-rich variants, belonging to the Al- or Ti-augite group (Wilshire and Shervais, 1975; Wilkinson, 1975*a*) or Group II (Frey and Prinz, 1978), which are generally less abundant than peridotitic inclusions of the Cr-diopside group or Group I xenoliths (Frey and Prinz, 1978). In particular the relatively rare garnet pyroxenites, which also occur as veins and dykes within ultramafic massifs (Carswell, 1968; Dickey, 1970; Kornprobst, 1970), have attracted considerable attention in attempts to elucidate relationships to their hosts and associated inclusions and also the P/T conditions under which they were formed. Despite the large volume of chemical, mineralogical, and experimental data now available on these particular inclusions their origin is still somewhat contentious.

This paper reports the results of an investigation of ultramafic inclusions from a nepheline mugearite dyke complex occurring in Brick Clay Creek approximately 16 km south-west of Walcha in north-eastern New South Wales. The dyke intrudes Tertiary gravels and contains a variety of mafic and ultramafic xenoliths, including Cr-diopside lherzolites, garnet websterites, two-pyroxene-garnet-plagioclase granulites, and rare amphibole-bearing spinel websterites. The mugearite also contains a variety of megacrysts and xenocrysts (up to 3 cm) which includes subcalcic clinopyroxene, anorthoclase, Al-spinel, and less commonly, kaersutite, magnetite, and titanbiotite. Large garnets observed in heavy mineral concentrates from the host (J. F. G. Wilkinson, pers. comm.) may also be high-pressure megacrysts, but none was found during the present study.

Portions of the dyke contain abundant, rounded inclusions (1-10 cm diameter) which, although in a relatively advanced state of alteration, still contain the characteristic emerald-green clinopyroxenes of Cr-diopside lherzolites. In contrast the more resistant garnet websterite and mafic granulite xenoliths (5-10 cm diameter) are typically weathered out of the host, although a number of smaller (1-3 cm diameter) garnet websterite and Cr-diopside lherzoite inclusions were found enclosed in relatively fresh host material.

Petrography

Cr-diopside lherzolites. The least altered specimens consist of dominant, partly serpentinized, olivine, with subordinate Ca-poor and Ca-rich pyroxene and minor reddish-brown to brown Cr-spinel. Several specimens with very low modal clinopyroxene are harzburgites. Pyroxenes are usually devoid of exsolution, often strained and display gently curved boundaries which terminate in triple junctions.

Garnet websterites. These rocks are composed of orthopyroxene, clinopyroxene, garnet $\pm$ spinel $\pm$ phlogopite. Moderate variation in the relative abundance of the pyroxenes give rise to orthopyroxene-rich, garnet-poor types (e.g. R49177

29.9 cpx, 57.8 opx, 12.3 gt wt. % respectively) and variants rich in clinopyroxene and garnet (e.g. R49168 46.3 cpx, 21.3 opx, 31.4 gt, 1.0 sp wt. % respectively). Several inclusions contain numerous 'megacrystals' of orthopyroxene (up to 2 cm in length) with discrete exsolution lamellae of garnet and Ca-rich pyroxene (0.02 mm wide) aligned parallel to 100. These 'megacrystals' occur in a medium-grained (1–3 mm) matrix of orthopyroxene, clinopyroxene, and garnet. Matrix pyroxenes are devoid of exsolution lamellae and their contacts are gently curved and display relatively well-developed triple-point junctions. Garnet principally occurs as elongate blebs located along grain boundaries, but it also forms necklace-type reaction coronas around xenoblastic brown spinel except where the latter is included within matrix ortho- or clinopyroxene. Despite careful optical examination, olivine was not identified in these inclusions. Rare crystals of phlogopite occur in textural equilibrium with matrix pyroxenes. The textural relationships displayed by the Walcha garnet websterites closely resemble those of several garnet pyroxenites from Salt Lake Crater, Oahu (Beeson and Jackson, 1970), and indicate that all of the garnet is derivative, having been exsolved from aluminous pyroxenes. The presence of the large orthopyroxene 'megacrystals' also indicates that at least some were originally websterites and that not all of the orthopyroxene is secondary (i.e. an exsolution product of original more Ca-poor clinopyroxene).

Amphibole-bearing spinel websterites. Rare amphibole-bearing spinel websterites (up to 2 cm diameter) are composed of granoblastic polygonal aggregates of orthopyroxene, clinopyroxene, clots of pargasitic amphibole, and minor pyrite and green spinel. Orthopyroxene 'megacrystals' (up to 5 mm diameter) contain fine lamellae of Ca-rich pyroxene and spinel which generally are restricted to the interiors of crystals. Recrystallized matrix orthopyroxenes and clinopyroxenes (0.25–0.5 mm diameter) are generally devoid of exsolution and strain effects.

Mafic granulites. These are equigranular fine-grained rocks (0.3–0.5 mm diameter) with granoblastic polygonal textures which are composed of pale-mauve to buff Ca-rich pyroxene, pleochroic Ca-poor pyroxene, garnet, sodic plagioclase, and accessory ilmenite. Garnet is in various stages of alteration to kelyphite and in some specimens is completely replaced.

Host. Euhedral to subhedral olivine and Ca-rich pyroxene microphenocrysts occur in a groundmass of euhedral, pale-green Ca-rich pyroxene (0.2 mm long), olivine, titanomagnetite, nepheline, and plagioclase, plus variable interstitial analcime, altered glass, and calcite. Megacrysts (up to 3 cm in length) of pyroxene, anorthoclase, and spinel are typically rounded and embayed where in contact with the host. Subcalcic clinopyroxene megacrysts have low-pressure Ca-rich pyroxene rims, and are devoid of zoning, exsolution, and deformation effects. Xenocrystal olivine, clinopyroxene, orthopyroxene, and spinel generally are characterized by various reaction rims and these xenocrysts resulted from mechanical disintegration of lherzolite and pyroxenite xenoliths.

Mineralogy

Mineral analyses were carried out using a TPD probe at the Research School of Earth Sciences, ANU, and a Jeol JSM-35, Tracor-Northern instrument at the University of New England. Operating conditions and correction procedures are outlined by Ware (1981). Each analysis represents an average of three to six points.

Olivines in Group I lherzolites and harzburgites range from Fo_{87} to Fo_{91}, but are essentially uniform in composition within individual inclusions. The CaO contents are generally below the detection limit (i.e. < 0.07 wt. %) and NiO is in the range 0.24–0.46 wt. %. Olivines from the host nepheline mugearite range from Fo_{77} to Fo_{63}.

Pyroxene. Ca-rich pyroxenes from Group I inclusions, which include harzburgites, lherzolites, and spinel websterites (Table I, nos. 1, 3, and 5), are Cr-diopsides using the nomenclature of Stephens and Dawson (1977) with moderate Cr contents (0.63–1.58 wt. % Cr_2O_3). Coexisting Ca-poor pyroxenes (*mg** = 87–91) are Cr-Al enstatites and bronzites (Stephens and Dawson, 1977) and both types are very similar in composition to those from Group I inclusions elsewhere (cf. Frey and Green, 1974; Wilkinson, 1975*a*; Frey and Prinz, 1978).

In contrast the pyroxenes from the garnet websterites (Table I, nos. 7–12) differ in several important respects from those characterizing Group II inclusions. Although the relatively high Al_2O_3 (7.26–7.46 wt %) and low Cr_2O_3 contents (0.21–0.46 wt. %) of the Ca-rich types are consistent with other Group II Ca-rich pyroxenes, the high *mg*-values (88–90) and low TiO_2 contents (0.35–0.41 wt. %) are atypical of Ca-rich pyroxenes from Group II spinel- or garnet pyroxenites (Irving, 1974*a*, *b*; Wilkinson, 1975*a*; Frey and Prinz, 1978). Coexisting Ca-poor pyroxenes have correspondingly high *mg*-values and Al contents, and low Cr_2O_3. Pyroxenes with similar *mg*-values and Cr and Ti contents also characterize pyroxenites occurring within ultramafic massifs from Etang de Lers, France (Dickey, 1970; Table 3, analysis *a*), and the Ivrea zone of the western Alps, Italy (Rivalenti *et al.*, 1981; Table 3, Mo378).

Coexisting Ca-rich and Ca-poor pyroxenes from the mafic granulites are considerably more Fe-rich (*mg* = 64–67) than pyroxenes from garnet websterite inclusions. In particular the Ca-rich types are markedly

*$mg = 100\ Mg/(Mg+Fe)$ where Fe = total Fe as FeO

TABLE I. *Pyroxene analyses*

	Group I						Group II						Granulite		Host		
Sample No.	R49189		R49183		R49174		R49168		R49178		R49177		R49170		R49180		
Analysis No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO_2	53.10	56.51	54.27	55.39	51.36	54.83	51.78	53.95	51.70	54.00	51.32	54.15	50.78	51.38	47.89	49.94	50.12
TiO_2	0.18	-	-	0.15	0.54	-	0.35	-	0.36	-	0.41	-	0.80	0.28	1.34	1.14	1.06
Al_2O_3	3.47	2.28	3.16	4.29	5.60	4.68	7.26	6.00	7.27	5.95	7.46	5.99	6.02	3.30	10.36	4.85	2.66
Cr_2O_3	1.39	0.45	1.07	0.40	0.63	0.29	0.21	-	0.22	-	0.46	0.21	-	-	-	0.29	-
FeO*	2.19	6.15	2.23	5.80	3.33	8.38	3.62	7.38	3.71	7.38	3.04	6.82	10.73	21.76	7.96	7.54	10.03
MnO	-	-	-	-	-	-	-	0.11	-	-	-	-	-	0.17	-	-	0.16
MgO	16.53	34.17	16.21	33.07	15.92	31.76	15.90	31.26	16.00	31.62	15.46	31.91	12.31	21.27	13.05	13.34	12.22
CaO	22.30	0.45	21.57	0.64	21.52	0.64	19.77	1.09	19.77	1.03	20.22	0.79	17.53	1.42	17.60	22.17	22.79
Na_2O	1.03	-	1.56	-	0.89	-	1.22	-	1.43	-	1.38	-	1.69	0.23	1.59	0.72	0.74
Total	100.19	100.01	100.07	99.74	99.79	100.58	100.11	99.79	100.46	99.98	99.75	99.87	100.03	99.81	99.79	99.99	99.78
Pyroxene cation groups (6 oxygens)																	
z	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Σxy	2.016	2.001	2.011	1.994	2.016	2.003	2.009	2.002	2.021	2.005	2.012	2.000	2.015	2.011	2.029	2.025	2.039
mg[1]	93.1	90.9	92.8	91.0	89.5	87.1	88.7	88.3	88.5	88.4	90.1	89.3	67.2	63.5	74.5	75.9	68.5
Atom %																	
Ca	47.4	0.9	47.0	1.3	46.5	1.3	44.2	2.2	44.0	2.0	45.9	1.6	40.7	2.9	41.9	47.6	47.7
Mg	48.9	90.0	49.2	89.9	47.9	86.0	49.5	86.2	49.6	86.6	48.8	87.9	39.8	61.5	43.3	39.8	35.6
Fe'	3.7	9.1	3.8	8.8	5.6	12.7	6.3	11.6	6.4	11.4	5.3	10.5	19.5	35.6	14.8	12.6	16.7

* Total Fe as FeO

[1] *mg* = 100Mg/(Mg+Fe) where Fe = total Fe as FeO

Fe' = Fe^{2+}+Mn

1-6 Coexisting Ca-rich and Ca-poor pyroxenes from Group I harzburgite (R49189), lherzolite (R49183) and spinel-amphibole websterite (R49174) xenoliths

7-12 Coexisting Ca-rich and Ca-poor pyroxenes from Group II garnet websterites

13-14 Coexisting Ca-rich and Ca-poor pyroxenes from two-pyroxene-garnet granulite (R49170)

15 Subcalcic clinopyroxene megacryst

16 Clinopyroxene phenocryst (core)

17 Groundmass clinopyroxene

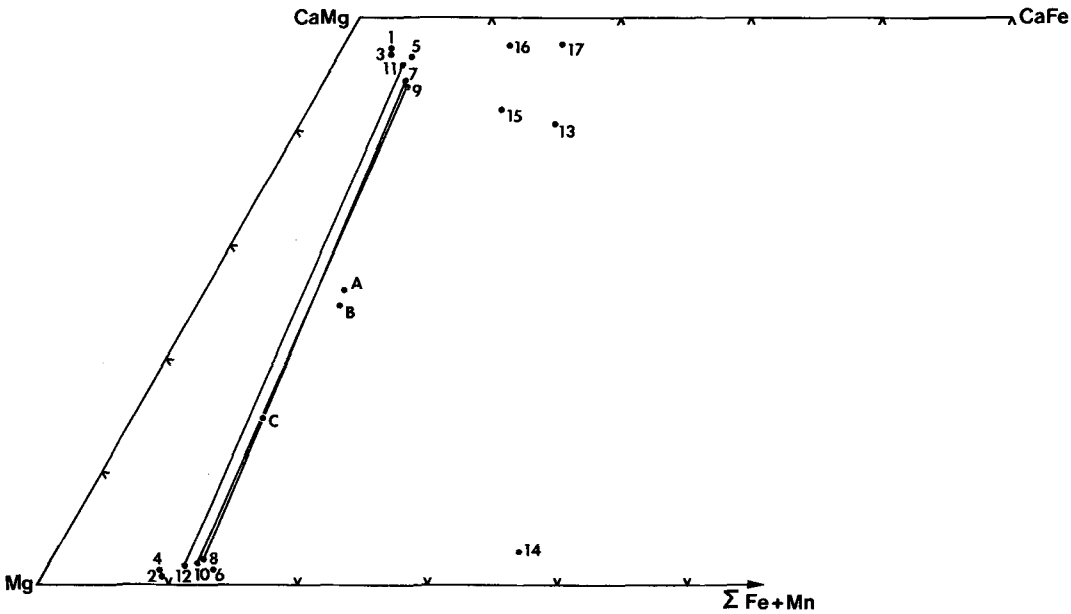

FIG. 1. Plot of pyroxenes from the Walcha xenoliths and host in the magnesian portion of the pyroxene quadrilateral. Bulk compositions of garnet websterites R49178 (A), R49168 (B), and R49177 (C) are also plotted. Tie-lines join coexisting Ca-rich and Ca-poor pyroxenes from these xenoliths. The numbers refer to analysis numbers in Table I.

subcalcic and relatively enriched in Na_2O, compared with those in two-pyroxene granulites from Delegate, NSW (Lovering and White, 1969). Clinopyroxenes from southern African granulites with similar CaO contents (Griffin *et al.* 1979) have significantly higher Na_2O contents (2.5–4 wt. %) than the Walcha analogues.

Clinopyroxene megacrysts and phenocrysts in the host (Table I, nos. 15 and 16) have comparable *mg*-values but differ markedly in their Al_2O_3, CaO, and Na_2O contents. The megacrysts are relatively enriched in Al_2O_3 and Na_2O and depleted in CaO reflecting increased jadeite and Ca-Tschermak components. Groundmass clinopyroxenes (Table I, no. 17) have lower Al_2O_3, TiO_2, Na_2O, and *mg*-values than associated megacrysts and phenocrysts. Although the lower Na_2O and decreased Al^{vi}/Al^{iv} are consistent with low-pressure crystallization, the lower TiO_2 and Al_2O_3 (even though principally as Al^{iv}) contrasts with megacryst-groundmass pyroxene compositional relations in other strongly undersaturated alkaline hosts elsewhere (Wilkinson, 1975*a*; Wass, 1979).

Analyses of pyroxenes from the inclusions and host are plotted in the magnesian portion of the pyroxene quadrilateral (fig. 1) together with the bulk analyses of the garnet websterite xenoliths. The bulk compositions of the garnet websterites plot on the Fe-rich side of the tie-lines joining coexisting Ca-rich and Ca-poor pyroxenes from these rocks reflecting the preferential partitioning of Fe into exsolved garnets.

Garnet which occurs as fine exsolution lamellae in Ca-poor pyroxenes or as blebs concentrated along grain boundaries in the garnet websterites (Table II, nos. 1–3) is essentially constant in composition within a single specimen, indicating that equilibrium compositional relationships were maintained under subsolidus conditions. The garnets are Cr-poor pyrope-rich types with moderate grossular and almandine contents. They most closely resemble the chrome-pyrope group proposed by Dawson and Stephens (1975, 1976) but have Cr contents at the low end of the range. Garnets from other ultramafic inclusions with similar *mg*-values are usually significantly enriched in Cr_2O_3 (e.g. Cox *et al.*, 1973).

The garnets from the mafic granulites (Table II, no. 4) are pyrope–almandine types with moderate grossular contents. Comparable garnets occur in garnet granulites from South Africa (Griffin *et al.*, 1979) and Delegate, NSW (Lovering and White, 1969), although the latter have slightly higher CaO contents (*c.* 7 wt. % CaO).

Spinel. Cr-spinels with significant $Cr \rightleftharpoons Al$ substitution characterize Group I, xenoliths and grains within individual xenoliths are quite uniform in composition. Spinels from harzburgitic xenoliths (Table III, no. 1) have higher Cr/(Cr + Al) ratios than those from lherzolitic types (Table III, no. 2) which is consistent with the observation of Carswell (1980) that spinel Cr/(Cr + Al) ratios increase with increasing 'depletion' (increasing *mg*) of the host. However, the moderately Cr-rich spinel from the spinel–amphibole websterite (Table III, no. 3) seems inconsistent with this interpretation.

The brown spinels in the garnet websterites are Al-rich Cr-poor types with very restricted compositional variation.

Two species of spinel megacrysts occur in the host nepheline mugearite, the most abundant being a pleonaste (Table III, no. 6), and the other a Ti-poor magnetite (Table III, no. 7). Both occur as unzoned crystals lacking reaction rims and are too large (0.5–1.0 cm diameter) to have been derived by disaggregation of xenolithic material. Analyses of the groundmass titanomagnetite in the host (Usp_{48}) and an ilmenite from the mafic granulite are also listed in Table III.

Amphibole. The amphiblole which occurs as polygonal aggregates within spinel websterite R49174 (Table IV, no. 1) is pargasite in the nomenclature of Leake (1978) and differs from the kaersutite megacrysts (Table IV, no. 2) in its slightly higher *mg*-values and lower TiO_2, Na_2O and K_2O. The *mg*-values of the kaersutite megacrysts (*mg* ~80) are somewhat higher than those of associated subcalcic clinopyroxenes (*mg* ~75) which is in contrast to amphibole–pyroxene pairs from other megacryst suites (White *et. al.*, 1972; Irving, 1974*c*; Wilkinson, 1975*a*, *b*) and the kaersutites might be xenocrystal, produced by disaggregation of unidentified xenolithic material.

Mica. Sparse, dispersed mica crystals (0.3–0.5 mm) from several garnet websterites display equilibrium grain-boundary relationships with adjacent silicates consistent with 'primary' textural characteristics of micas from South African garnet peridotite xenoliths (Dawson and Powell, 1969; Carswell, 1975; Delaney *et al.*, 1980). 'Secondary-textured' micas from ultramafic inclusions apparently occur either as alteration rims around other

TABLE II. *Garnet analyses*

Analysis No.	1	2	3	4
SiO_2	42.05	41.87	42.26	38.99
TiO_2	0.09	-	-	0.29
Al_2O_3	23.97	23.71	23.68	22.16
Cr_2O_3	0.18	0.16	0.41	-
Fe_2O_3*	0.94	1.51	0.67	0.73
FeO	7.57	7.00	7.32	21.25
MnO	0.30	0.40	0.28	0.48
MnO	20.16	20.30	20.38	10.11
CaO	5.11	5.05	5.15	5.56
Total	100.37	100.00	100.15	99.57
M^1	82.6	83.8	83.2	45.9
End members (mole %)				
Pyrope	71.3	72.3	71.9	38.4
Almandine	15.1	14.0	14.5	45.4
Spessartine	0.6	0.8	0.6	1.0
Grossular	9.7	8.4	10.1	12.3
Andradite	2.8	4.1	1.8	2.9
Uvarovite	0.5	0.4	1.1	-

* Fe_2O_3 calculated assuming stoichiometry

[1] $M = 100\ Mg/(Mg+Fe^{2+})$

1, 2 & 3 from garnet websterites R49168, R49178 and R49177 respectively

4 from two-pyroxene-garnet granulite R49170

TABLE III. *Spinel and ilmenite analyses*

	Group I			Group II		Host			Granulite
Analysis No.	1	2	3	4	5	6	7	8	9
TiO_2	0.41	0.33	0.34	-	-	1.35	2.95	17.25	53.31
Al_2O_3	32.15	52.68	49.69	64.03	63.85	54.77	2.11	3.52	0.64
V_2O_3	0.14	0.15	0.19	-	-	0.23	0.12	0.26	-
Cr_2O_3	36.04	15.02	15.76	2.85	2.63	-	-	-	-
Fe_2O_3*	2.15	1.82	2.76	2.41	3.01	10.06	60.73	31.84	1.50
FeO	13.87	8.69	12.59	8.66	8.04	18.32	32.97	45.91	40.81
MnO	0.52	0.22	0.29	-	-	0.18	0.42	0.73	0.26
NiO	-	0.29	0.22	0.43	0.47	-	-	-	-
MgO	15.20	20.50	17.58	21.60	21.95	15.23	0.43	0.74	3.85
Total	100.48	99.70	99.42	99.98	99.95	100.14	99.73	100.25	100.37
M^1	66.1	80.8	71.3	81.6	83.0	59.7	-	-	-
Cr^2	42.9	16.1	17.5	2.9	2.7	-	-	-	-

* Calculated assuming stoichiometry

[1] $M = 100Mg/(Mg+Fe^{2+})$

[2] $Cr = 100Cr/(Cr+Al)$

1-3 Spinels from Group I harzburgite (R49189), lherzolite (R49183) and spinel-amphibole websterite (R49174) xenoliths

4-5 Spinels from Group II garnet websterites R49168 and R49178 respectively

6-7 Spinel megacrysts from nepheline mugearite host (R49180)

8 Groundmass titanomagnetite in host

9 Ilmenite from two-pyroxene-garnet granulite (R49170)

phases, rims to 'primary-textured' micas, or in veins filling fractures, and typically they are enriched in FeO and TiO_2 compared to 'primary-textured' types. The phlogopites from the Walcha garnet websterites (Table IV, nos. 3 and 4) display minor compositional variation and are probably in chemical equilibrium with coexisting orthopyroxenes (*mg* = 88–89). They have significantly higher TiO_2, Al_2O_3, and FeO contents, and lower Cr_2O_3, MgO, and SiO_2 than 'primary' phlogopites from South African garnet lherzolites (Carswell, 1975; Delaney *et al.*, 1980; Jones *et al.*, 1982) and phlogopites from the Finero spinel lherzolites in the Ivrea zone, Italian Alps (Exley *et al.*, 1982). 'Secondary-textured' micas in peridotite xenoliths from Bultfontein mine, South Africa (Jones *et al.*, 1982), have similar *mg*-values and TiO_2 and Cr_2O_3 contents, but lower Al_2O_3 and higher SiO_2 than the Walcha micas. If the phlogopites in the Walcha garnet websterites are secondary, having resulted from infiltration of hydrous fluids enriched in K, Ti, and Fe, then subsequent prolonged annealing has produced the 'primary' textural characteristcs.

Feldspar. Listed in Table V are analyses of anorthoclase megacrysts, plagioclase from mafic granulite R49170, and groundmass feldspars from the nepheline mugearite host. The anorthoclase megacrysts are comparable with those found in a wide variety of alkaline volcanic hosts (cf. Binns, 1969; Binns *et al.*, 1970; Irving, 1974*c*; Laughlin *et al.*, 1974; Wilkinson, 1975*b*). The very sodic nature of the plagioclase from the mafic granulite (An_{29}) contrasts with the normative plagioclase composition of the host [100 An/(Ab + An) = 59] reflecting the substantial anorthite component occult in garnet.

Chemistry

Representative major element analyses and CIPW norms of garnet websterite and mafic granulite inclusions together with data on the host nepheline mugearite are reported in Table VI. The most notable chemical features of the garnet websterites include their high M^*-values, and low TiO_2, Na_2O, K_2O, and Cr_2O_3 contents. Although these xenoliths have been classified as Group II

* $M = 100\ Mg/(Mg+Fe^{2+})$

TABLE IV. *Amphibole and mica analyses*

Analysis No.	1	2	3	4
SiO_2	42.11	41.97	38.70	38.73
TiO_2	2.78	4.78	3.57	5.27
Al_2O_3	16.21	14.51	18.88	17.67
Cr_2O_3	0.19	-	0.18	0.23
FeO*	5.90	6.44	5.01	6.52
NiO	-	-	0.22	0.29
MgO	16.09	14.66	20.69	19.27
CaO	11.20	10.98	-	-
Na_2O	3.00	3.53	-	0.40
K_2O	0.93	1.81	10.23	9.52
Total	98.41	98.68	97.48	97.90
mg[1]	83.0	80.2	88.0	84.1

* total Fe as FeO

[1] *mg* = 100Mg/(Mg+Fe) where Fe = total Fe as FeO

1 Pargasite from spinel websterite xenolith R49174

2 Kaersutite megacryst

3 Most Mg-rich phlogopite from garnet websterite R49173

4 Most Fe-rich phlogopite from garnet websterite R49179

TABLE V. *Feldspar analyses*

Analysis No.	1	2	3	4
SiO_2	66.22	61.72	60.49	62.44
Al_2O_3	20.75	24.15	24.82	22.90
FeO*	0.20	0.45	0.83	0.65
CaO	0.81	5.12	5.77	4.19
Na_2O	9.36	8.16	7.20	8.62
K_2O	2.45	0.63	0.71	1.14
Total	99.78	100.24	99.83	99.94
Or	14.1	3.7	4.3	6.4
Ab	82.0	71.5	66.3	73.8
An	3.9	24.8	29.4	19.8

* Total Fe as FeO

1 Anorthoclase megacrysts from host (R49180)

2 Plagioclase from two-pyroxene-garnet granulite (R49170)

3-4 Groundmass feldspars in host (R49180)

types on the basis of their mineralogy (i.e. Cr-poor pyroxenes and spinels), their bulk compositions are more magnesian than is typical of most Group II xenoliths which generally have $M < 83$–85. Similar compositional features characterize some magmatic-type mafic layers from the Serrania de la Ronda massif, Spain (Dickey, 1970), and the French Pyrenees (Herzberg, 1978), as well as occasional garnet websterite xenoliths from Delegate, NSW (Irving, 1974*b*), and Malaita, Solomon Islands (Nixon and Boyd, 1979). Several spinel pyroxenites and wehrlites from Siberia (Kutolin and Frolova, 1970), Mindora, NSW (Wilkinson, 1973), San Carlos, Arizona (Frey and Prinz, 1978), and Mt. Shadwell, Victoria (Irving, 1980), have comparable compositions and a few examples are listed in Table VI for comparison with the Walcha garnet websterites. Low Cr_2O_3 contents relative to Group I xenoliths characterize most of the above pyroxenites and wehrlites with the exception of some Mindora, Siberian, and San Carlos pyroxenites which have low to moderately high Cr_2O_3 contents (i.e. 0.21–O.95 wt. % Cr_2O_3) and contain Cr-diopside. The latter have simlar mineralogical characteristics to spinel websterite R49174 and are better classified as Group I xenoliths. Trace-element data for the Walcha garnet websterites (Table VII, nos. 1–3) indicate low concentrations of most incompatible elements, the exception being the relatively high Ba (353 μg/g) of specimen R49177.

The analysed mafic granulite (Table VI, no. 9) is *hy*- and *ol*-normative and broadly basaltic in composition but with Al_2O_3, Na_2O, and K_2O contents which are perhaps transitional to picritic compositions. Garnet-bearing and pyroxene granulites from Delegate (Lovering and White, 1969; Irving, 1974*b*) and Lesotho (Griffin *et al.*, 1979) typically have higher CaO and lower MgO contents. The Walcha granulites (Table VII, no. 4) also have higher Ni, Cr and lower Rb than the Lesotho granulites.

The host nepheline mugearite (Table VI, no. 10) is strongly undersaturated (*ne* = 13.9 %) and chemically quite 'evolved' as evidenced by its low *M*-value (43.6), normative plagioclase = 20.3, and moderately high differentiation index (51.3). Trace-element data for the host (Table VII, no. 5) indicate moderate enrichment in Zr, Nb, Ba, Zn, and *LREE* but not notable depletion in Cr and Ni.

P/T estimates

Subsolidus equilibration temperatures for the Walcha xenoliths were estimated using established geothermometers based on the two-pyroxene solvus and garnet-clinopyroxene equilibria. Early calibrations of the two-pyroxene solvus geothermometer were based on experimental data for the 'simple' system $Mg_2Si_2O_6$–$CaMgSi_2O_6$ (Boyd and Schairer, 1964; Davis and Boyd, 1966). More recent experimental calibrations of the two-pyroxene solvus (Nehru and Wyllie, 1974; Mori and Green, 1975;

TABLE VI. *Major element analyses and C.I.P.W. norms*

Analysis No.	1	2	3	4	5	6	7	8	9	10
SiO_2	48.46	49.33	51.95	46.68	48.33	49.99	44.57	46.41	46.54	44.81
TiO_2	0.26	0.27	0.22	0.19	0.31	0.23	0.67	1.98	1.83	1.06
Al_2O_3	12.62	11.63	8.55	12.91	11.83	8.66	14.33	8.53	12.16	14.68
Cr_2O_3	0.32	0.29	0.39	0.25	0.47	0.95	0.05	-	0.07	0.03
Fe_2O_3	1.67	1.46	0.99	0.99	0.48	0.99	1.11	2.47	4.42	4.26
FeO	4.57	4.55	4.93	5.43	4.43	5.05	4.10	9.82	10.83	7.94
MnO	0.17	0.16	0.16	0.17	0.12	0.13	0.13	0.15	0.21	0.23
MgO	20.40	20.12	25.36	20.81	22.38	24.16	18.06	20.81	10.58	4.33
NiO	0.08	0.07	0.10	0.08	0.11	0.13	-	-	0.09	0.02
CaO	10.84	11.55	6.97	10.33	9.86	7.86	14.74	7.38	8.74	7.64
Na_2O	0.75	0.83	0.49	0.96	0.77	0.71	0.74	1.58	1.97	6.24
K_2O	<0.01	<0.01	<0.01	0.00	0.01	0.03	0.05	0.32	0.13	1.74
P_2O_5	<0.01	0.01	<0.01	0.00	0.00	0.07	0.03	0.20	0.20	1.39
H_2O^+	0.25	0.25	0.26	1.03	0.52	0.03	0.80	-	1.30	2.18
H_2O^-	0.27	0.28	0.27	0.10	0.11	0.51		-	1.20	1.32
CO_2	-	-	-	-	-	-	0.62	-	-	1.55
Total	100.66	100.79	100.64	99.93	99.73	99.50	100.00	100.00	100.27	99.42
M[1]	87.6	87.8	90.2	87.4	90.6	89.5	88.2	78.4	60.0	43.6
C.I.P.W. norms*										
Or	-	-	-	-	0.06	0.18	0.30	1.90	0.77	10.28
Ab	6.35	7.02	4.15	8.12	6.52	6.01	4.03	13.42	16.67	27.11
An	31.07	28.01	20.31	30.92	28.79	20.35	35.63	15.30	23.95	6.91
Ne	-	-	-	-	-	-	1.21	-	-	13.92
Di	17.96	23.11	11.25	16.09	15.84	14.33	26.35	16.07	14.80	10.15
Hy	21.52	21.14	51.45	12.57	23.05	38.86	-	14.86	23.33	-
Ol	20.73	18.54	10.22	28.83	22.39	15.78	27.59	31.24	10.38	15.64
Mt	1.49	1.44	1.43	1.55	1.19	1.46	1.25	2.97	3.64	2.89
Il	0.49	0.51	0.42	0.36	0.59	0.44	1.27	3.78	3.48	2.01
Ap	-	0.02	-	-	-	0.16	0.07	0.47	0.46	3.22
Cr	0.47	0.43	0.57	0.37	0.69	1.40	0.07	-	0.10	0.04
Rest	0.52	0.53	0.53	1.13	0.63	0.54	2.21	-	2.50	7.03
Pyroxene cation groups (6 oxygen atoms)										
z	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	-	-
Σxy	2.003	2.000	1.992	2.045	2.026	2.017	2.050	2.078	-	-

* Calculated with $Fe_2O_3/FeO = 0.20$

[1] $M = 100Mg/(Mg+Fe^{2+})$

1-3 Garnet websterite xenoliths R49168, R49178 and R49177 respectively, Walcha, New South Wales

4-5 Magmatic-type mafic layers, Serrania de la Ronda, Spain (Dickey, 1970, Table 1, analyses e & f respectively)

6 Spinel pyroxenite xenolith (MIN-2), Mindora, New South Wales (Wilkinson, 1973, Table 5, analysis 1)

7 Spinel-garnet websterite xenolith (R394), Delegate, New South Wales (Irving, 1974b, Table 2, No. R394)

8 Average Hawaiian subalkaline picrite (Macdonald and Katsura, 1964, Table 10, analysis 3)

9 Two-pyroxene-garnet granulite (R49170), Walcha, New South Wales

10 Nepheline mugearite host (R49180) for the Walcha xenoliths

Lindsley and Dixon, 1976) and empirical extrapolations of these data (Wood and Banno, 1973; Wells, 1977) have refined this geothermometer. The garnet-clinopyroxene geothermometer, based on the partitioning of Fe^{2+} and Mg^{2+} between these phases, has also been refined (Råheim and Green, 1974; Ellis and Green, 1979; Ganguly, 1979; Saxena, 1979). A comparative study of the two-pyroxene and garnet-clinopyroxene geothermometers (and several others) on a large suite of garnet lherzolite nodules from northern Lesotho (Carswell and Gibb, 1980) demonstrated a high degree of internal consistency between the methods of Wells (1977), Mori and Green (1978), and Ellis and Green (1979).

Calculations in this study employed the two-pyroxene method of Wells (1977) and the garnet-clinopyroxene geothermometer of Ellis and Green (1979). Since the latter requires an estimate of the equilibration pressure, temperatures were first calculated using the Wells equation. Equilibration pressures were then calculated using the method of Harley and Green (1982) which is a refinement of the method of Wood (1974) and based on the solubility of Al in orthopyroxene coexisting with garnet. Temperatures for garnet-bearing rocks were then calculated following Ellis and Green (1979). All temperatures and pressures were based on mineralogical data with total Fe expressed as FeO and also using Fe_2O_3 and FeO values calculated assuming stoichiometry. It is widely recognized that the latter procedure tends to overestimate Fe_2O_3 and hence the two values obtained in each case were regarded as limiting maxima and minima respectively. The garnet-clinopyroxene geothermometer appears to be more sensitive to variations in Fe_2O_3/FeO than the two-pyroxene method, exhibiting a range of 50-60 °C, whereas minimum and maximum temperatures estimated by the latter technique generally vary by less than 20 °C. Garnet-clinopyroxene temperatures calculated using calculated Fe_2O_3 and FeO values (i.e. minimum temperatures) most closely correspond to those derived from the two-pyroxene geothermometer.

Estimated final equilibration temperatures for the garnet websterites are in the range 1005-1065 °C for the pressures of 12.6-14.4 kbar. The mafic granulites also apparently equilibrated largely within this P/T interval with indicated temperatures of 990-1005 °C and pressures of 13.7-14.4 kbar. Temperature estimates for the spinel-amphibole websterite (935-955 °C) and the Group I lherzolites and harzburgites (870-890 °C) are slightly lower. Although MacGregor (1974) suggested that equilibration pressures could be estimated for spinel-bearing assemblages, more recent calculations and experimental work (Fujii and Takahashi, 1976; Obata, 1976; Presnall, 1976; Danckwerth and Newton, 1978; Lane and Ganguly, 1980; Perkins *et al.*, 1981) have shown that the shallow dT/dP of the Al_2O_3 isopleths severely constrains its use as a geobarometric indicator.

However, by comparison with the experimental data on spinel-garnet websterite R394 (Irving, 1974*b*) at temperatures of *c.* 950 °C, it can be inferred that the Walcha spinel-amphibole websterite (R49174) probably equilibrated at pressures of 9-12 kbar, defined by the appearance of garnet at higher pressures and plagioclase ± olivine at lower pressures.

The Walcha mafic granulite (R49170) is apparently not directly comparable to the Delegate two-pyroxene granulite R698 (Irving, 1974*b*) since the calculated equilibration temperature (*c.* 1000 °C) and pressure (*c.* 14 kbar) places it in the cpx + ga + plag field of R698 (i.e. *c.* 1.5-2.0 kbar outside the opx + cpx + ga + plag field). However, experimental work on a range of basaltic compositions (Green and Ringwood, 1967*a*, 1972) has shown that the appearance of garnet and disappearance of plagioclase by reaction with orthopyroxene is dependent on the M-value and silica saturation level of the system. In relatively more silica-saturated rocks the disappearance of plagioclase is delayed to higher pressures. Persistence of the two-pyroxene + ga + plag assemblage to higher pressures in R49170 is thus consistent with its higher normative-*hy* content, compared with Delegate granulite R698.

TABLE VII. *Trace element data (μg/g)*

Analysis No.	1	2	3	4	5
V	272	268	196	198	62
Cr	2157	1953	2689	477	178
Ni	599	548	813	702	131
Cu	5	5	105	52	35
Zn	42	32	40	135	225
Rb	<1	<1	<1	1	29
Sr	24	21	25	255	1954
Y	10	11	5	15	22
Zr	14	15	8	39	326
Nb	<1	<1	<1	8	86
Ba	59	38	353	596	1313
La	<2	<2	<2	9	117
Ce	<4	<4	<4	19	208
Nd	<3	<3	<3	16	107

1-3 Garnet websterites R49168, R49178 and R49177 respectively.

4 Two-pyroxene-garnet granulite (R49170).

5 Host nepheline mugearite (R49180).

The P/T data indicate that the garnet websterites, mafic granulites, and perhaps spinel-amphibole websterites were sampled by their host over a restricted depth interval (of the order of 48-55 km) within the uppermost mantle assuming that the crust in eastern Australia is of the order of 30-45 km thick (Finlayson, 1968; Collins, 1978; Dooley, 1980). Comparable P/T conditions and depths of origin are indicated for garnet pyroxenites from Delegate, NSW, on the basis of mineralogical data and experimental studies (Irving, 1974*b*). The lower equilibration temperatures indicated for the spinel lherzolites and harzburgites suggest slightly shallower depths of derivation. The geothermal gradient for eastern Australia which may be inferred from these data (20-24 °C/km) significantly exceeds the normal continental geotherm proposed by Clark and Ringwood (1964), i.e. approximately 15-20 °C/km for depths of 50 km.

Discussion

Group I lherzolite and harzburgite xenoliths. Numerous studies of Group I xenolith suites (e.g. Frey and Green, 1974; Hutchinson *et al.*, 1975; Wilkinson, 1975a; Frey and Prinz, 1978) have demonstrated considerable compositional variation, considered to reflect heterogeneity within the upper mantle which has resulted from various degrees of depletion of primary upper mantle by partial fusion. The mineralogical features of the Walcha lherzolites and harzburgites are consistent with this model and hence they may be regarded as refractory upper mantle material following one or more episodes of partial melting.

Mafic granulites. High-pressure mafic-ultramafic granulites are generally regarded as either: (*a*) metamorphosed gabbros which crystallized within the lower crust or upper mantle (Lovering and White, 1969; Wilkinson, 1974; Meyer and Brookins, 1976; Edwards *et al.*, 1979); (*b*) residues from the partial fusion of intermediate or basic lower crustal rocks (Dawson, 1977; Griffin *et al.*, 1979); or (*c*) metamorphosed cumulates from basaltic magmas (Edwards *et al.*, 1979). The restricted data available for the Walcha mafic granulites preclude a detailed evaluation of their origin. Nevertheless the indicated P/T conditions for final equilibration suggest derivation from the upper mantle, hence the granulites cannot be regarded as residua from the partial fusion of intermediate or basic lower crustal rocks. These inclusions may represent metamorphosed cumulates or crystal segregates which resulted from relatively large degrees of crystallization of olivine tholeiite or olivine basalt magma at pressures of 13-16 kbar (Green and Ringwood, 1967*b*). This interpretation gains some support from the high Ni and Cr contents and the low concentrations of incompatible trace elements in the analysed xenolith (Table VII, no. 5). However, the Walcha granulites display no evidence of layering which is present in some Delegate granulites (Irving, 1974*b*) and which may suggest a cumulative origin. If the mafic granulites are the metamorphosed equivalents of crystal segregates from basaltic melts, the relatively low M-value of the analysed specimen ($M = 60$) indicates that the parent melt was also quite Fe-rich compared to alleged 'primary' basaltic melt compositions (i.e. $M > 66$; Irving and Green, 1976).

Garnet websterites. The origin of this group of xenoliths has been widely debated. It has been proposed that spinel and garnet pyroxenites represent: (*a*) refractory upper-mantle residua from which a basaltic melt fraction has been extracted (Beeson and Jackson, 1970); (*b*) primary upper mantle which is parental to most basalts and resulting in lherzolitic residua (Reid and Frey, 1971). This proposal was subsequently abandoned (Reid and Prinz, 1971; Frey, 1980); (*c*) accidental xenoliths from a heterogeneous upper-mantle (Kutolin and Frolova, 1970; Kurat, 1971; Shervais *et al.*, 1973; Wilkinson, 1973); (*d*) products of partial fusion of relatively undepleted upper-mantle peridotite-yielding picritic melts which then crystallized essentially *in situ* (Dickey, 1970; Kornprobst, 1970; Wilkinson, 1974, 1976; Herzberg, 1978, 1979); (*e*) high-pressure cumulates from basaltic magmas (Green, 1966; Lovering and White, 1969; Richter, 1971; White *et al.*, 1972; Irving, 1974*b*, 1980; Conquere, 1979; Frey and Prinz, 1978; Suen and Frey, 1978; Frey, 1980; Obata, 1980).

(*a*) The proposal that garnet pyroxenites represent refractory residua from basalt genesis is inconsistent with the melting behaviour of a generally accepted upper-mantle lherzolitic source. Experimentally determined melting relations of anhydrous lherzolites (Mysen and Kushiro, 1977; Jaques and Green, 1980) indicate that Ca-rich pyroxene is the first major phase to be consumed during melting, thus a clinopyroxene-rich residuum appears implausible. Futhermore the M-values of most garnet pyroxenites ($M < 80$-3) indicate that they would not be in equilibrium with basaltic melts ($M = 60$-70) assuming a value of 0.33 for K_D (the olivine-liquid Fe/Mg exchange partition coefficient) at elevated pressures (Roeder and Emslie, 1970; Cawthorn *et al.*, 1973; Jaques and Green, 1983). Although olivine is absent from these rocks, $K_D^{Fe/Mg}$ olivine-orthopyroxene is close to unity for peridotitic assemblages (O'Hara, 1963).

(*b*) The suggestion by Reid and Frey (1971) that garnet pyroxenites may represent parental material for basaltic melts leaving lherzolitic residua was

subsequently abandoned on the basis of aberrant age relationships in composite xenoliths of these rock types. Furthermore, estimates from field relationships of diapiric ultramafic bodies (Conquere, 1979; Dickey *et al.*, 1979) indicate that pyroxenites comprise a relatively minor component (*c.* 5%) of ultramafic massifs and therefore are probably only a comparatively minor component of the upper mantle.

(*c*) That some pyroxenite inclusions in alkaline volcanics represent xenoliths from a heterogeneous upper mantle was emphasized by Wilkinson (1973) for Mg-rich spinel pyroxenites with moderately high Cr contents from Mindora, NSW. These are similar to Group I pyroxenites of Frey and Prinz (1978) and spinel-amphibole websterite R49174, plus tectonic-type (Dickey, 1970) or chromian pyroxenite layers (Obata, 1980) associated with the more common lherzolites and Cr-poor mafic layers within the Serrania de la Ronda massif, Spain. Although an accidental relationship with the host is generally clear for inclusions of this type, the problem of this upper-mantle heterogeneity awaits clarification.

(*d*) An origin involving partial fusion of upper-mantle lherzolite followed by *in situ* crystallization has been proposed for garnet pyroxenite xenoliths (particularly the more Fe-rich variants with $M < 80$–83) from alkaline volcanics (Wilkinson, 1974, 1976) and their alleged analogues which occur as magmatic-type layers in ultramafic massifs from Kalskaret, Norway (Carswell, 1968), Serrania de la Ronda, Spain (Dickey, 1970), Beni Bouchera, Morocco (Kornprobst, 1970), and Montcaup (Kornprobst and Conquere, 1972) and Freychinede (Herzberg, 1978, 1979), France. Wilkinson (1976) argued that the close approximation to pyroxene formulae displayed by garnet pyroxenites from Salt Lake Crater, Oahu, indicates that they represent picritic melts which crystallized as essentially single-phase subcalcic clinopyroxenites at pressures of approximately 20 kbar, followed by lower temperature subsolidus re-equilibration to garnet-clinopyroxene assemblages. However, most garnet pyroxenites have low K_2O, P_2O_5 (usually < 0.1 wt. %), and TiO_2 contents compared to an average Hawaiian picrite composition (Table VI, no. 8) from Macdonald and Katsura (1964). Loubet *et al.* (1976) and Frey and Prinz (1978) have also argued that comparable pyroxenites display insufficient enrichment in *LREE* to permit their derivation by simple partial melting of undepleted upper-mantle peridotite, although a source depleted in *LREE* by a previous melting event may be appropriate.

While it is possible that some of the more Fe-rich pyroxenites ($M < 80$–83) (e.g. Beeson and Jackson, 1970; Kornprobst and Conquere, 1972; Forbes and Swainbank, 1974; Wilkinson, 1974; Schulze and Helmstaedt, 1979) are products of partial fusion of upper-mantle peridotites, it is unlikely that the Walcha garnet websterites were produced in this manner because the composition of residual olivine ($mg = 95.5$) in equilibrium with a liquid of $M = 87.6$ is significantly more magnesian than is characteristic of olivines from refractory dunites and harzburgites (i.e. mg generally < 92). Even if melts with such high mg values and strongly picritic characteristics (cf. Table VI, nos. 1 and 2) could be generated by large degrees of melting (*c.* 50%) of lherzolites of 'pyrolite' type, comparison with experimentally determined melt compositions on the Tinaquillo lherzolite at 15 kbar and 1550 °C (Jaques and Green, 1980) suggests that they should have significantly higher normative *ol* and resemble komatiites, following the entry of significant olivine into the partial melts.

(*e*) The most popular model for the genesis of spinel- and garnet pyroxenites interprets them as cumulates or crystal segregates from basaltic melts. Crystallization over a range of P/T conditions and removal of the residual liquid at various stages may result in variable assemblages and M-values of the cumulates. At present this model seems to be the most plausible for the genesis of the Walcha garnet websterites. However, it should be noted that their high M-values dictate that the parent melt was picrite or picritic basalt in composition ($M = 70$–75). The inclusions are thus clearly not cogenetic with the nepheline mugearite host ($M = 44$), a conclusion supported by the presence of metamorphic textures in the xenoliths.

If this model is correct several constraints can be placed on the P/T regime in which the pyroxenites accumulated and the nature of the parent melt. Garnet appears as a liquidus or near-liquidus phase in most alkaline or tholeiitic Mg-rich basaltic compositions at pressures greater than 27 kbar (Green and Ringwood, 1967*b*; Bultitude and Green, 1967, 1971; Ito and Kennedy, 1968; Green, 1970, 1973). Since textural evidence indicates that primary garnet is absent from the Walcha garnet websterites, accumulation of near-liquidus phases occurred below this pressure. In the more magnesian (picritic) compositions the liquidus phase under anhydrous conditions is usually olivine up to about 27 kbar where it is joined or replaced by garnet. Olivine apparently is in a reaction relationship with the liquid at pressures of approximately 20 kbar to produce a subcalcic clinopyroxene (Tilley and Yoder, 1964) or orthopyroxene + spinel (Ito and Kennedy, 1968). The absence of olivine in the Walcha xenoliths indicates that either it did not crystallize during accumulation of the pyroxenites or with falling temperature it was completely

consumed by reaction with the melt. The necessity for early separation of crystals from residual liquid in the crystal segregation model supports the former interpretation. The presence of orthopyroxene 'megacrystals' in several specimens suggests that Ca-poor pyroxene was the liquidus phase followed by clinopyroxene and perhaps minor spinel. The experimentally determined crystallization behaviour of Mg-rich olivine tholeiite compositions with $M = 72$ (Green and Ringwood, 1967*b*) and $M = 76$ (Ito and Kennedy, 1968) at 13.5–18.0 kbar most closely approximates that required to generate the pyroxenite cumulates. Orthopyroxene is the liquidus phase at 13.5–18.0 kbar joined by clinopyroxene within 25 °C and minor spinel at 13.5 kbar. Garnet appears in the 18 kbar runs at approximately 75 °C below the liquidus.

Clinopyroxenes crystallized from an olivine tholeiite ($M = 72$) at 13.5–18.0 kbar (Green and Ringwood, 1967*b*) are aluminous subcalcic varieties ($mg = 82$–88) and near-liquidus orthopyroxenes are aluminous enstatites ($mg = 89.6$–91.4). Although TiO_2 and Na_2O were not determined on these pyroxenes, near-liquidus clinopyroxenes from DSPD3-18 + 9% olivine at 15–20 kbar (Green *et al.*, 1979) have 0.3% TiO_2 and 0.4–0.5% Na_2O. The low TiO_2 contents of the Walcha garnet websterites require that the precipitating clinopyroxene had similarly low Ti contents which contrast with near-liquidus clinopyroxenes from alkaline undersaturated melts (Bultitude and Green, 1971; Green, 1973; Thompson, 1974).

Thus a model involving crystallization of a relatively Mg-rich tholeiite melt ($M = 70$–75) in the pressure range 14–16 kbar seems most appropriate for the generation of the Walcha garnet websterites. Zoned pyroxenite layers from Freychinede, France (Conquere, 1979), may have formed in an analogous manner. Orthopyroxene-rich websterites (similar to R49177) may have accumulated initially adjacent to vein margins. These grade into clinopyroxene-rich websterites (similar to R49168) and clinopyroxenites towards the core of the lenses. Cooling in the subsolidus results in the exsolution of garnet and orthopyroxene from aluminous clinopyroxenes, and to a lesser extent, garnet and Ca-rich pyroxene from aluminous orthopyroxene. This is consistent with the subsolidus phase relationships of Delegate spinel–garnet websterite R394 (Irving, 1974*b*) which indicate that essentially isobaric cooling from approximately 1150–1220 °C to 1000–1050 °C over the pressure range 12–16 kbar causes an initial cpx + opx + sp assemblage to pass into the garnet pyroxenite field.

It has been argued (Green, 1966; Wilkinson, 1974) that any intercumulus liquid should crystallize as near-solidus phases such as olivine, aluminous pyroxenes and spinel, garnet, or plagioclase depending on the composition of the liquid and the ambient P/T conditions. The spinel in the Walcha garnet websterites may have crystallized from an intercumulus liquid, although the very small amount (< 1 wt. %) indicates that the amount of trapped liquid was very minor. It has been suggested on the basis of *REE* data (Dickey *et al.*, 1979; Loubet *et al.*, 1976) that some pyroxenites may have undergone partial melting following initial accumulation or crystallization which could explain the removal of an intercumulus (low melting) fraction. A simpler model which would reduce the amount of trapped intercumulus liquid might involve nucleation and crystallization of the parent melt on an advancing front from the peridotitic walls of the vein in a similar fashion to that proposed by McBirney and Noyes (1979) for layered intrusions.

Megacrysts. Subcalcic clinopyroxene, kaersutite, titanobiotite, and anorthoclase have been reported as megacryst phases in nepheline mugearites from Victoria and Wee Jasper, NSW (Irving, 1974*c*, Ellis, 1976). Spinel and magnetite megacrysts have apparently not been recognized in these eruptives but occur in basanites, olivine nephelinites, and nepheline trachyandesite from north-eastern NSW (Binns, 1969; Binns *et al.*, 1970). It was noted above that the high *mg*-values of the Walcha kaersutites probably indicate a xenocrystal origin. However, crystallization of subcalcic clinopyroxene and titanbiotite from the host melt with approximately 2 wt. % H_2O at 13.5–20.0 kbar is consistent with the experimentally determined liquidus relationships of a nepheline mugearite from Victoria (Irving and Green, 1972). Crystallization of the anorthoclase megacrysts at similarly high pressures is less certain since sodic feldspar has not been observed as a near-liquidus phase in natural basaltic compositions under any conditions. Chapman (1976) showed that anorthoclase is a near-liquidus phase in an anhydrous mixture of analcime basalt + 10% anorthoclase at 5 kbar pressure, but is not found above the solidus at 10 kbar. Crystallization of anorthoclase at near-solidus temperatures and relatively low pressures (Irving, 1974*c*) seems unlikely in view of the rapid ascent rate required by the xenolith-bearing host and the absence of megacrystic olivine which should be a near-liquidus phase below 13.5 kbar (Irving and Green, 1972). An origin by mixing with intermediate magmas crystallizing at lower pressures (Chapman and Powell, 1976; Bahat, 1979) also seems unlikely since other low-pressure liquidus or near-liquidus phases in addition to the anorthoclase should be represented in the final mixture. The origin of anorthoclase

megacrysts in alkaline hosts appears to require further experimental investigation of a range of melt compositions at varying pressures, H_2O and CO_2 contents.

Conclusions

1. Ultramafic and mafic granulite xenoliths in the Walcha nepheline mugearite are accidental inclusions from the uppermost mantle.

2. The subsolidus P/T conditions at which the garnet websterites and mafic granulites finally equilibrated are in the range 12.5–14.5 kbar and 1000–1050 °C. Slightly lower equilibration temperatures and pressures are indicated for spinel-amphibole websterites (*c.* 950 °C), Cr-diopside lherzolites, and harzburgites (870–890 °C).

3. Cr-diopside lherzolites and harzburgites are considered to be refractory upper-mantle peridotites from a previous melting event.

4. The mafic granulites may represent metamorphosed crystal segregates which resulted from relatively large degrees of crystallization of tholeiitic basaltic magma.

5. The garnet websterites are interpreted as crystal segregates from a Mg-rich olivine tholeiite melt at 14–16 kbar followed by re-equilibration at subsolidus temperatures.

6. Subcalcic clinopyroxene and spinel megacrysts precipitated from the nepheline mugearite host at pressures of 14–20 kbar prior to its ascent and acquisition of upper-mantle materials.

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