

Fluid activity in the lower crust and upper mantle: mineralogical evidence bearing on the origin of amphibole and scapolite in ultramafic and mafic granulite xenoliths

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Abstract

Xenoliths in an olivine nephelinite from the McBride Province, North Queensland, include Cr-diopside lherzolites, spinel and garnet websterites, felsic, 2-pyroxene and garnet granulites, and hornblendites. The spinel and garnet websterites are interpreted as crystal segregations from olivine basalt or alkali olivine basalt magma at ~ 12 kbar followed by isobaric cooling (to approximately 900–1000 °C) and subsolidus reequilibration. Garnet and 2-pyroxene granulites are mineralogically and texturally distinct and are considered to represent relatively large degrees of crystallization of basaltic magmas at comparable or slightly lower pressures (8–12 kbar). Mafic and ultramafic xenoliths have been modified to varying degrees following the relatively recent influx of a H₂O- and CO₂-bearing fluid. Variable amounts of amphibole and mica developed in response to the introduced fluid and it is argued that some hornblendites are the end-products of this process acting on spinel websterites. Felsic and 2-pyroxene granulite xenoliths display only minor evidence of increased $P_{\text{H}_2\text{O}}$. Mineralogical and textural evidence indicates high-sulphur Ca-rich scapolite in several garnet granulites did not form in response to the increased fluid activities. It is proposed the scapolite was a primary cumulate phase precipitated from alkali basaltic magma under elevated f_{O_2} and f_{SO_2} conditions.

KEYWORDS: granulite xenoliths, scapolite, amphibole, lower crust, upper mantle, McBride Province, Queensland, Australia.

Introduction

A NUMBER of studies of xenoliths from basaltic and kimberlitic hosts (e.g. Griffin *et al.*, 1979; Dostal *et al.*, 1980; Kay and Kay, 1981, 1983; Leyreloup *et al.*, 1982; Hunter *et al.*, 1984) suggest that the continental lower crust is broadly basaltic in composition with relatively minor amounts of associated silicic material. In addition to imposing constraints on the composition of the lower crust, studies of granulite xenoliths may also aid in clarifying the role of fluids in mantle–crust interactions. The presence of hydrous phases in pyroxenite or mafic granulite xenoliths has been commonly attributed to crystallization of interstitial hydrous melt during solidification of basaltic magma within the upper mantle or lower crust (Best, 1975; Basu and Murthy, 1977; Bergman *et al.*, 1981). However, microstructural evidence sometimes suggests a secondary origin for the amphibole by subsolidus reaction of the anhydrous assemblage with hydrous

fluids derived from crystallizing basaltic melts (Roden *et al.*, 1984; Menzies *et al.*, 1985) or a deeper mantle source (Lloyd and Bailey, 1975; Boettcher and O'Neil, 1980; Bailey, 1982). In contrast, Wass and Hollis (1983) argued that the presence of essentially pure CO₂ fluid inclusions in some amphibole-bearing granulites and pyroxenites suggested they represent partially dehydrated assemblages resulting from the influx of a CO₂-rich fluid.

It is important to establish the mechanism(s) by which hydrous phases are developed in upper mantle and lower crustal rocks and the source(s) and composition(s) of the fluids involved since amphibole and mica are important sources of alkalis and incompatible trace elements which may contribute to early-formed melts. Several studies have shown that development of hydrous phases in some lherzolite xenoliths is accompanied by increased incompatible minor and trace element contents (Roden *et al.*, 1984; Menzies *et al.*, 1985; Griffin

and O'Reilly, 1986). Effects due to transfer of mantle-derived fluids and dissolved components into the lower crust are less well documented although Stosch and Lugmair (1984) proposed that the upper mantle and lower crust beneath the Eifel, West Germany has been modified by mantle-derived fluids or melts resulting in significant development of amphibole in mafic and ultramafic xenoliths. Clearly, knowledge of the mineralogical and chemical changes which accompany introduction of mantle-derived fluids into the lower crust and the extent of such effects will have important implications for petrogenetic models which seek to generate salic magmas by partial fusion of lower crustal rocks (e.g. Barker *et al.*, 1975).

High-sulphur Ca-rich scapolite is occasionally a modally important constituent of xenoliths in basaltic or kimberlitic eruptives and breccias (Lovering and White, 1964; Wilkinson, 1974; Griffin *et al.*, 1979; Jones *et al.*, 1983). Most of the xenoliths are considered to have equilibrated to varying degrees within the lower crust prior to entrainment in their hosts, and it is generally argued that the scapolite is metamorphic or metasomatic in origin (von Knorring and Kennedy, 1958; Lovering and White, 1964; Okrusch *et al.*, 1979; Jones *et al.*, 1983). However the recognition of scapolite as a megacryst phase in alkaline volcanics from the Eifel, West Germany (Boivin and Camus, 1981), elicits the possibility that scapolite in some mafic granulites may be igneous in origin, having accumulated with plagioclase and clinopyroxene from alkali basaltic or basaltic magmas.

This study focusses on the mineralogy and microstructural features of lower crustal and associated upper mantle xenoliths from cone #32 (< 3 Ma; Griffin and McDougall, 1975), a small, low-relief, partially eroded olivine nephelinite scoria cone in the McBride Province, North Queensland (Fig. 1) (Stephenson and Griffin, 1976; Stephenson *et al.*, 1980). Xenoliths (up to 0.3 m diameter) are abundant and include Cr-diopside lherzolites, spinel and garnet websterites, felsic, 2-pyroxene and garnet granulites, hornblendites, and silicic igneous rocks. Many of the mafic and ultramafic variants from cone #32 contain abundant amphibole \pm mica, and scapolite is an abundant phase in several garnet granulites. The mineralogical data and microstructural information are used to assess the origin of the scapolite and hydrous phases in these xenoliths and the *P/T* conditions of formation.

Petrography

Ultramafic xenoliths. Relatively rare Group I lherzolites are composed of granuloblastic aggre-

gates of olivine (Fo_{84}), Cr-diopside, orthopyroxene, amphibole, phlogopite and Cr-spinel. Amphibole occurs as aligned elongate blebs in Ca-poor pyroxene and in aggregates associated with spinel and minor phlogopite. Relatively coarse-grained phlogopite (up to 5 mm), forms a coating on one xenolith and may represent the remains of a disrupted vein system.

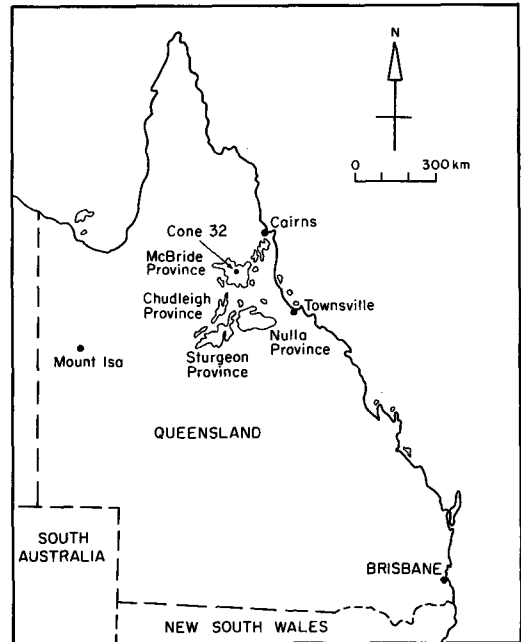
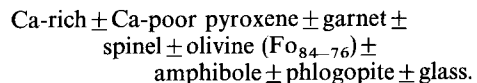


FIG. 1. Map showing location of cone #32 and the adjacent volcanic provinces in northeast Queensland, Australia.

Group II xenoliths are most abundant and include spinel and garnet websterites and clinopyroxenites composed of



Amphibole is present in most specimens and occurs in four principal modes: (1) elongate blebs and similarly oriented lamellae, mainly concentrated in the interiors of Ca-poor pyroxenes (Fig. 2a); (2) large interstitial optically continuous grains; (3) reaction coronas around spinel; and (4) as polygonal grains in more thoroughly recrystallized specimens. In addition, some amphibole-rich specimens contain cavities into which idioblastic amphibole crystals project. Several amphibole-free

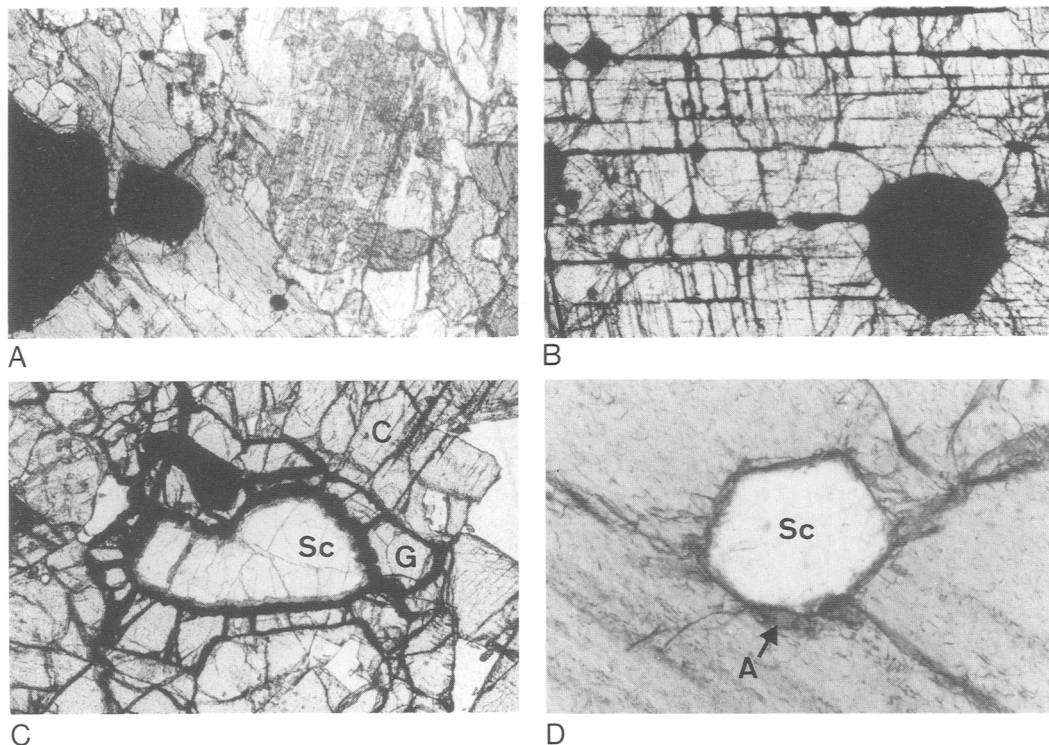


FIG. 2. (a) Amphibole blebs and lamellae in orthopyroxene from a spinel websterite. Adjacent discrete amphibole contains opaque inclusions. Plane polarized light (PPL). Field width 1.5 mm. (b) Garnet exsolution lamellae and subidioblastic garnet included in clinopyroxene from a garnet granulite. CPL. Field width 3.5 mm. (c) Garnet (G) reaction corona around scapolite (Sc) surrounded by clinopyroxene (C) in garnet granulite. A small spinel grain (opaque) above the scapolite is also rimmed by garnet. PPL. Field width 1.5 mm. (d) Idioblastic scapolite (Sc) included in clinopyroxene from a garnet granulite. Minor amphibole (A) is developed at the contact between the scapolite and enclosing clinopyroxene. PPL. Field width 1.5 mm.

specimens contain a trace of phlogopite. Spinel is invariably rimmed by garnet in the garnet websterites. Hornblendites which occur as discrete and composite xenoliths with spinel websterite are composed almost entirely of amphibole with minor phlogopite \pm Ca-rich and Ca-poor pyroxene \pm apatite \pm opaques \pm olivine (Fo_{83}) \pm anorthoclase ($\text{An}_{20}\text{Ab}_{67}\text{Or}_{13}$ to $\text{An}_7\text{Ab}_{76}\text{Or}_{17}$). Idioblastic amphibole crystals project into cavities, and fluid inclusions are abundant.

Mafic granulites. The garnet granulites are composed of Ca-rich pyroxene + garnet + plagioclase \pm Ca-poor pyroxene \pm amphibole \pm mica \pm spinel \pm scapolite \pm ilmenite \pm rutile (or magnetite) \pm apatite. Ca-rich pyroxenes may contain exsolution lamellae of Ca-poor pyroxene, plagioclase, garnet, and idioblastic garnet inclusions (Fig. 2b) that appear to have developed from exsolved domains (cf. Ellis and Green, 1985). Garnet also occurs as xenoblastic or polygonal aggregates, grain boundary blebs and

necklace-type reaction coronas around spinel, plagioclase and scapolite (Fig. 2c). Scapolite occurs in 4 of the 30 garnet granulite xenoliths examined, and comprises up to 20% of the mode in specimen 32–80 from which plagioclase is absent. Plagioclase (An_{61-21}) and scapolite coexist in other specimens and idiomorphic inclusions of scapolite occur in plagioclase and clinopyroxene (Fig. 2d). In the latter case minor amphibole occurs at the contact between clinopyroxene and included scapolite. Scapolite grain boundaries are irregular and cloudy, and consist of a zone of fine-grained plagioclase (An_{78-63}) and carbonate. Amphibole is present in most specimens and occurs in similar forms as in the Group II xenoliths.

The 2-pyroxene granulites are composed of

Ca-rich + Ca-poor pyroxene + plagioclase
 $(\text{An}_{74-23}) \pm$ amphibole \pm mica \pm
 ilmenite \pm titanomagnetite \pm apatite.

These rocks are more thoroughly recrystallized than the garnet granulites and, typically, granuloblastic textures are well developed. Some mineralogical banding is evident in most specimens and several pyroxene-rich specimens (e.g. 32-13) are plagioclase-bearing websterites.

There are two dominant felsic granulite assemblages; plagioclase + garnet + quartz + rutile ± sillimanite, and plagioclase + garnet + quartz + Ca-poor pyroxene + rutile ± Ca-rich pyroxene ± biotite, both with accessory zircon and apatite. Some specimens display a crude banding due to segregation of garnet and orthopyroxene from quartz and feldspar.

Mineralogy

Phases were analysed on a Jeol JSM-35, Tracor-Northern instrument at the University of New England. Operating conditions and correction procedures are outlined by Ware (1981). Tabulated analyses represent averages of 3-6 points unless specified and cover the range of mineral compositions in the suite of 130 xenoliths examined. Extensive comparison of core and rim analyses of all phases indicated compositional homogeneity within and between grains for most specimens

(unless specified), within the limits of analytical precision.

Pyroxene. Representative analyses of Ca-rich and Ca-poor pyroxenes from the various xenolith types are given in Table 1 and plotted with coexisting garnet (where appropriate) in the pyroxene quadrilateral (Fig. 3). Moderately high Cr and low Ti contents of Ca-rich pyroxenes from the Group I lherzolites contrast with those from garnet and spinel websterites and garnet granulites which have Cr contents below the detection limit (0.07 wt. % Cr₂O₃) and moderate Ti contents (0.5-1.5 wt. % TiO₂). Ca-rich pyroxenes from the 2-pyroxene granulites have low but detectable Cr and consistently lower Ti contents than Ca-rich types from other granulites and Group II xenoliths. High total Al and Al^{VI} characterize Ca-rich pyroxenes from all xenoliths. Clinopyroxenes from the lherzolites and several garnet granulites (e.g. Table 1, No. 32-34), are markedly subcalcic and have higher Na contents than those from the other assemblages. In terms of Di + He - Jd - Ts (Fig. 4), most analyses plot in the fields for granulites and eclogites from Delegate, N.S.W. (Lovering and White, 1969), and Anakie, Victoria (Wass and Hollis, 1983).

Garnet. Compositions (Table 2) span a relatively restricted range for specific xenolith groups and are

Table 1. Analyses of Ca-rich and Ca-poor pyroxenes.

	Clinopyroxenes						Garnet						Hornblende					
	Lherzolite		Spinel Websterites		Garnet Granulites		Garnet Granulites		2-Pyroxene Granulites		Hornblende							
	32-34	32-94	32-88	32-96	32-4	32-49	32-82	32-8	32-44	32-70	32-74	32-15	32-72	32-32	32-21	32-33		
SiO ₂	53.44	50.85	51.50	49.08	49.50	49.76	49.58	49.52	50.68	49.92	51.87	46.59	50.81	51.64	51.11	49.24		
TiO ₂	-	0.79	0.57	0.98	0.82	1.12	0.91	1.50	0.76	1.05	0.50	1.34	0.30	0.40	0.34	1.09		
Al ₂ O ₃	6.32	8.77	7.31	9.91	8.80	8.32	6.97	7.95	7.44	7.00	7.06	10.03	6.60	3.66	4.66	8.76		
Cr ₂ O ₃	0.92	-	-	-	-	-	-	-	-	-	-	-	0.21	0.13	0.18	-		
FeO#	4.52	2.66	4.06	4.46	6.46	8.62	6.15	7.74	7.58	8.22	9.65	9.37	5.11	7.34	9.89	9.88		
MgO	14.19	14.52	14.70	12.99	13.41	12.56	13.17	13.35	12.39	12.19	11.91	9.97	13.90	13.83	12.42	12.23		
CaO	17.68	20.97	20.45	21.58	19.57	18.17	21.94	18.69	20.17	20.20	16.98	21.79	22.51	22.56	21.25	17.08		
Na ₂ O	2.45	1.70	1.31	1.13	1.22	1.66	0.92	1.49	1.76	1.45	2.46	0.96	0.67	0.42	0.62	1.68		
Total	99.52	100.26	99.90	100.13	99.78	100.21	99.64	100.24	100.78	100.03	100.43	100.05	100.11	99.98	100.47	99.96		
mg ¹	84.8	90.7	86.6	83.8	78.7	72.2	79.2	75.5	74.4	72.6	68.7	65.5	82.9	77.1	69.1	68.8		
	Orthopyroxenes															Felsic Granulites		
																	32-38	32-25
SiO ₂	54.85	53.97	54.04	51.63	51.58	51.35	51.34	51.98	52.49	53.02	51.28		52.61	52.12	50.53	53.68	52.33	
TiO ₂	-	0.09	0.11	0.10	0.22	0.26	0.15	0.38	0.12	0.11	0.17		-	-	0.11	-	-	
Al ₂ O ₃	3.36	6.35	4.56	8.28	6.97	5.80	5.62	5.59	3.84	3.41	4.35		5.42	2.68	3.39	2.45	2.01	
Cr ₂ O ₃	0.24	-	-	-	-	-	-	-	-	-	-		0.11	-	-	-	-	
FeO#	10.20	7.03	9.86	11.49	13.48	16.98	17.65	14.47	17.09	17.99	20.28		13.48	21.51	22.95	17.66	22.31	
MnO	0.22	-	-	0.23	0.15	0.14	-	0.12	-	-	0.26		-	0.29	0.41	-	-	
MgO	30.86	32.56	31.01	28.57	27.31	25.08	25.29	26.89	26.35	25.61	22.37		28.56	23.46	22.11	26.05	23.00	
CaO	0.77	0.51	0.62	0.38	0.86	0.93	0.44	0.99	0.44	0.60	1.63		0.28	0.37	0.53	0.30	0.42	
Total	100.50	100.51	100.20	100.68	100.57	100.54	100.49	100.42	100.33	100.74	100.34		100.46	100.43	100.03	100.14	100.20	
mg ¹	84.4	89.2	84.9	81.6	78.3	72.5	71.9	76.8	73.3	71.7	66.3		79.1	66.0	63.2	72.4	64.8	

#FeO = Total Fe as FeO; 1 mg = 100Mg/(Mg + Fe) where Fe = total Fe as Fe²⁺

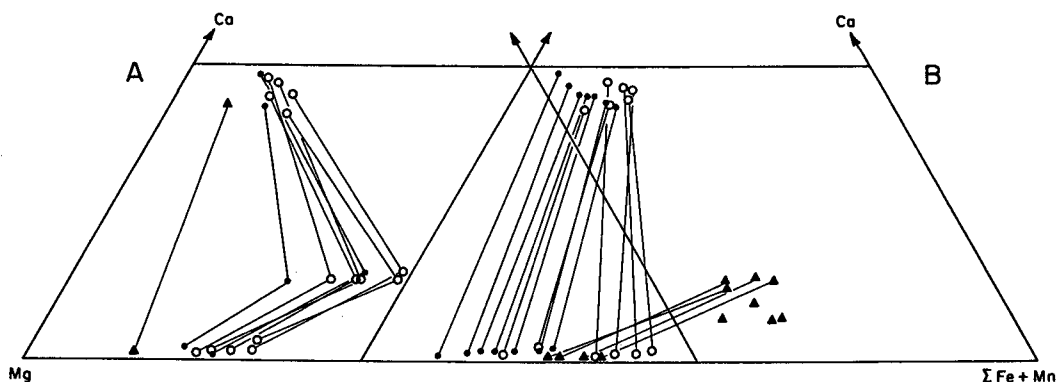


FIG. 3. Compositions of coexisting pyroxenes and garnets plotted in the pyroxene quadrilateral for (A) spinel lherzolite (triangle), garnet websterites (dots), garnet granulites (open circles) and (B) spinel websterites (dots), 2-pyroxene granulites (open circles) and felsic granulites (triangles). Tie-lines join coexisting pyroxenes and garnets in A, and orthopyroxene-garnet pairs in B.

predominantly pyrope-almandine solid solutions with a moderate grossular component. Ca contents are highest in several garnet granulites (e.g. Table 2, No. 32-15) and lowest in garnets from sillimanite-bearing felsic granulite xenoliths (e.g. Table 2, No. 32-46). Garnet exsolution lamellae and idioblastic garnet inclusions in Ca-rich pyroxene from the garnet granulites have compositions comparable with associated discrete grains.

Amphibole. Cr-rich, Ti-poor amphiboles in Group I lherzolites (Table 3) are comparable (except for slightly higher K₂O) with interstitial amphiboles from other spinel peridotite xenoliths (e.g. Varne, 1970; Stosch and Seck, 1980; Griffin *et al.*, 1984). Amphiboles in the spinel websterites, hornblendites, garnet granulites and megacrysts from the host nephelinite have overlapping compositions which, typically, are depleted in Cr, Si and Mg and enriched in Ti, Al, Fe and Ca relative to

Group I types. Amphiboles from the 2-pyroxene granulites are similar but have slightly higher Cr and lower Ti contents. The compositions of amphiboles which occur as lamellae and 'bleb-like' inclusions in pyroxene are usually indistinguishable from those of discrete grains in the same rock. However, several garnet granulites contain amphibole with widely varying Na₂O/K₂O including unusually potassic pargasites (e.g. Table 3, No. 32-15). Occasionally amphibole associated with mica-rich segregations in hornblendites are also significantly more K-rich than those in the mica-free parts of the same section implying significant variation in the availability of K during the formation of hydrous phases in these rocks. Values of *mg* for coexisting amphibole/clinopyroxene pairs display a reasonable linear correlation for the spinel websterites but more scatter is evident amongst the garnet granulites (Fig. 5). Significant

Table 2. Analyses of garnet.

	Garnet Websterites		Garnet Granulites					Felsic Granulites		
	32-82	32-8	32-36	32-44	32-70	32-74	32-15	32-38	32-25	32-46
SiO ₂	39.45	40.71	40.01	39.91	39.59	39.22	39.50	39.28	38.61	39.09
TiO ₂	0.09	0.31	0.11	-	-	-	-	-	-	-
Al ₂ O ₃	22.43	22.83	22.31	22.43	22.02	22.32	21.77	22.37	22.15	22.50
FeO#	20.53	15.92	18.08	19.87	20.65	22.87	19.15	22.64	25.01	23.42
MnO	0.50	0.39	0.56	0.75	0.45	0.64	1.22	0.33	0.63	0.60
MgO	11.55	15.22	13.18	12.33	11.74	10.29	9.08	10.78	8.57	11.71
CaO	5.64	5.11	5.86	5.19	5.56	5.14	9.24	4.72	5.08	2.72
Total	100.19	100.49	100.11	100.48	100.01	100.48	99.96	100.12	100.05	100.04
<i>mg</i>	50.1	63.0	56.5	52.5	50.3	44.5	47.4	45.9	37.9	47.1

#Feo = Total Fe as FeO

Table 3. Analyses of amphiboles.

	Iherzolite		Spinel Websterites			Hornblendites			2-Pyroxene Granulites			Garnet Websterites		Garnet Granulites			Host Megacryst		
	32-34	32-94*	32-88	32-96	32-4	32-49	32-86	32-71	32-33	32-72	32-32	32-21	32-82	32-8	32-44	32-70		32-15	
SiO ₂	43.99	43.13	42.69	42.38	40.50	40.80	41.43	40.03	40.59	42.84	42.92	42.13	42.55	41.37	41.88	41.40	39.64	43.15	40.23
TiO ₂	0.91	2.11	1.57	2.40	3.75	4.80	4.67	5.72	4.86	1.28	1.88	2.44	2.33	4.70	2.96	3.26	2.89	2.58	4.87
Al ₂ O ₃	13.77	15.93	16.56	17.04	15.72	14.62	15.44	14.81	14.74	15.79	13.11	13.30	14.88	14.48	14.15	13.81	15.16	18.05	14.23
Cr ₂ O ₃	1.67	-	-	-	0.16	-	-	-	-	0.33	-	0.23	-	-	-	-	-	-	-
FeO#	6.32	4.63	5.64	6.96	8.76	11.47	7.97	11.49	12.74	7.52	12.06	13.71	10.27	10.39	10.88	12.11	13.46	10.28	12.21*
MgO	16.98	16.64	16.30	15.35	13.66	12.34	13.71	11.56	11.47	15.65	13.33	12.26	13.95	13.99	13.72	12.91	11.23	8.44	11.55
CaO	9.39	10.61	11.12	11.07	11.03	10.31	10.31	10.49	10.06	11.82	11.95	11.10	11.36	9.80	10.86	10.85	11.79	9.61	10.36
Na ₂ O	3.58	3.28	2.60	3.26	2.21	2.82	2.91	2.31	2.62	2.52	1.53	2.07	2.93	3.54	3.15	2.93	2.08	1.18	2.51
K ₂ O	1.40	1.60	1.81	0.09	2.41	1.59	1.97	2.06	1.73	0.78	1.77	0.93	0.17	0.23	0.79	1.24	1.89	5.48	2.30
Total	97.61	97.93	98.29	98.51	98.21	98.75	98.41	98.47	98.81	98.53	98.55	98.17	98.44	98.50	98.39	98.51	98.14	98.77	98.26
mg	82.4	86.5	83.7	79.7	73.5	65.7	75.4	64.2	61.6	78.8	66.4	61.4	70.8	70.6	69.2	65.5	59.8	59.4	62.8

#FeO = Total Fe as FeO; * Fe₂O₃ = 12.45, FeO = 1.01; + vein amphibole

variation of amphibole *mg* (e.g. 32-81 *mg* = 62.5-71.4), also occurs within several garnet granulite and spinel websterite xenoliths but is not reflected by coexisting pyroxenes. Since disequilibrium amphiboles are more Fe-rich than associated amphiboles and pyroxenes, some enrichment in Fe apparently accompanied their development.

Mica. Interstitial micas in Group I Iherzolites (Table 4) are enriched in Cr and Ti compared with micas from the other xenolith types and megacrysts from the host and are similar to interstitial micas

from other spinel Iherzolite xenoliths (Francis, 1976a; Griffin *et al.*, 1984), except for their lower *mg* values which reflect bulk rock compositional differences. Vein micas coating Group I Iherzolites are Cr-poor compared with interstitial types but have similar *mg* values and Ti contents.

Spinel and ilmenite. Representative analyses of spinels and ilmenites are provided in Table 5. Cr-spinels with moderate *Cr*-values [100Cr/(Cr + Al)] characterize the Iherzolites, whereas Cr-poor green or brown pleonaste is typical in the spinel and garnet websterites, hornblendites and garnet granulites. However, spinels from several websterites and hornblendites display moderate Cr enrichment (e.g. Table 5, No. 32-95). Magnetite,

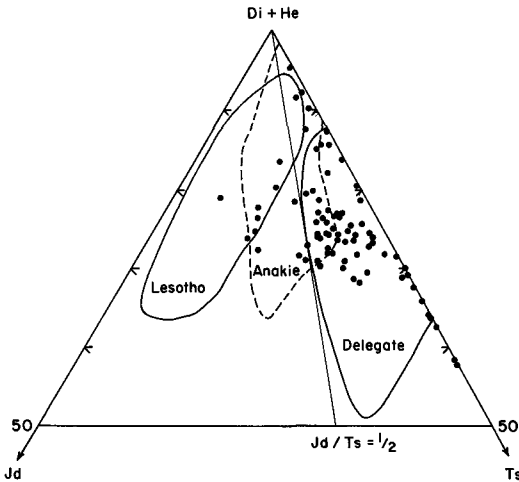


FIG. 4. Compositions of clinopyroxenes from all xenolith types plotted in terms of the diopside+hedenbergite (Di + He), jadeite (Jd) and Ca-tschermak (Ts) components. Fields covered by clinopyroxenes from other xenolith suites, Delegate (Lovering and White, 1969), Lesotho (Griffin *et al.*, 1979) and Anakie (Wass and Hollis, 1983) are shown for comparison. The line for Jd:Ts = 0.5 is from White (1964) and usually distinguishes clinopyroxenes from granulites and eclogites.

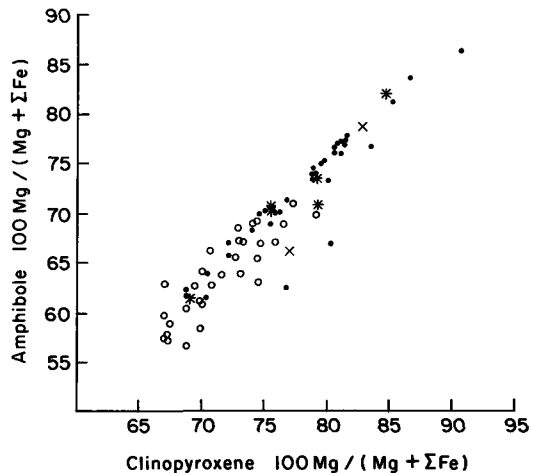


FIG. 5. Plot of *mg*-values for coexisting amphiboles and clinopyroxenes from spinel websterites (dots), garnet granulites (open circles), 2-pyroxene granulites (crosses), garnet websterites, spinel Iherzolite and hornblendites (asterisks).

Table 4. Analyses of mica.

	Lherzolite		Spinel		Hornblendites		2-Pyroxene		Felsic		Host Megacryst
	32-34	32-34+	Websterites		32-86	32-71	Granulite 32-32	Granulites			
			32-94+	32-4				32-25	32-38		
SiO ₂	37.90	38.07	37.96	36.62	37.21	36.22	37.25	37.86	37.13	34.98	
TiO ₂	2.11	2.54	3.30	6.01	7.42	9.28	6.40	4.59	7.90	6.94	
Al ₂ O ₃	16.36	16.34	17.98	16.80	16.71	15.63	14.95	14.77	15.15	14.95	
Cr ₂ O ₃	1.74	0.26	-	-	-	-	-	-	-	-	
FeO#	6.69	6.96	4.71	9.61	8.96	12.67	13.59	11.44	10.62	23.01	
MgO	19.99	20.56	20.90	16.42	16.43	12.68	14.32	16.66	15.74	8.02	
Na ₂ O	0.76	0.92	0.72	0.28	0.62	0.34	-	0.38	-	0.78	
K ₂ O	9.55	9.63	9.99	10.19	9.75	9.48	10.08	10.20	9.45	9.32	
Total	95.10	95.28	95.56	95.93	97.10	96.30	96.59	95.90	95.99	98.00	
mg	84.2	84.0	88.8	75.3	76.6	64.1	65.3	72.2	72.5	38.3	

#Feo = Total Fe as FeO; + vein mica

Table 5. Analyses of spinel and ilmenite.

Lherzolite	Spinel				Garnet		2-Pyroxene				Hornblendites				
	32-34	32-94	32-88	32-96	32-10	32-75	Websterite 32-8	32-44	Garnet 32-41	Granulites 32-90	32-50	Granulites 32-60	32-60	32-86	32-95
TiO ₂	0.40	-	0.13	-	0.28	0.20	1.00	0.44	24.14	4.35	49.47	34.28	49.12	0.49	0.15
Al ₂ O ₃	30.84	67.69	64.59	66.31	61.00	0.58	58.67	52.78	1.68	12.00	0.74	0.39	1.74	65.10	55.13
V ₂ O ₃	0.17	-	0.10	-	-	0.24	0.15	0.16	0.43	0.68	-	-	-	-	-
Cr ₂ O ₃	33.97	0.51	2.26	-	0.32	-	1.45	0.84	-	1.26	-	0.38	0.18	-	10.43
Fe ₂ O ₃ *	3.29	0.32	2.34	1.02	2.47	66.12	4.32	12.04	20.15	46.84	8.93	3.15	11.58	0.97	1.91
FeO	18.80	9.08	11.03	14.58	23.25	4.57	20.35	22.28	52.04	32.92	35.19	55.01	29.85	14.14	16.03
NiO	0.20	0.50	0.36	0.16	0.24	25.22	0.28	0.12	-	-	-	-	-	0.26	0.21
MnO	0.26	-	-	-	-	-	-	-	-	-	-	0.30	0.28	-	0.21
MgO	11.78	21.88	20.69	18.29	12.06	1.02	14.30	12.11	1.03	3.01	5.21	4.60	7.87	18.54	16.08
Total	99.71	99.98	101.50	100.36	99.62	99.17 ³	100.52	100.77	99.47	101.06	99.54	98.11	100.62	99.50	100.15
M [†]	52.8	81.1	77.0	69.1	48.0	28.5	55.6	49.2	3.4	13.7	20.9	13.0	32.0	70.0	64.1
Cr ²	42.5	0.5	2.3	-	0.4	-	1.6	1.1	-	-	-	-	-	-	11.3

* Fe₂O₃ calculated assuming stoichiometry; 1 M = 100Mg/(Mg+Fe²⁺)2 Cr = 100Cr/(Cr+Al); 3 includes 1.22% SiO₂

titanomagnetite or Ti-poor aluminous magnetite (Table 5, No. 32-90) occur in the 2-pyroxene and garnet granulites and hornblendites. Ilmenite rarely coexists with titanomagnetite in these assemblages, but often rims rutile in the felsic granulites. A Ni-bearing Fe-rich opaque phase occurs in some spinel websterites, 2-pyroxene and garnet granulites (but not scapolite-bearing examples), hornblendites and felsic granulites. The most Ni-rich variant analysed (Table 5, No. 32-75) closely resembles trevorite (Deer *et al.*, 1962, Table 12, No. 14). This phase exhibits considerable variation in its Ni content and grades towards Ti-poor magnetite. The Fe-Ni oxides are considered to have been produced by oxidation of original pyrrhotite-pentlandite or magnetite-pentlandite intergrowths concomitant with the development of

amphibole. The unaltered analogues of these intergrowths have been reported from South African lherzolite and eclogite xenoliths (Smith *et al.*, 1973; Tsai *et al.*, 1979).

Scapolites display restricted compositional variation (Table 6) and are medium to high-sulphur meionites and mizzonites typical of mafic granulite xenoliths (Lovering and White, 1969; Edwards *et al.*, 1979; Jones *et al.*, 1983). Cl was below the level of detection in all samples.

Pressure/temperature estimates

Equilibration conditions of the xenoliths prior to entrainment in their host have been calculated using a variety of geothermometers and geobarometers (Table 7). Calculations were made using

Table 6. Analyses of scapolite and compositions of coexisting plagioclase.

	Garnet		Granulites	
	32-91	32-90	32-90	32-69
SiO ₂	45.51	45.87	46.13	
Al ₂ O ₃	27.33	27.18	26.01	
FeO#	0.22	-	-	
CaO	18.40	18.09	16.60	
Na ₂ O	2.84	2.98	3.57	
K ₂ O	0.10	0.12	-	
SO ₃	3.47	4.05	6.05	
CO ₂ *	2.83	2.53	1.36	
Total	100.71	100.82	99.72	
Me#	77.8	76.6	72.1	
(Ca/(Ca+Na+K))				
S/(S + C)	0.40	0.47	0.71	
An	- (78.3)	49.9 (72.3)	44.0 (63.4)	
Ab	- (20.0)	47.9 (25.9)	55.1 (35.4)	
Or	- (1.7)	2.2 (1.8)	0.9 (1.2)	

#FeO = Total Fe as FeO; Cl < 0.07 wt. % in all samples;

* CO₂ calculated from 1/12 (Si + Al) - (Cl + S).

Plagioclase compositions in brackets are of breakdown products of scapolite whereas others represent equilibrium compositions.

adjacent rim compositions with pyroxene Fe³⁺ calculated on the basis of stoichiometry. As Fe³⁺ is usually overestimated by this method, the results represent maximum and minimum temperatures for the 2-pyroxene and garnet-clinopyroxene methods, respectively, and maximum pressures. There is reasonable agreement between temperatures calculated using the methods of Wells (1977), Ellis and Green (1979) and Powell (1985), whereas estimates from the pyroxene solvus method of Bertrand and Mercier (1985) are consistently lower, by up to 100 °C. Comparison of the Wells data (Fig. 6) suggests that the majority of garnet and 2-pyroxene granulites last equilibrated at temperatures 50–100 °C lower than the ultramafic xenoliths. Garnet-biotite temperature estimates (Thompson, 1976; Ferry and Spear, 1978; Perchuk *et al.*, 1981) for several felsic granulites (Table 7) suggest similar or slightly lower equilibration temperatures than for the 2-pyroxene granulites.

Equilibration pressures calculated for the garnet-orthopyroxene-bearing assemblages (Harley and Green, 1982), employing Wells temperatures, span the range 6.2–17.7 kbar. Comparable pressure estimates are obtained from the Wood (1974) calibration, whereas the equation of Nickel and Green (1985) gives estimates 3–4 kbar higher. Pressure estimates for the garnet-orthopyroxene

(Newton and Perkins, 1982) and garnet-sillimanite-bearing (Newton and Haselton, 1981) felsic granulites are in the ranges 8.8–10.2 kbar and 7.2–8.9 kbar, respectively. These geobarometers are relatively insensitive to variations in temperature and a reduction of 100 °C reduces calculated pressures by only about 500 bars.

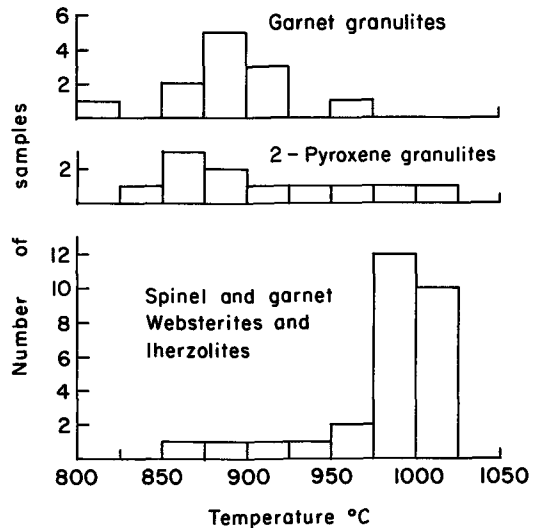


FIG. 6. Histogram showing the distribution of calculated equilibration temperatures (after Wells, 1977) for the major xenolith types.

In summary, most garnet, felsic and 2-pyroxene granulites probably last equilibrated in the temperature range 750–900 °C. The maximum equilibration pressure for the 2-pyroxene granulites (which predominantly have *qz*-normative tholeiitic compositions) is constrained to approximately 10 kbar at 900 °C by comparison with experimental work on similar compositions (Green and Ringwood, 1967; Irving, 1974). These estimates are broadly in agreement with those of Kay and Kay (1983) for comparable 2-pyroxene and garnet granulites. Several garnet granulites and the garnet and spinel websterites appear to have equilibrated at slightly higher temperatures (900–1000 °C) and pressures (10–12 kbar).

These data suggest derivation of the xenoliths from a significant depth interval encompassing the lowermost crust and uppermost mantle by comparison with the depth to the Moho beneath cone #32 (Fig. 7) inferred from seismic data (Finlayson, 1968; Dooley, 1980). O'Reilly and Griffin (1985) argued that the seismically defined

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Table 7. Calculated temperatures (°C) and pressures (kb) for selected xenoliths.

Sample No.	Wells (1977)	Bertrand & Mercier (1985)	Ellis & Green (1979)	Powell (1985)	Harley & Green (1982)	Wood (1974)	Nickel & Green (1985)
Garnet Websterites							
32-8	1000	978	1063	1053	11.6	12.0	15.2
32-82	860	750	747	726	6.2	5.6	8.9
Garnet Granulites							
32-28	918	887	902	899	9.1	8.0	12.8
32-36	815	722	921	904	8.2	8.2	11.0
32-44	875	803	860	853	10.6	12.2	13.4
32-69	920	823	880	877	12.1	10.1	16.9
32-70	880	797	926	912	11.3	11.1	14.8
32-74	960	944	908	907	11.0	11.2	16.3
32-93A	902	818	916	884	16.0	18.4	19.9
32-93B	900	806	871	824	17.7	25.6	22.0
32-98	858	778	853	843	9.8	13.3	13.0
32-105	896	801	877	873	11.2	10.4	15.3
Spinel Websterites							
32-3	991	979					
32-4	994	951					
32-49	985	959					
32-58	1017	1009					
32-84	969	939					
32-87	868	736					
32-88	966	931					
32-94	914	924					
32-96	892	806					
Spinel Iherzolite							
32-34	985	1003					
2-Pyroxene Granulites							
32-2	853	698					
32-13	1008	985					
32-21	903	766					
32-32	869	725					
32-72	873	756					
	Thompson (1976)	Ferry & Spear (1978)	Perchuk et al. (1981)	Newton & Perkins (1982)	Newton & Haselton (1981)		
Felsic Granulites							
32-38	750	865	740	9.9			
32-25	660	695	650	8.8			
32-7						8.4	
32-46			Assuming T = 800°C			7.2	

'Moho' beneath southeastern Australia coincides with the depth of the spinel lherzolite to garnet lherzolite transition (~55 km) predicted by a xenolith-derived geotherm, and that the gradational nature of the seismic velocity profiles in that region (V_p c. 7.0 km/sec to 7.8 km/sec from 25–55 km depth) is best explained by a transition zone consisting of spinel lherzolite interleaved with spinel and garnet pyroxenites. P wave seismic velocities beneath northeast Queensland are not as gradational as in southeastern Australia and the relatively sharp transitions from velocities of 6.6 km/sec to 7.8 km/sec (or > 8.0 km/sec), at depths of 35–45 km (Dooley, 1980) more likely represent a transition from mafic granulite to spinel lherzolite on the basis of calculated seismic velocities for these rock types (O'Reilly and Griffin, 1985).

There is some debate whether P/T estimates based on mineralogical data reflect pre-entrainment equilibrium conditions for the assemblages or past

thermal or tectonic events (Fraser and Lawless, 1978; Harte *et al.*, 1981). Evidence of such events may be preserved as the assemblages continued cooling below the blocking temperatures which prevent further Ca–Mg and Fe–Mg exchange between coexisting phases. The lack of compositional zoning in pyroxenes and garnets (O'Reilly and Griffin, 1985) and close agreement between geothermometers based on the pyroxene solvus and garnet–clinopyroxene Fe–Mg exchange, which appear to have different blocking temperatures (Ellis and Green, 1985), suggests that the calculated temperatures do not reflect past thermal events.

Discussion

Development of amphibole. Interstitial or poikilitic amphibole in pyroxenites or mafic granulites which represent segregations or cumulates from basaltic

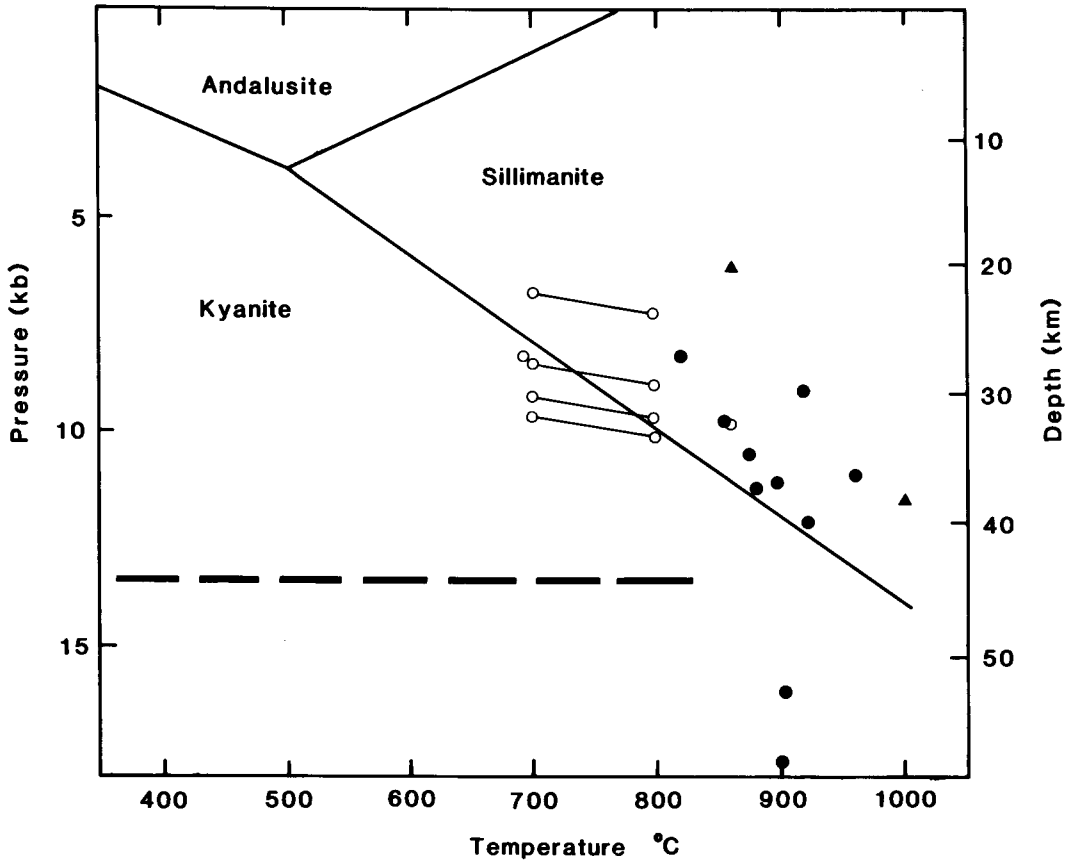


FIG. 7. Pressure-temperature plot showing calculated equilibration conditions for garnet granulites (dots) and garnet websterites (triangles). Temperatures were calculated following Wells (1977) and pressures using the method of Harley and Green (1982). Open circles with tie-lines indicate pressure estimates for felsic granulite assemblages (Newton and Haselton, 1981; Newton and Perkins, 1982) for assumed temperatures of 700 and 800 °C. Other open circles indicate temperatures calculated from coexisting garnet and biotite compositions (Ferry and Spear, 1978). The experimentally deduced stability field for the Al₂SiO₅ polymorphs is after Holdaway (1971), and the thick dashed line indicates the depth to the Moho beneath cone #32 from Finlayson (1968).

magmas may, in some instances, represent crystallized interstitial hydrous melt. However, the origin of amphibole which occurs in intricate intergrowths with pyroxene and spinel is more contentious. Amphibole lamellae in Ca-rich and Ca-poor pyroxenes are relatively common in the cone #32 and some other mafic granulites and ultramafic xenoliths (Papike *et al.*, 1969; Francis, 1976a, b; Okrusch *et al.*, 1979; Isaacs *et al.*, 1981; Wass and Hollis, 1983). Formation of the lamellae has been ascribed to (i) primary epitaxial intergrowth of the two phases (ii) exsolution of amphibole from the host pyroxene (iii) partial conversion of amphibole to pyroxene and (iv) selective or indiscriminant replacement of pyroxene by amphibole. Development of the amphibole as a primary intergrowth

seems unlikely since many of the lamellae are restricted to the interiors of pyroxene grains and amphibole of similar composition also occurs as discrete grains and sometimes rims garnet of subsolidus origin.

Exsolution of amphibole from pyroxene may seem feasible where the ratio of amphibole lamellae to host is small. However in some of the cone #32 xenoliths amphibole lamellae comprise up to 40 volume percent of the composite grains (Fig. 2a). Calculated compositions of possible precursor phases (based on microprobe analyses of lamellae and adjacent host), depart significantly from ideal pyroxene formulae. In particular, bulk K₂O contents (0.3–0.5 wt. % K₂O) are conspicuously higher than in pyroxenes from comparable anhydrous

granulitic assemblages (cf. Wilkinson, 1975; Kay and Kay, 1983).

Wass and Hollis (1983) argued in favour of an origin for amphibole lamellae in pyroxenes from Victorian granulite xenoliths by partial conversion of amphibole to pyroxene due to influx of a CO₂-rich fluid phase. The presence of discrete unaffected amphibole grains adjacent to lamellae-bearing pyroxenes (Fig. 2a) mitigates against such an origin. It seems unlikely that discrete amphibole grains would remain intact adjacent to pyroxenes with well developed triple junctions if influx of a CO₂-rich fluid phase (which presumably would migrate along grain boundaries) were an effective mechanism of dehydration.

Replacement of Ca-rich pyroxene by amphibole occurs adjacent to a hornblende vein in spinel websterite 32-94. Amphibole of similar composition has also formed by reaction between clinopyroxene, orthopyroxene, spinel and fluid (Francis, 1976b) adjacent to spinel traversed by the vein. Amphibole blebs observed in Ca-rich pyroxene hosts adjacent to Ca-poor lamellae and tiny spinel inclusions presumably are products of the same reaction. Concentration of amphibole lamellae in the interiors of Ca-poor pyroxenes mimics the occurrence of Ca-rich pyroxene lamellae in comparable anhydrous assemblages and suggests selective replacement of the latter by reaction of lamellae, adjacent host, fluid, and perhaps, exsolved spinel. These microstructural relationships indicate that development of amphibole principally occurred after the last major recrystallization event which homogenized the margins of the pyroxenes, presumably by migration of the marginal lamellae out of their hosts to form discrete grains. Furthermore, the disequilibrium amphibole compositions in several garnet granulite specimens indicate that amphibole development was a relatively recent event since such compositional variations would not be expected to persist for an extended period under granulite-facies conditions.

Hornblende or lherzite veins which occasionally occur in composite xenoliths with spinel lherzolite or pyroxenite, and in similar relationships in exposed peridotite bodies, have usually been interpreted as crystallized veins of hydrous basanitic melt (Basu and Murthy, 1977; Bergman *et al.*, 1981) or precipitates from hydrous fluids derived from basaltic melts (Wilshire *et al.*, 1980; Irving, 1980). The gradational variation in modal characteristics between amphibole-bearing spinel websterites and hornblende suggest the latter may also represent the end product of metasomatic processes acting on a spinel websterite starting composition. This interpretation is supported by the patchy development of hornblende in

amphibole-bearing spinel websterites, and the presence in some hornblendites of relict pyroxenes with similar compositions, exsolution structures and amphibole replacement lamellae to those in the spinel websterites. If this is the case, a significant change in bulk composition is implied and introduction of a fluid containing Na, K, Ti and LREE must be postulated (Stolz and Davies, in prep.). Since the xenoliths represent upper mantle material rapidly transported to the surface, the fluids must have originated from the mantle. Whether the fluid phase was derived from crystallizing basaltic magma (Menzies *et al.*, 1985), or represents a fugitive mantle volatile phase (Bailey, 1982), cannot be discerned from the available data.

Origin of scapolite. High-sulphur Ca-rich scapolite in lower crustal xenoliths is generally considered to be metamorphic or metasomatic in origin (von Knorring and Kennedy, 1958; Lovering and White, 1964; Okrusch *et al.*, 1979; Jones *et al.*, 1983), formed by a complex reaction involving a relatively CO₂-rich fluid phase, calcic plagioclase and accessory sulphides. The fluid phase is apparently responsible for oxidation of primary sulphides thereby releasing sulphate anions for incorporation into scapolite. Extensive textural reequilibration of many granulite xenoliths makes it difficult to verify this mode of origin. However, textural and mineralogical features of several cone #32 garnet granulites suggest that, in some cases, scapolite may be a primary phase which crystallized from basaltic melts at pressures broadly equivalent to those at which the xenoliths equilibrated prior to their entrainment.

Several mildly recrystallized garnet granulites display a crude banding (possibly of igneous origin), characterized by alternating clinopyroxene-plagioclase-rich and clinopyroxene-scapolite-rich layers, although some scapolite occurs in the plagioclase-rich layers and vice versa. In addition, idioblastic scapolite is occasionally observed as inclusions in clinopyroxene and plagioclase, a relationship difficult to explain by the metasomatic model. Amphibole developed at the contact between included scapolite and the host clinopyroxene (Fig. 2d) indicates formation of scapolite prior to amphibole, and garnet reaction coronas around scapolite (Fig. 2c) indicate it was also present prior to formation of garnet. Furthermore, several scapolite-free garnet granulites, felsic and 2-pyroxene granulites contain a Ni-rich Fe-oxide phase (trevorite?) interpreted as a secondary phase resulting from oxidation of original sulphides. It is interesting that none of these plagioclase-bearing xenoliths contain scapolite even though an oxidized sulphide phase was apparently present, and they have recrystallized under similar *P/T*

conditions. Lovering and White (1964) also commented on the variable development of scapolite in 2-pyroxene granulites of similar composition, but attributed this to availability of sulphur during metamorphism.

Metasomatic production of Na- and Cl-rich scapolites on a large scale has been proposed for basement complexes where it is well developed (Buddington, 1939; Edwards and Baker, 1953). An igneous source for the Na and Cl is often proposed, although interbedded evaporite sequences may also be an appropriate source (Ramsay and Davidson, 1970; Vanko and Bishop, 1982). The very low Cl/S ratios and Ca-rich compositions which typify scapolites from mafic granulites do not support the involvement of similarly derived fluids in their genesis. Since sulphur substitutes in scapolite as SO_4^{2-} anions (Chappell and White, 1968), metasomatic production of sulphur-rich scapolite would require an environment with a relatively high f_{O_2} and presumably $f_{\text{H}_2\text{O}}$. This contrasts with the relatively CO_2 -rich H_2O -poor fluid phase typically inferred for granulite terrains from fluid inclusion studies (Ormaasen, 1977; Selverstone, 1982), and required by experimental studies for stabilization of Ca-rich scapolite at high temperatures (Aitken, 1983). Oxidation of sulphides has clearly occurred in the cone #32 garnet granulites. However this most likely occurred concomitant with amphibole development in response to an introduced H_2O -bearing fluid and, which as noted above, post-dated development of scapolite.

The possibility that scapolite may be a primary phase in carbonate- or sulphate-bearing basic or intermediate magmas at elevated pressures was acknowledged by Newton and Goldsmith (1975) on the basis of their experimental determination of its stability relations. Layered scapolite-bearing garnet-plagioclase clinopyroxenite xenoliths from Delegate N.S.W., were interpreted as cumulates from basaltic magmas (Irving, 1974), although it was not specifically argued that the scapolite was of igneous origin. Strong evidence for the existence of igneous scapolite is provided by its occurrence as phenocrysts in a latite dome from Arizona (Goff and Eddy, 1979), and as megacrysts in a basanite from the Eifel, West Germany (Boivin and Camus, 1981), with apatite, amphibole, clinopyroxene and Fe-Ti oxides. In the latter case it was inferred from compositional data on coexisting pyroxene and Fe-Ti oxide megacrysts that the scapolite precipitated from its host at elevated pressures (> 10 kbar), and a temperature of approximately 1100°C under relatively high f_{O_2} (10^{-6} atm.) and f_{SO_2} conditions.

Summary of the genesis of the xenoliths. The spinel lherzolite xenoliths are interpreted as upper mantle

material that has been modified by a H_2O -bearing fluid. The Cr-rich nature of the spinel ($Cr = 42.3$) seems out of character with the relatively Fe-rich compositions of the coexisting olivines and pyroxenes ($mg = 84$) since Cr-rich spinels usually typify more magnesian (depleted) lherzolites and harzburgites (Carswell, 1980). The lherzolites may represent depleted upper mantle which was enriched in Fe by the fluid responsible for development of the amphibole. This has apparently occurred in lherzolite wall-rock adjacent to amphibole-rich selvages in composite xenoliths from Dish Hill, California (Irving, 1980; Wilshire *et al.*, 1980), and the presence of relatively Fe-rich disequilibrium amphiboles in several cone #32 spinel websterite xenoliths supports this interpretation. However, it is possible the xenoliths represent fragments of a somewhat less depleted, relatively Fe-rich upper mantle (cf. Wilkinson and Binns, 1977) in which Cr-enrichment of spinel was a byproduct of amphibole development, but the marked Fe-enrichment of the bulk rock was not.

Group II ultramafic xenoliths are generally interpreted as high-pressure cumulates or crystal segregations from basaltic magmas (Frey and Prinz, 1978; Irving, 1980), and are inferred to be interleaved with spinel lherzolite in the upper mantle due to their occurrence in composite xenoliths. Isobaric cooling of the websterite segregations at *c.* 12 kbar resulted in exsolution of Ca-poor pyroxene and spinel from aluminous clinopyroxene and minor Ca-rich pyroxene from orthopyroxene. Subsolvus development of garnet after spinel in the garnet websterites may have occurred at slightly higher pressures. Introduction of a H_2O - CO_2 -bearing fluid caused variable subsolvus development of amphibole and mica at the expense of pyroxenes and spinel, locally resulting in the development of hornblende.

Chemical data (Stolz and Davies, in prep.) indicate that most garnet and 2-pyroxene granulites are products of relatively large degrees of crystallization of basaltic magmas. Subsolvus cooling of clinopyroxene + plagioclase \pm orthopyroxene \pm spinel cumulates at approximately 10–12 kbar produced the garnet granulites. Garnet, Ca-poor pyroxene and occasionally plagioclase were exsolved from higher temperature aluminous subcalcic clinopyroxene. Subsolvus development of amphibole occurred in the garnet granulites in response to an increase in $P_{\text{H}_2\text{O}}$. However the high-sulphur scapolite is not metasomatic in origin and is considered to be a primary cumulate phase from alkali basaltic magma. The felsic granulites equilibrated in the lower crust under similar P/T conditions to the 2-pyroxene granulites (< 10 kbar) and the relatively minor development of hydrous

phases in these assemblages indicates that lower fluid activities prevailed in the crustal regions from which they were extricated.

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