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Heterogeneity in upper-mantle lherzolites and harzburgites

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[Plate 1]

Harzburgite nodules from kimberlites can be subdivided into two groups on the basis of the CaO (0.24 compared with 0.96 % by mass) and Al_2O_3 (0.96 compared with 2.98 % by mass) in their orthopyroxenes. Theoretically, the CaO and Al_2O_3 from the high-Al orthopyroxenes can be quantitatively represented as garnet and clinopyroxene in solid solution, which would appear if the assemblages had been subjected to lower T or higher P. Some garnet lherzolites and orthopyroxene megacrysts from several S African localities exhibit textures indicative of exsolution of garnet and diopside from orthopyrozene during deformation and recrystallization and it is proposed that lherzolites with small amounts of garnet (less than 3 %) and diopside (less than 1 %) may have developed from an igneous harzburgite with high-Al orthopyroxene during subsolidus cooling and recrystallization. The simplest assumption in upper-mantle models, that garnet lherzolite is a relatively homogeneous rock capable of differentiation into a basaltic liquid and a 'barren' harzburgite residuum, must be modified to take into account different degrees of partial melting and subsequent recrystallization to metamorphic assemblages.

1. Introduction

Most models of the upper mantle broadly agree that a zone of denser garnet lherzolites at depth is overlain by a shallower zone of less dense harzburgite plus dunite, in which may be lenses or pools of eclogite (see, for example, O'Hara *et al.* 1975). The relation between the various types of upper-mantle peridotites can be most simply expressed by starting with a lherzolite containing appreciable amounts of garnet and diopside and with minor phlogopite. Partial melting of this parental fertile lherzolite, and extraction of basic or ultrabasic liquids, gives rise to a series of residual rocks ranging from depleted garnet lherzolite (less than 5 % garnet, less than 3 % diopside) through garnet harzburgite to highly refractory harzburgite and dunite, depending upon the degree of partial melting.

The origin of garnet lherzolite is rarely questioned, though O'Hara *et al.* (1975) have suggested various ways in which it may be formed; it may represent (i) source mantle; (ii) source mantle partly depleted in garnet and clinopyroxene by partial melting; or (iii) source mantle completely freed of garnet and clinopyroxene by partial melting to produce harzburgite, which subsequently generated minor amounts of garnet and clinopyroxene by exsolution from orthopyroxene upon cooling to a subsolidus geotherm.

This paper summarizes evidence for heterogeneity in harzburgites (Hervig *et al.* 1978), and provides evidence for the solid-state transformation of 'fertile' harzburgites into lherzolite containing just a little garnet and clinopyroxene.

2. HARZBURGITES

Although this group of rocks apparently has a rather monotonous mineralogy, one that does not lend itself to current thermobarometry, recent studies have revealed quite strong variations in the chemistry of the orthopyroxenes. Using cluster analysis, Stephens & Dawson (1977) identified five chemically distinct groups of orthopyroxene in kimberlite and associated xenoliths. There is considerable overlap between ranges of individual oxides between the five groups and future research should lead to extended classifications. Some of the enstatites contain relatively large amounts of Al, Cr and Ca, and some contain significant Na. These elements can be regarded as pyrope, spinel and diopside components in solid solution in the enstatites. Significantly, Cr–Al–enstatites (group 2) came mainly from lherzolites and harzburgites that contain no large crystals of garnet or high-Al spinel.

TABLE 1. OBSERVED AND THEORETICAL MINERAL COMPOSITIONS

	(1)†	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
SiO_2	58.5	56.2	57.4	(55)‡	(42)†	58.1	0.15	56.4	56.4
TiO_2	0.00	0.00	0.00	0.09	0.17	0.06	0.02	0.07	0.07
Al_2O_3	0.96	2.98	2.91	2.50	(21)	0.82	17	2.48	2.53
Cr_2O_3	0.32	0.85	0.79	1.45	3.47	0.32	52	0.58	0.74
FeO	4.24	4.84	4.43	2.02	8.01	4.80	18	5.04	5.09
MnO	0.10	0.10	0.06	(0.3)	0.10	0.19	0.19	0.12	0.12
MgO	35.9	34.8	34.9	16.8	20.0	35.5	13	34.1	33.9
NiO	0.07	0.07	0.08	(0.15)	(0)	0.11	0.19	0.10	0.10
CaO	0.24	0.96	0.83	20.7	5.17	0.46	0.03	0.97	0.97
Na_2O	0.02	0.16	0.03	1.68	(0)	0.12	0.00	0.12	0.12
total	**100.35**	**100.96**	**100.47**	**100.35**	**100.12**	**100.39**	**100.58**	**100**	**100**

† (1) Orthopyroxene: mean for thirteen barren harzburgites. (2) Orthopyroxene: mean for two high-Na fertile harzburgites. (3) Orthopyroxene: mean for nine low-Na fertile harzburgites. (4) Cr-diopside: mean for group 5 (Stephens & Dawson 1977). (5) Cr-pyrope: mean for cluster 9 (Dawson & Stephens 1975). (6) Orthopyroxene: mean for fourteen garnet lherzolites (Hervig *et al.* 1978). (7) Cr-spinel: from table 2 for harzburgite BD1366. (8) Orthopyroxene: theoretical composition for 30 % column (6), 0.2 % column (4) and 2.7 % column (5), normalized to 100 %. (9) Orthopyroxene: theoretical composition for 30 % column (6), 0.2 % column (4), 2.7 % column (5) and 0.1 % column (7), normalized to 100 %.

‡ Bracketed values in columns (4) and (5) added on basis of analyses made at Chicago on typical specimens.

Subsequently, high sensitivity electron microprobe analyses of coarse-grained harzburgite xenoliths from southern African kimberlites (Bultfontein, Monastery, Letseng, Kao, Dutoitspan, Wesselton, Newlands, Liqhobong) have revealed two principal types of harzburgites. Orthopyroxenes from 'barren' ones contain much less Al_2O_3, Cr_2O_3 and CaO than orthopyroxenes from 'fertile' ones (Al_2O_3, 1.0 compared with 3.0 %†; Cr_2O_3, 0.3 compared with 0.8 %, CaO, 0.2 compared with 0.9 %; table 1, columns 1–3; Hervig *et al.* 1978). All of the orthopyroxenes have little or no detectable Ti and most contain little Na_2O. However, two out of the eleven orthopyroxenes from fertile harzburgites contain substantial Na_2O (0.16 %) (table 1, column 2). It should be emphasized that the two types of harzburgite are indistinguishable petrographically; that Cr-spinel is an accessory phase in both types (often in fingerprint intergrowth with silicates (Dawson & Smith 1975); that the olivines contain even smaller amounts of Al, Cr and Ti than olivines from garnet lherzolites; and that ongoing

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† All percentages are by mass.

ion-microprobe analyses are yielding various contents of Li and other trace elements (Hervig *et al.* 1979). The principal question here is whether 'fertile' harzburgites could exsolve garnet and clinopyroxene to yield garnet lherzolite.

3. Garnet lherzolites and orthopyroxene megacrysts

(*a*) *Garnet lherzolites*

The term 'garnet lherzolite' has been applied loosely to what is actually a quite heterogeneous group of rocks containing variable proportions of forsterite, enstatite, green Cr-bearing diopside and purple-red Cr-bearing Mg-rich garnet. Although the rocks generally contain more than 50 % modal olivine, the abundances of the other three minerals vary widely (figure 1) and only 16 out of 97 published modes contain the over 5 % clinopyroxene required for 'lherzolite' in the I.U.G.S. (Streckeisen) classification. Furthermore, published analyses of phases in 'garnet lherzolites' show four types of chemically distinct garnet, four of orthopyroxene and five of clinopyroxene (Dawson & Stephens 1976; Stephens & Dawson 1977). Some of these types with relatively low Mg/(Mg+Fe) and high Ti are most frequent in lherzolite with deformed texture (Boyd & Nixon 1975), but they also occur in some coarse granular lherzolites.

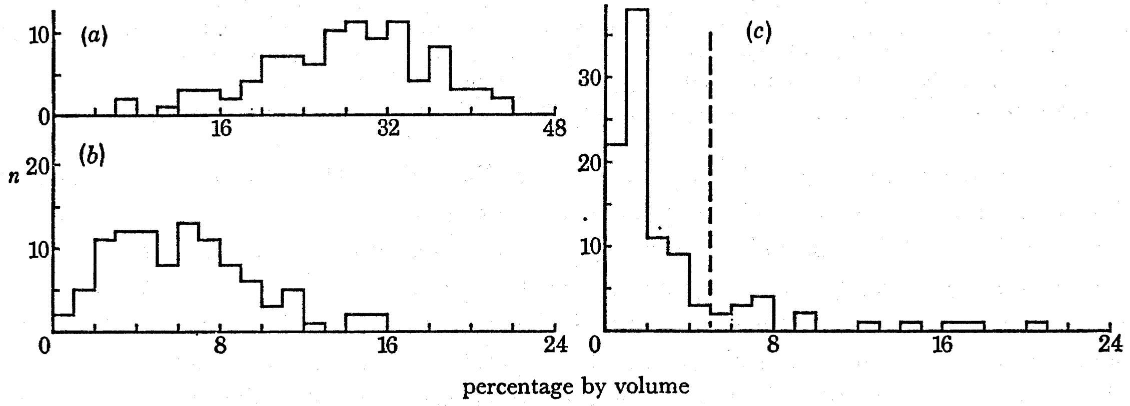

Figure 1. Histograms of modal percentages of (*a*) orthopyroxene, (*b*) garnet and (*c*) clinopyroxenes in 97 garnet 'lherzolites'. Data from Dawson (1960), Carswell & Dawson (1970), Rickwood *et al.* (1968), Chen (1971) and Cox *et al.* (1973).

One large group of garnet lherzolites with fairly consistent modes and mineral chemistry contains more than 50 % modal olivine (Fo_{90-92}) associated with low-Al enstatite (En_{90-94}) chrome diopside (terminology of Stephens & Dawson 1977) and chrome pyrope (terminology of Dawson & Stephens 1976). Attention is now drawn to rare members of this group in which at least some of the garnet and clinopyroxene developed by exsolution from orthopyroxene. Large orthopyroxene crystals set in a fine matrix of olivine, green diopside and garnet, are characteristically veined by garnets and, to a lesser extent, by diopside, and show different degrees of deformation. Two examples with a relatively high ratio of orthopyroxene/olivine are now described.

Nodule BD2695 from Bultfontein consists of a large (9 cm), kinked and garnet-veined orthopyroxene crystal set in a porphyroclastic–mosaic matrix of olivine, garnet, diopside and orthopyroxene (figure 2*a*, *b*, plate 1). The weaker olivine has recrystallized preferentially to give a fine-grained matrix around the garnet, diopside and orthopyroxene porphyroclasts. Since most of the orthopyroxene porphyroclasts occur near the large orthopyroxene, and since some contain garnet veinlets, they are interpreted as fragments from the margin of the large deformed orthopyroxene crystal. Whatever the complexities of the deformation history, annealing could ultimately produce a matrix with garnet and diopside derived from orthopyroxene.

TABLE 2. ANALYSES OF BD1366 SPINEL–GARNET, LHERZOLITE, MONASTERY MINE, SOUTH AFRICA

	(1)†	(2)	(3)	(4)	(5)	(6)	(7)
SiO_2	41.9	57.2	42.0	41.6	41.2	54.1	0.15
TiO_2	0.000	0.004	0.00	0.00	0.000	0.000	0.02
Al_2O_3	0.016	0.90	21.3	21.5	21.8	2.00	17
Cr_2O_3	0.011	0.22	2.0	2.8	2.7	1.46	52
FeO	7.0	4.5	7.4	7.6	7.6	1.48	18
MnO	0.075	0.087	0.45	0.49	0.39	0.04	0.19
MgO	52.1	36.8	21.4	21.0	21.1	16.8	13
NiO	0.40	0.088	0.01	0.01	0.000	0.04	0.19
CaO	0.017	0.22	4.8	5.1	5.4	22.2	0.03
Na_2O	0.000	0.031	0.02	0.00	0.008	1.42	0.00
total	**101.524**	**100.050**	**99.38**	**100.10**	**100.198**	**99.540**	**100.58**

† (1) Olivine: average of three analyses; P_2O_5, 0.005 %. (2) Orthopyroxene: average of three areas without visible lamellae; K_2O, 0.00. (3) Garnet: narrow lamella inside orthopyroxene; K_2O, 0.00. (4) Garnet: average of centres of two coarse lamellae inside orthopyroxene; K_2O, 0.00. (5) Garnet: grain enclosed in spinel. (6) Clinopyroxene: grains next to spinel; K_2O, 0.00. (7) Cr-spinel: mean of four grains.

Analysts: J. V. Smith, Geophysical Laboratory microprobe; R. L. Hervig, Chicago microprobe.

An annealed equivalent of 2695 is spinel–garnet lherzolite BD1366 from the Monastery Mine (Dawson & Smith 1973). Orthopyroxene crystals up to 15 mm long are set in a granuloblastic matrix of 1.0–2.5 mm polygonal crystals of forsterite, pyrope and clinopyroxene. Most orthopyroxene megacrysts are bent, and narrow rods or plates of garnet have exsolved on (100) planes at places of maximum curvature. Other crystals, strongly resembling the large orthopyroxene crystal in 2695, are kinked on {100} [001], and have exsolved garnet blebs, rods and lamellae together with thin lamella of ? clinopyroxene on (100) planes (figure 2*c*); at kink-junctions, separating rotated segments of orthopyroxene, garnet blebs have coalesced to form garnet veinlets containing occasional diopside crystals (figure 2*d*). Matrix diopsides and garnets tend to ring the large orthopyroxene grains like the 'necklace' texture in some eclogites and grospydites whose garnets cluster around the clinopyroxenes from which they have exsolved (Harte & Gurney 1975; Lappin 1978). In 1366, the composition of garnet in thick lamellae is very similar to that in the granuloblastic matrix (table 2, columns 4 and 5), but the garnet in thin lamellae has lower Cr_2O_3 and CaO though the MgO, Al_2O_3 and FeO are similar. These chrome pyropes and the other phases have similar compositions to those in 'common' garnet lherzolites (cf. tables 1 and 2).

Pyroxene thermobarometry is still highly controversial, but 1366 probably equilibrated near 950(±50?) °C and 45(±5?) kbar (4.5(±0.5?) GPa).

(*b*) *Orthopyroxene megacrysts*

Although lherzolite xenoliths containing orthopyroxenes veined by garnet and diopside are very rare (only one other, a specimen from Lashaine, Tanzania, is known to the authors

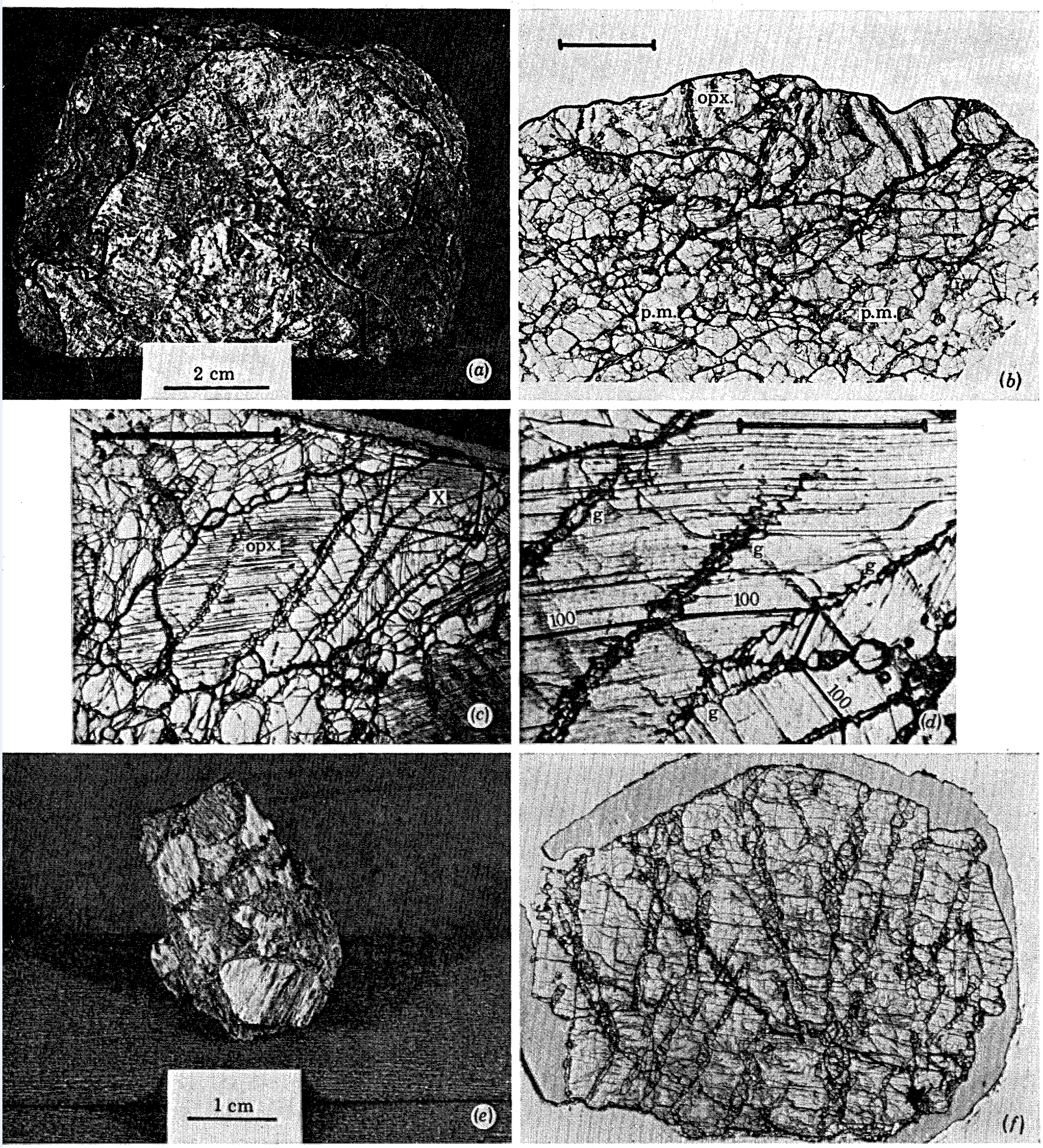

FIGURE 2. (*a*) Photograph of approximately half of the hand specimen of BD2695, Bultfontein. The margins of the large enstatite crystal, occupying most of this side of the specimen, have been inked in for clarity; dark veinlets cutting the light-coloured enstatite are of garnet, with minor diopside. (*b*) Thin section of BD2695, illuminated from rear. The large orthopyroxene (opx., margins inked in) is kinked and cut by dark garnet veins. The porphyroclastic-textured matrix (p.m.) comprises olivine, orthopyroxene, diopside and garnet. Scale bar = 10 mm. (*c*) Thin section of BD1366, Monastery Mine, illuminated from the rear. A large kinked enstatite crystal (opx., margins inked in), exsolving garnet, is set in a matrix of olivine, garnet and diopside. Area X enlarged in (*d*). Scale bar = 5 mm. (*d*) Photomicrograph of area X in (*c*) showing coalescing blebs of exsolved garnet (*g*) along kink bands, and displacement of (100) planes across the dislocations. Scale bar = 1 mm. (*e*) Kinked megacryst of enstatite with rotated segments welded by exsolved garnet (abundant) and diopside. BD2015/3, Frank Smith Mine (see table 3 for analysis). (*f*) Photomicrograph of enstatite megacryst with exsolved lamellae of pyrope. Maximum length of crystal is 16 mm. BD1951, Bultfontein Mine (see table 3 for analyses).

(J. B. Dawson, unpublished data)), indirect evidence for the former presence of similar xenoliths is found in large single crystals of orthopyroxene with exsolved garnet and diopside veinlets, rods or blebs, or in apparent 'aggregates' of garnet- and diopside-cemented orthopyroxenes (actually highly kinked orthopyroxenes with exsolved garnet and diopside concentrated in kinks) that occur in the concentrates from several South African kimberlite mines. These specimens from Wesselton, Dutoitspan, Bultfontein, Bellsbank, Jagersfontein, Monastery and Frank Smith observed by J. B. Dawson (see, for example, figure 2*e*) are assumed to derive by fragmentation of xenoliths similar to 2695 and 1366.

TABLE 3. ANALYSES OF LARGE, SINGLE ENSTATITE CRYSTALS FROM KIMBERLITE AND EXSOLVED PHASES

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10*a*)	(10*b*)	(11*a*)	(11*b*)
SiO_2	57.9	41.5	54.5	0.1	57.8	41.9	55.0	58.3	42.0	53.64	54.86	54.34	55.60
TiO_2	0.09	0.16	0.17	1.28	0.04	0.09	0.09	0.02	0.04	tr.	tr.	tr.	tr.
Al_2O_3	0.70	19.1	2.35	8.62	0.85	20.9	3.00	0.80	21.0	4.26	3.98	4.07	3.78
Cr_2O_3	0.36	5.55	2.45	55.49	0.36	4.03	1.96	0.40	4.54	0.80	0.78	0.84	0.74
Fe_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.10	1.14	1.46	1.25
FeO	5.16†	8.30†	2.56†	21.93†	5.02†	7.47†	2.60†	4.40†	6.75†	3.80	3.91	3.34	3.43
MnO	0.16	0.59	0.16	0.67	0.10	0.43	0.10	0.12	0.38	0.15	0.15	0.12	0.12
MgO	34.8	19.3	15.7	11.4	35.1	20.3	15.9	35.1	20.8	32.32	33.04	32.40	33.08
CaO	0.34	5.55	19.3	n.d.	0.45	5.18	19.2	0.37	4.74	1.81	1.90	1.95	2.04
Na_2O	0.0	n.d.	2.58	n.d.	0.0	n.d.	2.97	0.0	0.0	0.27	0.25	0.27	0.26
total	**99.5**	**100.0**	**99.8**	**99.5**	**99.7**	**100.3**	**100.8**	**99.5**	**100.2**	**100.10**		**100.34**	

(1–4) Host orthopyroxene, exsolved garnet, diopside and spinel respectively, BD1943, Wesselton Mine. Maximum dimension of orthopyroxene, 11 mm.

(5–7) Host orthopyroxene, exsolved garnet and diopside respectively, BD1944, Wesselton Mine. Maximum dimension of orthopyroxene, 12 mm.

(8, 9) Host orthopyroxene, exsolved garnet respectively, BD1951 Bultfontein Mine. Maximum dimension of orthopyroxene, 16 mm. Analyst 1–9, A. Peckett (Durham microprobe).

(10*a*, 11*a*) Orthopyroxene megacrysts, veined by garnet and diopside, with minor secondary phlogopite and serpentine. BD2015/3 and 2015/5, Frank Smith Mine, respectively. Totals for analyses (10*a* and 11*a*) contain respectively 0.30 and 0.27 % K_2O, 1.29 and 1.15 % H_2O^+, and 0.36 and 0.12 % H_2O^-. Analyst, J. R. Baldwin (classical wet analyses).

(10*b*, 11*b*) Analyses 10*a* and 11*a* recalculated, minus phologopite and water; phlogopite calculated on basis of $9K_2O$: $1Na_2O$: $15Al_2O_3$: $1.5Cr_2O_3$: $1Fe_2O_3$: 2FeO: 25MgO: $40SiO_2$: $4H_2O$.

† Total iron as FeO.

Microprobe analyses of single orthopyroxene crystals and their exsolved garnet, clinopyroxene and spinel (table 3) show them to be enstatite, chrome pyrope, chrome diopside and magnesian chromite closely comparable chemically to the phases in 'common' garnet lherzolites. Whereas host orthopyroxene and exsolved garnet in individual specimens are very consistent in composition, exsolved clinopyroxene shows some variation, particularly in Al_2O_3, CaO and Na_2O.

Bulk analyses of orthopyroxene crystals containing exsolved garnet and diopside (table 3) show significant amounts of Na_2O, Al_2O_3, Cr_2O_3 and CaO, but low TiO_2. The analyses, recalculated to eliminate small amounts of secondary mica and water, are most closely comparable with the high Na-orthopyroxenes in the fertile harzburgite group (table 1, column 2).

(*c*) *Significance of inferred coarse-grained parents*

The above observations indicate the existence of a facies of peridotite, whose grain size is considerably larger than is normally found in garnet lherzolite nodules. Members of this facies would contain olivine and orthopyroxene, perhaps with a little garnet. The orthopyroxene would be rich in Al, Cr and Ca, probably because the coarse-grained facies developed at solidus temperature in association with a basaltic liquid. During subsequent cooling, most members of the facies would completely recrystallize to a lherzolite with minor amounts of garnet and clinopyroxene, as proposed theoretically by O'Hara *et al.* (1975), and as envisaged for garnet lherzolites from Matsoku (Gurney *et al.* 1975). Only a few fortunate survivors display the intermediate stages of dynamic metamorphism in which we can observe the combination of hydrostatic and shearing stresses causing recrystallization of weak olivine, coupled with brittle fracture of orthopyroxene and attendant exsolution of garnet and clinopyroxene. Partial annealing is demonstrated in 1366.

It is well established experimentally in the pyrope–enstatite system (see, for example, Boyd & England 1964; MacGregor 1974) an increase of hydrostatic pressure favours the denser pair pyrope–enstatite over the less dense high-Al enstatite, though many complications resulting from Cr, Al and Fe, Mg, Ca substitutions await detailed experimentation; these need not be pursued here except to emphasize that assemblages involving Cr,Al-spinel tend to occur at lower pressure and/or higher temperature than those involving Cr,Al-bearing garnet, with spinel–garnet assemblages (as in 1366) involving intermediate conditions. What we should like to emphasize is the apparent importance of the stress element in providing dislocations within the orthopyroxene where exsolution can occur preferentially.

Further examples of garnet exsolving from large stressed orthopyroxenes are reported in tectonically emplaced peridotite lenses in the basement complex of the Bois de Feuilles, Massif Central, France (Lasnier 1971), and in the Norwegian Caledonian fold belt (Carswell 1973), so we infer that coarse-grained parental rocks are not confined to the upper mantle beneath the South African craton.

The inferred coarse parents need not be chemically identical, and indeed the minerals in 1366 are essentially free of TiO_2 (table 2), whereas some of the enstatite crystals and exsolved phases in Wesselton specimens have significant amounts (table 3). We now investigate compositional restraints on the possible interrelations between fertile harzburgites and lherzolites.

4. CHEMICAL RELATIONS BETWEEN HARZBURGITES AND LHERZOLITES

The simplest assumption that all the garnet and clinopyroxene of a lherzolite resulted from recrystallization of the orthopyroxene in a parent harzburgite would be readily testable from accurate analyses of the individual minerals if the modal abundances were accurately known. Unfortunately the modal abundances of exotic nodules are highly variable, even within single specimens, and subject to the vagaries of transportation, fragmentation and sample size. Furthermore, lherzolites with abundant garnet and diopside may well have been collected more enthusiastically than the less spectacular harzburgites and lherzolites with rare garnet and diopside. Bearing this in mind, the histograms of published modal percentages of orthopyroxene, garnet and clinopyroxene in 97 garnet 'lherzolites' from kimberlites show that many contain little clinopyroxene (less than 2%) and garnet (less than 5%) and roughly 30% orthopyroxene, with the remaining 60–70% as olivine (figure 1). Columns (8) and (9) of table 1 are calculated compositions of orthopyroxene from various proportions of orthopyroxene, Cr-diopside and Cr-pyrope with compositions typical for garnet lherzolites; it is assumed that olivine stays inert during cooling. The bulk compositions, after normalization to 100%, give an approximate match to the composition of orthopyroxenes from fertile harzburgites (table 1, columns 2 and 3) and to the bulk orthopyroxenes (table 3, columns 10, 11). There are, however, some variations when the compositions are examined in detail, especially for Na_2O, TiO_2 and CaO.

First, the typical enstatite from common garnet lherzolite has four times as much Na_2O (0.12 %) as the typical orthopyroxene of the low-Na fertile harzburgites. Only the pyroxenes in the two rarer high-Na fertile harzburgites (Na_2O, 0.16 %) and the recalculated bulk orthopyroxenes (table 3) are rich enough to produce the Na-bearing clinopyroxene and orthopyroxene found in common garnet lherzolite.

Secondly, the orthopyroxenes from all the harzburgites are essentially devoid of TiO_2 (as are the olivines), whereas the theoretical composition contains 0.07 %. One possible explanation is that a minor Ti-rich phase should be incorporated into the theoretical harzburgite, and indeed rutile is a not uncommon phase in nodules from kimberlites (Smith & Dawson 1975). A second factor is the deliberate avoidance of 'dirty' areas of orthopyroxene during electron microprobe analysis; preliminary measurements of such dirty areas have shown variable but significant amounts of TiO_2, probably from tiny inclusions of rutile or ilmenite. Actually, the exsolved garnet and clinopyroxene in 1366 are essentially devoid of TiO_2, and the spinel has only a tiny amount (table 2), thereby ruling out the presence of substantial TiO_2 in the original orthopyroxene of this specimen.

A further factor is the overall CaO/Al_2O_3 ratio of the harzburgite precursor. In the case of low-Ca rocks, such as garnet harzburgite 2093 from Liqhobong (Dawson *et al.* 1978), the absence of diopside reflects the virtual absence of CaO in the bulk rock before recrystallization.

Probably the best conclusion at this stage is that there are two possible 'fertile' harzburgites: (*a*) the high-Na variety, capable of producing common garnet lherzolite, and (*b*) the low-Na fertile harzburgites that are similar but not identical. A possibility is that the low-Na fertile harzburgites developed at shallower depths than garnet lherzolites. The Na content of garnets appears to increase with depth (Bishop *et al.* 1978) and that of pyroxenes may tend to do likewise, though there are likely to be complications. Perhaps the Ti content also varies with depth in view of observed weak correlations with Na (Bishop *et al.* 1978). Because of the higher pressure and temperature, dynamic metamorphism should become more intense with depth, and the likelihood of preservation of a pristine sample of fertile harzburgite should decrease. Consequently we suggest that the low Na fertile harzburgites derive from relatively shallow depths and may prove to be the parents of spinel lherzolites containing little, if any, jadeite component in the clinopyroxene. This possibility is now under investigation.

Of course, metasomatism cannot be ruled out as an important factor associated with dynamic metamorphism, and indeed there is abundant evidence reported by many workers. K-rich phases are not typically present in harzburgites, and mica–garnet lherzolites could not be generated by exsolution from harzburgites unless substantial K was introduced by metasomatism.

Finally, it is worth comparing columns (2) and (8) in table 1 to obtain an idea of the variations of orthopyroxene composition with modal amount of exsolved diopside and garnet assumed in models. Garnet in common garnet lherzolite has a Cr_2O_3/CaO ratio closer to unity than that in the coexisting diopside; because all the orthopyroxenes in table 1 have a Cr_2O_3/CaO ratio near unity, the predicted garnet/clinopyroxene ratio must be considerably greater than one for garnet lherzolites produced by exsolution from harzburgites containing orthopyroxenes with a Cr_2O_3/CaO ratio greater than unity. Presence of a Cr-rich spinel allows an increase of Cr_2O_3 and Al_2O_3 in the theoretical orthopyroxene without an increase of CaO (compare columns 9 and 8), and improves the fit with column 2; of course, extra Cr and Al may be present in the hypothetical orthopyroxene of the harzburgite precursor, as indicated by the bulk orthopyroxene analyses (table 3, columns 10, 11). There is considerable qualitative evidence that the Cr content of minerals tends to increase with depth in the upper mantle, as is desirable for cosmochemical models of the bulk composition of the Earth (Smith 1977), and high-Cr orthopyroxenes should not be ruled out in the hypothetical harzburgite precursors.

5. SUMMARY

Exsolution of garnet and clinopyroxene has been observed in deformed orthopyroxene megacrysts in kimberlites, thereby supporting the idea that a harzburgite precursor may have yielded garnet lherzolites with low abundance of garnet and clinopyroxene when metamorphosed dynamically.

Two types of harzburgite have been recognized in the xenolith suites from South African kimberlites. One highly refractory group may be the residue of considerable partial melting (two successive episodes or a single episode with multiple escapes of magma?), but the other contains appreciable amounts of Na, Ca, Al and Cr in the orthopyroxene. This 'fertile' group has retained potential garnet and clinopyroxene in solid solution, and may provide a guide to the inferred coarse harzburgites that gave rise during cooling and dynamic metamorphism to some garnet lherzolites with minor amounts of garnet and clinopyroxene. Subtle chemical features lead to the suggestion that the chemical composition of the 'fertile' harzburgites tend to vary with depth, and that some developed at a higher level than the hypothetical parents of garnet lherzolites. Whether the fertile harzburgites were primary cumulates or the restites from a single episode of partial melting of earlier garnet lherzolites requires further testing by measurement of trace elements, especially with an ion microprobe.

The combination of reliable mineralogical and petrographic observations with plausible theoretical suggestions shows that some compositional heterogeneities in the upper mantle must result from partial melting and subsequent kinetic deformation. One-step models (e.g. fertile parent – melt – barren residue) are inadequate for estimation of the bulk composition of the upper mantle. When considering the origin of basalts and the chemical differentiation of the Earth from as wide a viewpoint as possible (Smith 1979), the new evidence for mantle heterogeneity must be taken into consideration.

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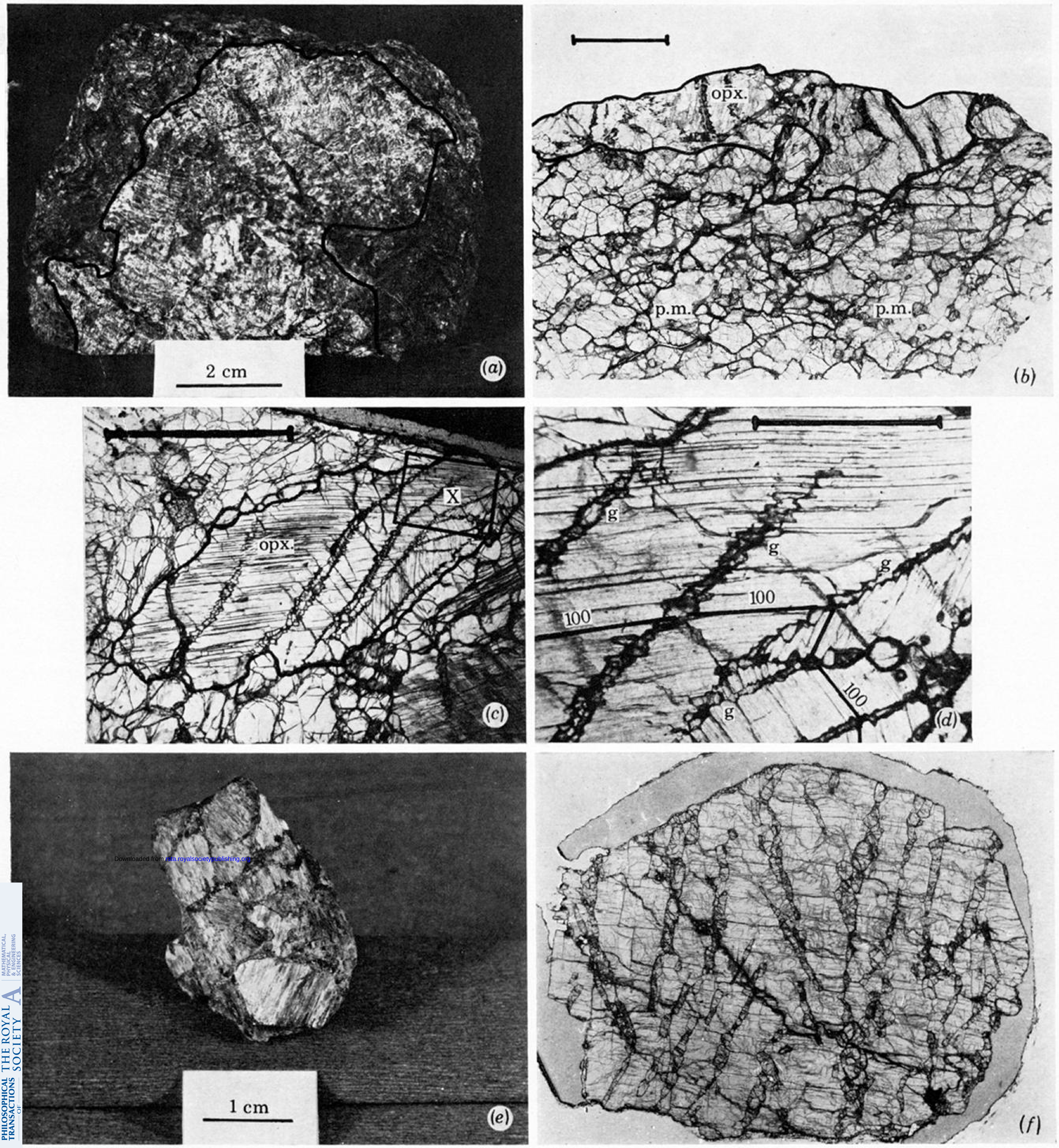

FIGURE 2. (*a*) Photograph of approximately half of the hand specimen of BD2695, Bultfontein. The margins of the large enstatite crystal, occupying most of this side of the specimen, have been inked in for clarity; dark veinlets cutting the light-coloured enstatite are of garnet, with minor diopside. (*b*) Thin section of BD2695, illuminated from rear. The large orthopyroxene (opx., margins inked in) is kinked and cut by dark garnet veins. The porphyroclastic-textured matrix (p.m.) comprises olivine, orthopyroxene, diopside and garnet. Scale bar = 10 mm. (*c*) Thin section of BD1366, Monastery Mine, illuminated from the rear. A large kinked enstatite crystal (opx., margins inked in), exsolving garnet, is set in a matrix of olivine, garnet and diopside. Area X enlarged in (*d*). Scale bar = 5 mm. (*d*) Photomicrograph of area X in (*c*) showing coalescing blebs of exsolved garnet (*g*) along kink bands, and displacement of (100) planes across the dislocations. Scale bar = 1 mm. (*e*) Kinked megacryst of enstatite with rotated segments welded by exsolved garnet (abundant) and diopside. BD2015/3, Frank Smith Mine (see table 3 for analysis). (*f*) Photomicrograph of enstatite megacryst with exsolved lamellae of pyrope. Maximum length of crystal is 16 mm. BD1951, Bultfontein Mine (see table 3 for analyses).