The paragenesis of upper-mantle xenoliths from the Quaternary volcanics south-east of Gees, West Eifel, Germany

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Abstract

Group I xenoliths, orthopyroxene-rich and orthopyroxene-free, contain Cr-spinel and clinopyroxene ± phlogopite, and occur together with Group II clinopyroxenites ± Ti-spinel ± phlogopite in K-mafic pyroclastics southeast of Gees. The petrography and clinopyroxene chemistry of orthopyroxene-rich (opx-rich sub-group) Group I xenoliths is consistent with an 'original' harzburgitic mantle that has been transformed to lherzolite by the addition of endiopside. In harzburgites, orthopyroxenes are reacting to diopside + olivine + alkali-silicate melt, and, by inference, the orthopyroxene-free (opx-free sub-group) Group I, dunite–wehrlite series can be linked to the opx-rich sub-group via this reaction. Progressive enrichment of dunitic material in endiopside–diopside has resulted in the formation of wehrlite. Phlogopite is titaniferous and occurs as a trace mineral in opx-rich, Group I xenoliths, whereas substantial phlogopite vein-networks are confined to the opx-free sub-group (dunite–wehrlite series). Interstitial, alkali-felsic glass occurs are veins within, and as extensions of, the phlogopite networks. Clinopyroxenes in phlogopite-veined xenoliths are decreased in $Mg/(Mg + Fe_{Total})$ (*mg*) and Cr and increased in Ti, Al and Ca, compared with clinopyroxenes in xenoliths which have trace phlogopite. It is proposed that harzburgitic and dunitic mantle has been infiltrated by a Ca- and alkali-rich, hydrous silicate melt rather than an ephemeral carbonatite melt. Dunite has been transformed to phlogopite wehrlite by the invasion of a Ca-, Al-, Ti- and K-rich, hydrous silicate melt. Ca-activity was high initially in the melt and was reduced by clinopyroxene precipitation. This resulted in enhanced K-activity which led to phlogopite veining of clinopyroxene-rich mantle. Group II phlogopite clinopyroxenites contain Ti-spinel and salites that are distinct in their Ti, Al and Cr contents from endiopsides and diopsides in Group I xenoliths. It is unlikely that these Group II xenoliths represent the culmination of the infiltration processes that have transformed dunite to wehrlite, nor can they be related to the host melt. These xenoliths may have crystallised from Ca- and K-bearing, hydrous silicate melts in mantle channelways buffered by previously precipitated clinopyroxene and phlogopite. Gees lherzolites contain pyroxenes and spinel with distinctly lower Al contents than these same minerals in lherzolites described previously from other West Eifel localities, which may reflect a distinctive lithology and/or processes of modification for the Gees mantle.

KEYWORDS: xenoliths, olivine, pyroxene, upper mantle, Gees, West Eifel, Germany.

Introduction

THE Quaternary West Eifel volcanic field is characterised by Group I and II (Frey and Prinz, 1978) ultramafic xenoliths found in scoria fans at 10 eruption centres (Frechen, 1959, 1962; Lloyd, 1972). Studies have concentrated on the Dreis (Dreiser Weiher) site (Frechen, 1973; Aoki and Kushiro, 1968; Paul, 1971; Stosch and Seck, 1980; Stosch and Lugmair, 1986; Kempton *et al.*, 1988). Aoki and Kushiro (1968) investigated clinopyroxenes from the Dreis xenoliths whereas Lloyd and Bailey (1975) and Becker (1977) studied clinopyroxenes from 9 and 2 localities respectively. The

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TABLE 1. Salient petrographic features of the Gees xenoliths

Group	Distinguishing features	Sub-group	Primary characteristics	Secondary features	% relative abundance	Specimens analysed
I	Coarse, with some recrystallisation. Olivine-rich (Table II), with Cr-spinel and relatively Cr-rich and Ti-poor clinopyroxene	OPX-rich (Table II)	Lherzolites: coarse enstatites, endiopsides and strained olivines	Secondary endiopsides form stringers, commonly adjacent to olivine neoblasts (Fig. 1) Rare mica flakes associated with a band of secondary clinopyroxene	1	FL 15(1) FL 7 FL 7
			Harzburgites: large, isolated enstatites and coarse, strained olivines	Enstatites have incomplete reaction fringes of diopside + olivine microlites coated by pale-brown glass (Fig. 2)	10	FL 86(1)
				Selvage (0.01-0.05 mm across) of reddish brown glass to two adjacent xenolith edges		FL 86(1)
			Olivine websterite: coarse, rounded bronzites and olivines	Bronzites commonly fringed by olivine + augite granules	4	FL 245(1)
				Thin stringers and pools of orange glass		
		OPX-free (Table II)	Dunites: coarse, strained olivines	Secondary endiopsides or diopsides ± phlogopite flakes form stringers associated with olivine neoblasts (Fig. 3)	72(2)	FL 123(1) FL 4
				Glassy selvage to xenolith		FL 123(1)
I	Coarse, with some recrystallisation to neoblasts. Olivine-rich (Table II), with Cr-spinel and relatively Cr-rich and Ti-poor clinopyroxene	OPX-free (Table II)	Wehrlites: lenses and/or layers of coarse, strained olivines plus occasional coarse diopsides with patchy extinction.	Granular mosaic of olivines and diopsides encloses lenses, or interleaves with, primary material. Veins and stringers of phlogopite, together with interconnected pools of reddish-brown glass, occur within mosaic areas	72(2)	FL 14(1) FL 13(1) FL 251
II	Clinopyroxenites with trace or no olivine. Ti-bearing, non-chromiferous spinel plus relatively Ti-rich and Cr-poor clinopyroxene	Phlogopite-bearing	Phlogopite clinopyroxenites: coarse salites, rich in fluid inclusions and with some recrystallised grain margins. Phlogopite forms isolated, ovoid aggregates, or when > 50% forms a partial net that surrounds and overgrows salite	Pools and stringers of reddy-brown glass within, or as extensions of, the phlogopite net. Glass also as semi-pervasive coating to scalloped salites.	13	FL 18 FL 19(1)
		Anorthite-bearing	Coarse salites with some planar faces	Interstitial anorthite and pleonaste-hercynite relationships suggest (i) replacement of salite by anorthite (ii) replacement of anorthite by pleonaste-hercynite	Tr	FL 17

(1)Described in Edgar et al., 1989

(2)Includes all specimens of dunite-wehrlite series

relationship between Group I, orthopyroxene-rich (opx-rich) assemblages and Group I, orthopyroxene-free (opx-free) assemblages (Table 1), and between Group I and Group II xenoliths has received little attention. Recently Edgar *et al.* (1989) have studied the glass compositions in Group I and Group II xenoliths from Gees.

A working quarry southeast of Gees village in the West Eifel, West Germany, has yielded 225 xenoliths from a section in strombolean type alkali–mafic pyroclastic deposits. Of these 194 are Group I and they either contain enstatite and olivine as major constituents (opx-rich sub-group, Table 1) or olivine with accessory to essential clinopyroxene (opx-free sub-group, Table 1). Accessory Cr-spinel is typical of both sub-groups. Titaniferous phlogopite is found in all types of Group I xenoliths but only attains essential proportions in the opx-free varieties. Only two of the opx-rich assemblages are lherzolites, one with trace phlogopite, while 23 are harzburgites. There are also eight olivine websterites in which the orthopyroxene is bronzite rather than enstatite.

TABLE 2. Gees xenoliths, modal compositions of representative samples (vol. %)

Group	I, opx-rich:				I, opx-free:					II:	
Sample	FL 15	FL 7	FL 86	FL 245	FL 123	FL 4	FL 14	FL 13	FL 251	FL 18	FL 19
Olivine	67.6	78.7	70.0	38.4	85.1	78.4	60.4	51.6	44.3	-	-
Orthopyroxene	15.0	12.4	22.1	39.1	-	-	-	-	-	-	-
Clinopyroxene	16.3	7.8	5.4	14.2	13.4	8.3	34.3	31.8	41.5	91.9	44.5
Spinel	0.7	0.4	2.2	0.9	1.1	1.3	0.3	0.3	0.2	Trace	Trace
Phlogopite	-	0.4	-	-	Trace	11.6	0.2	13.2	10.7	7.2	51.2
Glass	0.3	0.2	0.3	7.5	0.3	0.3	4.8	3.1	3.4	0.9	-

Lherzolite: FL 15; Clinopyroxene-poor lherzolite: FL 7; Harzburgite: FL 86; Olivine websterite: FL 245; Olivine-rich wehrlite: FL 123; Clinopyroxene-phlogopite dunite: FL 4; Mica wehrlites: FL 14, FL 13, FL 251; Phlogopite clinopyroxenites: FL 18, FL 19.

Group II xenoliths from Gees are clinopyroxenites (salite) with rare, or no olivine and lacking orthopyroxene and commonly they contain titaniferous phlogopite and Ti-spinel; one is a hercynite to pleonaste–anorthite clinopyroxenite (Table 1).

Group I xenoliths, opx-rich (Table 1)

Lherzolites. Gees lherzolites are typically clinopyroxene-poor (Table 2) as are the well-documented West Eifel lherzolites of Dreis Maar (8 km N.W. of Gees) and the lesser-known lherzolites of Meerfeld Maar (12 km S. of Gees). Gees samples, however, are distinct in texture and mineral chemistry: (i) Gees lherzolites are porphyroclastic as defined by Mercier and Nicholas (1975) while Dreis samples show typical equigranular fabrics (Collée, 1963); (ii) trace interstitial phlogopite is recorded in Gees lherzolite (FL 7) but amphibole is absent, conversely, Dreis and Meerfeld lherzolites commonly contain trace amphibole or its breakdown products, but phlogopite is rare; (iii) Gees lherzolites are characterised by much lower Al contents in all their alumina-bearing minerals (spinel, clinopyroxene, orthopyroxene) compared with these minerals in Dreis lherzolites.

Late-crystallising hydrous minerals in Eifel lherzolites are the products of modal mantle metasomatism (Lloyd and Bailey, 1975; Kempton *et al.*, 1988). Gees lherzolite fabrics strongly indicate that bright-green endiopside-diopside is also a late crystallising phase which has been introduced into an assemblage of pale green endiopside + enstatite + olivine (Fig. 1).

Harzburgites. In the xenolith suites of continental, intraplate, alkaline volcanic provinces, harzburgites frequently occur with lherzolites e.g. Massif Central, France (Brown *et al.*, 1980); the Transdanubian volcanic province (Embey-Isztin *et al.*, 1989); the Bohemian dome (Jakěs and Vokurka, 1987). Harzburgites and lherzolites from the same province may exhibit similar types of metamorphic textures (Brown *et al.*, 1980; Embey-Isztin *et al.*, 1989) and they are usually considered to represent closely related mantle facies. Harzburgites are the more refractory assemblage and are often described as 'depleted' or 'infertile'.

The Gees harzburgites, however, contain distinctive features that are absent in Gees lherzolites. Harzburgite enstatites are particularly coarse and typically fringed by aggregates of olivine and diopside microlites. Amoeboid Cr-spinels, enclosed in these aggregates, are well developed in FL 86 (Fig. 2). Pools of alkali-rich felsic glass are found in embayments in spinels, and glass of identical composition occurs in spinels as minute spheroids and octahedral inclusions (Edgar *et al.*, 1989). Thus enstatite appears to be involved in two reactions:

(i) Enstatite + Ca-rich liquid $\rightleftharpoons$ olivine + diopside + liquid;
(ii) Cr-spinel (1) + Ca- and Si-rich liquid $\rightleftharpoons$ olivine + diopside + Cr-spinel (2) + liquid.

Olivine websterites. There is no clear relationship between the olivine websterites which contain bronzite and the other orthopyroxene-rich Group 1 xenoliths. The petrography indicates that bronzite has been involved in the same type

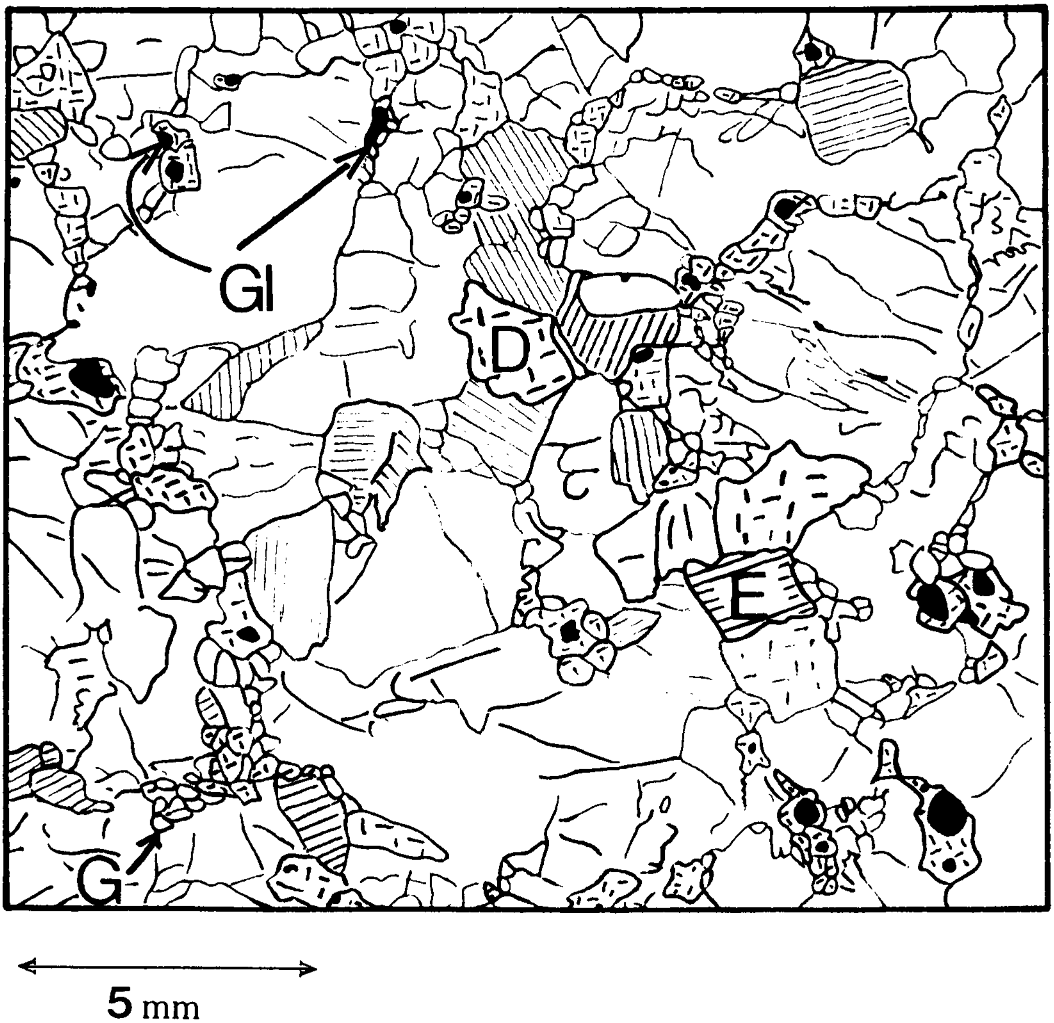

FIG. 1. Spinel lherzolite FL 15, Gees, W. Eifel. Small grains of secondary endiopside–diopside (brick ornament) form 'stringers' along olivine (non-ornamented) grain boundaries and enclose Cr-spinels (filled). Granular olivine (G) and rarely glass (G1) are found adjacent to 'stringers'. Larger grains of primary endiopside (D) occur together with enstate (E, striped) which is occasionally bent.

of reaction as that identified for enstatite in the harzburgites (Edgar *et al.*, 1989).

Group I xenoliths, opx-free subgroup (Table 1)

Dunite–wehrlite assemblages. These xenoliths appear to be fragments of a coherent series characterised by increasing clinopyroxene ± phlogopite (Table 2). Based on petrography, the members of this series cannot be related by fractionation or by reaction relationships. Fabrics indicate the introduction of clinopyroxene and mica into dunitic material (Fig. 3).

Group II xenoliths

Phlogopite clinopyroxenites. Texturally the phlogopite clinopyroxenites have 'network' distribution of phlogopite partially replacing salite which shows some recrystallisation of grain boundaries. These Group II assemblages do not have the same chemistry as the Mg-poor and felsic selvages and interstitial glasses which are found in both Group I and Group II xenoliths (Edgar *et al.*, 1989). Nor can the phlogopite clinopyroxenites be related to the chemistry of the host lavas which differ most significantly in Na: *c.* 3 wt.% Na_2O in the lavas (Mertes and Schmincke, 1985)

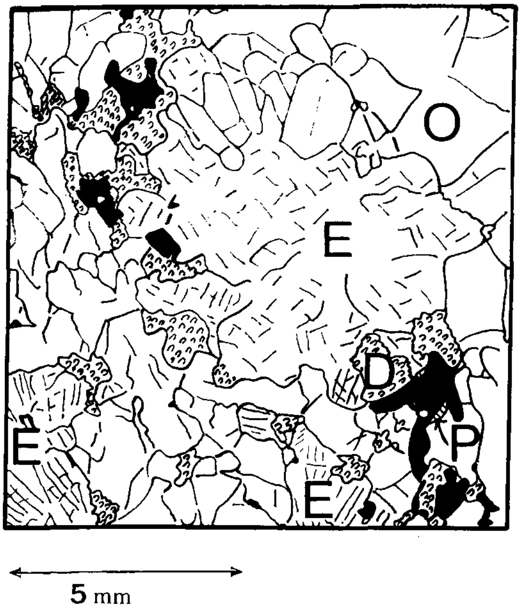

FIG. 2. Large enstatite (E) grain in harzburgite FL 86, Gees, W. Eifel with partial fringe of aggregates (D, circumflex ornament) of diopside + olivine granules, some of which penetrate between surrounding olivines (O, non-ornamented). Amoeboid Cr-spinel (filled) is almost completely enclosed in the granular aggregates. Pools of glass (P, striped and exaggerated X2) occur in embayments in Cr-spinels. Some olivines in contact with enstatite (centre-top) have developed planar surfaces indicative of recrystallisation.

as opposed to <1 wt.% Na_2O in the xenolith clinopyroxenes and phlogopites (Tables 6 and 7). In general alkali clinopyroxenite xenoliths are characterised by lower levels of Cr and Ni than their olivine-bearing, mafic host lavas (Lloyd et al., 1990).

Hercynite to pleonaste-anorthite clinopyroxenite. The salite in this xenolith has significantly lower Ti : Al than salite in the phlogopite clinopyroxenites with which it has no obvious relationship. Nor is there any identifiable relationship to clinopyroxenite from the nearby volcanic centre of Dreiss (FL 27, see *Petrography*: sample descriptions).

Clinopyroxene-rich xenoliths, some with hydrous minerals, are generally considered to have formed in the upper mantle (Nixon, 1987). The occurrence of these rock types in tectonically emplaced slices of upper mantle, their petrographic associations with lherzolites as composite xenoliths, their mineral chemistry and stabilities based on experimental studies support this conclusion (cf. Nixon, 1987).

Proposed petrographic scheme

The 'original' mantle beneath Gees consists of Group I, opx-rich assemblages in which clinopyroxene is an accessory mineral. Rare lherzolite xenoliths are fragments of clinopyroxene-enriched harzburgite while Group I, opx-free assemblages, such as clinopyroxene dunities are derived from harzburgitic mantle in which orthopyroxene has reacted to olivine and clinopyroxene. The dunite–wehrlite series represents progressive enrichment of the Group I, opx-free mantle facies in clinopyroxene ± phlogopite. In terms of modal mineralogy Group II phlogopite clinopyroxenites are the end-product of this progressive enrichment.

The purpose of this investigation is to evaluate this scheme in the light of the petrography and geochemistry of the Gees xenolith suite. In particular, the petrogenesis of the clinopyroxene-rich xenoliths of the Group I, opx-free sub-group (wehrlites) and Group II (clinopyroxenites) is considered to have important implications for the genesis of Ca-rich mantle beneath the Rhenish Shield in the European plate (Lloyd, 1987).

It is recognised that the scheme does not account for the olivine websterites or the fragment of hercynite to pleonaste–anorthite clinopyroxenite. These anomalous xenoliths serve to emphasise the complexity of mantle compositions and processes, and the fragmentary nature of the mantle sample. Additionally, it is not always valid to treat xenolith material from adjacent volcanoes as parts of the same sample.

Petrography

Unaltered mantle assemblage. This can be identified in the Gees xenolith suite as areas of coarse strained olivines together with orthopyroxenes in Group I, opx-rich lherzolites and harzburgites. Olivines are characterised by recrystallised borders and orthopyroxenes in harzburgites are in a reaction relationship (see *Harzburgites*). In Group I, opx-free dunites and wehrlites, areas of coarse, strained olivines are also likely 'original' mantle material. The only clinopyroxenes which appear to be inherited from the original mantle are coarse ones associated with orthopyroxene in the lherzolites plus the isolated, fluid inclusion-filled, coarse clinopyroxenes in some wehrlites.

Veining within Group I xenoliths. In broad terms two types of vein can be recognised: (i) small, bright-green clinopyroxenes (± phlogopite) enclosing Cr-spinels preferentially and forming discrete stringers, or a partial net, interstitial to 'original' mantle minerals in Group

I lherzolites and dunites; (ii) phlogopite veins which form discrete stringers, or a partial net, within clinopyroxene-rich areas in the wehrlites. Phlogopites in Group I (opx-free) xenoliths typically occur in veins and frequently overgrow, and therefore post-date, adjacent clinopyroxene. Reddy-brown, alkali-rich, silica undersaturated, felsic glass occurs within, and as extensions to, the phlogopite vein network, characteristically enclosing scalloped phlogopite plates and embaying adjacent clinopyroxenes.

Vein selvages to xenoliths. Fe-, Ca- and alkali-rich, silica undersaturated, reddish-brown glass (Edgar *et al.*, 1989) coats two adjacent sides of dreikanter-shaped xenoliths: harzburgite (FL 86) and dunite (FL 123). In the harzburgite, olivine in contact with this glass is overgrown by diopside–salite granules. In the dunite, endiopside in contact with the glass is overgrown by diopside. These glassy coatings are probably vein selvages which are the result of xenolith breakup along planar weaknesses (Irving, 1980) present in the mantle as a vein stockwork.

Pervasive alteration in Group I, opx-free xenoliths. In the wehrlites most of the diopside is considered to be of secondary (?infiltration) origin and has a pervasive distribution: granuloblastic diopsides and olivines together enclose lenses or bands of 'original' mantle of coarse, strained olivines. Sparse, coarse diopsides are also found within the areas of 'original' olivine, but they tend to be interstitial and, apart from size, they are petrographically indistinguishable from the granuloblastic diopsides.

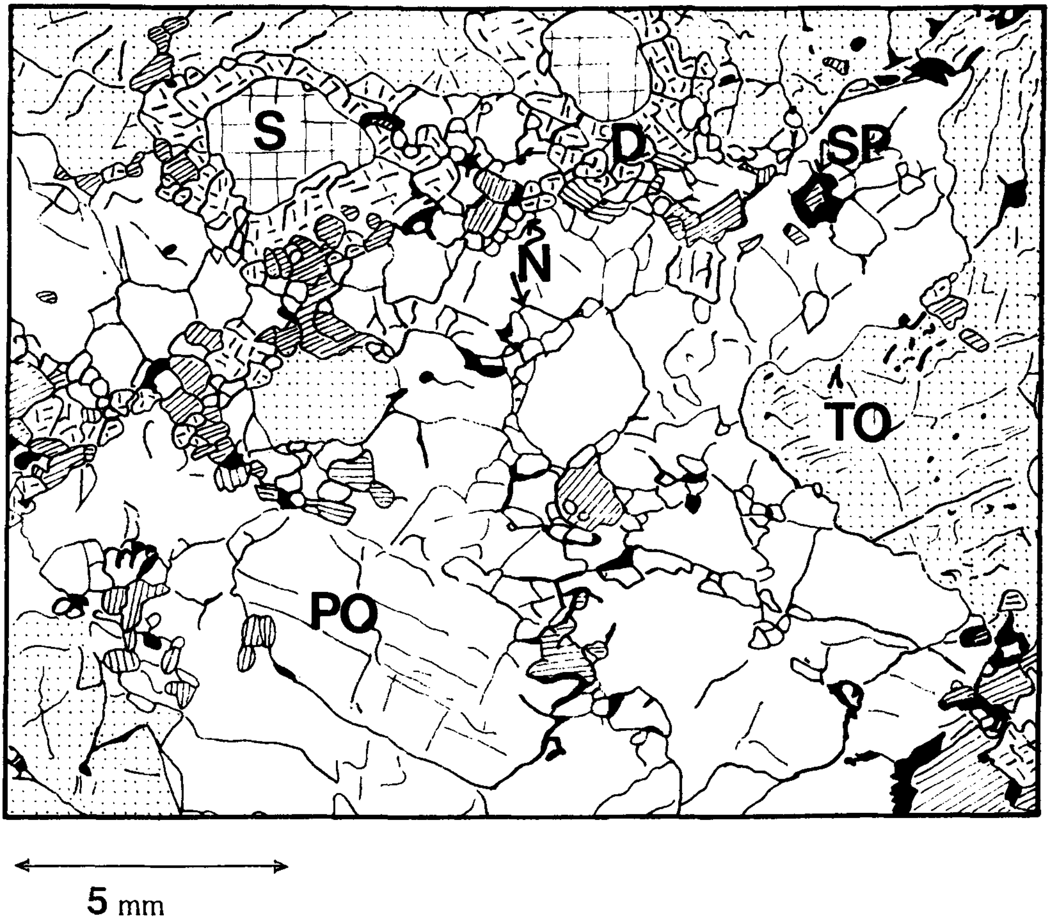

FIG. 3. Clinopyroxene-phlogopite dunite FL 4, Gees, W. Eifel. Small grains of diopside (D, brick ornament) enclose rounded Cr-spinels (S, cross hatch) and together with phlogopite plates (striped) and olivine neoblasts (N) form 'blebs' and 'stringers' between larger olivine which is turbid and irregular-shaped (TO, dotted) or clear with near-planar boundaries (PO) suggesting some recrystallisation. Traces of dark-brown glass (filled) are found surrounding, or forming 'pools' between scalloped phlogopite plates (SP), diopside granules and olivine neoblasts.

TABLE 3. Average mg [$100.Mg(Mg + Fe^1)^{-1}$] for silicate minerals from Gees xenoliths

Group	I, opx-rich:				I, opx-free:					II:			
Sample	FL 15	FL 7	FL 86	FL 245	FL 123	FL 4	FL 14	FL 13	FL 251	FL 18	FL 19	FL 17	FL 27
Olivine	89	91	91	82	90	86	85	82	84	-	84[4]	-	-
Orthopyroxene	91	91	92	84	-	-	-	-	-	-	-	-	-
Clinopyroxene	91	92	86(79)[2]	82	90(82)[2]	87	87(77)[3]	84	84	77	-	67	76
Phlogopite	-	91	-		-	84	83	80	83	76	71(91)[5]		

1: Total Fe expressed as Fe^{2+}
2: Av. mg of selvage clinopyroxenes
3: Av. mg of low-Mg clinopyroxenes
4: Av. mg of skeletal olivine within glass and associated with breakdown of phlogopite
5: Av. mg of high-Mg clinopyroxenes

Pervasive alteration in Group II phlogopite clinpyroxenites. In phlogopite-rich types (FL 19) phlogopite post-dates salite and forms a pervasive net which encloses lenses of the latter. Salite lenses have granular margins which are typically overgrown and occasionally replaced by phlogopite. Thus it appears that pervasive phlogopite infiltration of salite-rich material has occurred.

Ten representative xenoliths from Gees were chosen for analytical study and their salient petrographic features and modes are presented in Tables 1 and 2 respectively. Detailed petrographic descriptions of seven of these (FL 13, FL 14, FL 15, FL 19, FL 86, FL 123, FL 245) have been reported in Edgar *et al.* (1989). Clinopyroxenes from three further samples (FL 17 from Gees, FL 27 from Dreis and E 48Y from Merefeld) were analysed for comparison. Descriptions of the unpublished material (FL 7, FL 4, FL 251, FL 17, FL 27, E 48Y) follow:

TABLE 4. Representative compositions of olivines from Gees xenoliths

Group	I, opx-rich:					I, opx-free:				
Composition	Lherzolites:		Harzburgite:		Ol websterite:	Cpx dunite:	Cpx-phl dunite:	Phl wehrlites:		
No.	1	2	3	4	5	6	7	8	9	10
Sample	FL 15	FL 7	FL 86	FL 86	FL 245	FL 123	FL 4	FL 14	FL 13	FL 125
No. of grains	8(1)	4(1)	4(2)	6(3)	3	6(1)		9(1)	11(1)	9(1)
SiO_2	39.97	40.42	40.90	39.86	38.86	40.58	40.18	40.73	40.24	39.05
TiO_2	0.00	0.06	0.00	0.10	0.05	0.05	0.03	0.00	0.00	0.05
Al_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00
Cr_2O_3	0.06	0.09	0.11	0.05	0.08	0.04	0.04	0.07	0.00	0.05
FeO	10.22	9.15	8.39	11.66	17.30	10.14	13.35	14.08	16.73	15.66
MnO	0.17	0.10	0.10	0.17	0.32	0.14	0.27	0.22	0.27	0.29
MgO	48.23	48.87	48.83	46.04	43.27	48.62	45.59	43.99	41.84	43.77
CaO	0.16	0.13	0.16	0.62	0.20	0.13	0.30	0.15	0.35	0.28
NiO	0.23	n.a.	n.a.	n.a.	n.a.	n.a.	0.40	0.21	0.23	0.00
Total	99.04	98.82	98.49	98.50	100.08	99.76	100.19	99.38	99.66	99.15
Si	0.996	0.997	1.007	1.000	0.986	0.996	1.002	1.022	1.021	0.992
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001
Ti	0.000	0.001	0.000	0.002	0.001	0.001	0.000	0.000	0.000	0.000
Cr	0.001	0.002	0.003	0.001	0.002	0.001	0.000	0.001	0.000	0.001
Fe	0.213	0.188	0.172	0.244	0.366	0.207	0.278	0.295	0.355	0.331
Mn	0.004	0.002	0.002	0.004	0.007	0.003	0.006	0.005	0.006	0.006
Mg	1.786	1.808	1.803	1.732	1.646	1.791	1.694	1.645	0.582	1.668
Ca	0.004	0.003	0.004	0.017	0.006	0.003	0.008	0.004	0.009	0.008
Ni	0.005	n.a.	n.a.	n.a.	n.a.	n.a.	0.008	0.004	0.005	n.a.
mg	90	91	91	88	82	90	86	85	82	83

(1)Av of chemically indistinguishable large + small grains; (2)Av of chemically indistinguishable large + small grains fringing enstatite;
(3)Olivine in contact with selvage glass. Abbreviations as for Table 6.

TABLE 5. Representative compositions of orthopyroxenes from Gees xenoliths

Group	**I, opx-rich:**					
Composition	**Lherzolites:**				**Harzburgite**	**Ol websterite**
No.	1	2	3	4	5	6
Sample	FL 15	FL 7	Ia/211(1)	Ib/5(2)	FL 86	FL 245
No. of grains	3	3			3	10
SiO_2	56.61	56.91	55.84	54.16	57.72	54.83
TiO_2	0.05	0.10	0.02	0.06	0.02	0.05
Al_2O_3	0.80	0.32	3.06	5.37	0.50	1.41
Cr_2O_3	0.30	0.37	0.25	0.72	0.25	0.24
FeO	6.13	5.87	5.93	5.60	5.37	10.20
MnO	0.13	0.18	0.11	0.14	0.11	0.25
MgO	34.16	33.51	33.29	31.71	34.68	30.68
CaO	1.26	1.07	0.53	1.34	0.35	0.88
Total	99.44	98.33	99.09	99.19	99.00	98.54
Si	1.968	1.993	1.937	1.884	1.997	1.956
Al	0.032	0.007	0.063	0.116	0.003	0.044
Al	0.001	0.006	0.062	0.104	0.017	0.015
Ti	0.001	0.002	0.001	0.002	0.001	0.001
Cr	0.008	0.010	0.007	0.020	0.007	0.007
Fe	0.178	0.171	0.171	0.162	0.147	0.303
Mn	0.003	0.005	0.004	0.004	0.003	0.007
Mg	1.769	1.760	1.732	1.654	1.800	1.642
Ca	0.047	0.040	0.019	0.050	0.013	0.034
mg	91	91	91	91	92	84
Fs	8.93	8.68	8.90	8.68	7.50	15.31
Wo	2.35	2.03	0.99	2.68	0.66	1.72
En	88.72	89.29	90.11	88.64	91.84	82.97

(1) From amphibole lherzolite, Dreis, Stosch and Seck, 1980.
(2) From anhydrous lherzolite, Dreis, Stosch and Seck, 1980.

Group I, opx-rich sub group

Spinel lherzolite (FL 7) is dominated by coarse, strained and irregular to rounded olivines. Enstatite is coarse with straight to irregular boundaries and is typically associated with pale green endiopside of like habit. Small (average 0.1 mm diameter) bright green endiosides typically surround subhedral Cr-spinels and together with olivine neoblasts form granulate areas (compare with FL 15, Fig. 1). The rock is traversed by a band of isolated blebs (average 5 mm across) of endiopsides embayed by phlogopites. Occasionally both minerals have scalloped boundaries where they are coated by pale-brown glass.

Spinel lherzolite (E 48Y) from Meerfeld is a Group 1a xenolith (Stosch and Seck, 1980) with granuloblastic-equant texture typical of Dreis samples (Collée, 1963). Pargastic amphibole occurs in isolated 'vugs' enclosing lobate spinels and occasionally breaks down to bright-green diopside, Cr-spinel and pale-yellow glass (Seck and Reese, 1979). Rare phlogopite is interstitial to olivine.

Group I, opx-free sub group

Clinopyroxene–phlogopite dunite (FL 4) is composed of coarse olivines which are commonly irregular, strained and turbid with abundant fluid inclusions. Some are unstrained and clear with several planar faces. Blebs and stringers of small reddy brown phlogopite plates and diopside granules are associated with olivine neoblasts. Diopsides enclose sub-rounded Cr-spinels. Traces of dark brown glass commonly wet scalloped and etched grain boundaries of diopsides, phlogopites and olivine neoblasts indicating resorption of these minerals (Fig. 3).

Group II, feldspar-bearing

Hercynite to pleonaste–anorthite clinopyroxenite (FL 17). Coarse, irregular salite shows some development of planar faces and contains trains of fluid inclusions and spinel cuboids. The interfaces between salites and anorthites are typically vermicular and approach synplectic. Anorthites form interstitial plates whose borders poikilitically enclose and partially replace surrounding salites. Subhedral hercynite to pleonaste spinels display a range of conditions from where spinel is confined to the central portion of anorthite to where only a narrow, discontinuous rim of anorthite separates spinel from the surrounding salites. Thus this assemblage shows a sequence of replacements: salite by anorthite and anorthite by spinel.

Group II, phlogopite-bearing

Clinopyroxenite with trace phlogopite (FL 27) from Dreis is composed of coarse, anhedral salite with

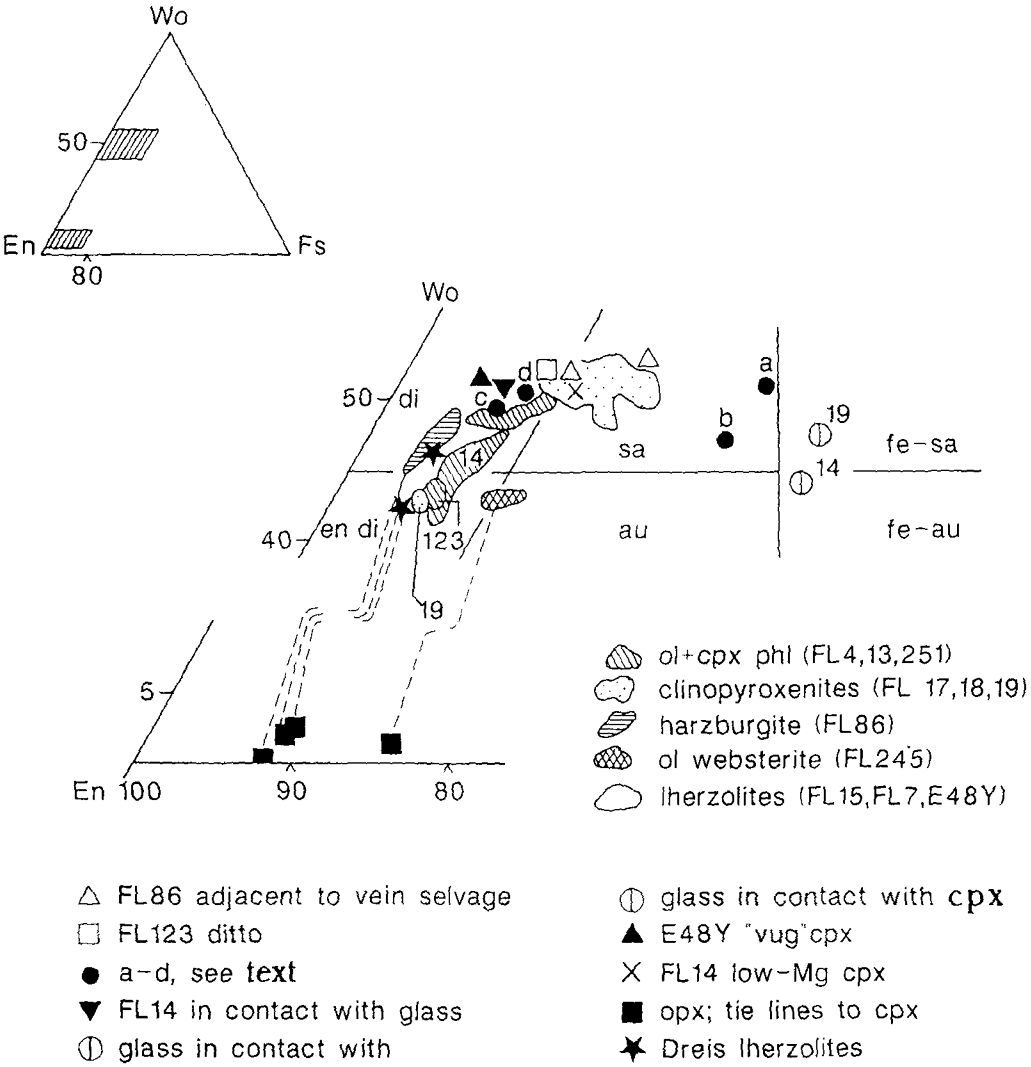

FIG. 4. Clinopyroxenes from Gees xenoliths plotted on the pyroxene quadrilateral (Poldervaart and Hess, 1951). Numbers: Gees samples (FL omitted, see Table 1); 14: High-Mg clinopyroxene from FL 14; 19: ditto from FL 19. Low-Mg clinopyroxenes from FL 19 plot as salite together with clinopyroxenes from the other clinopyroxenites. Abbreviations: en-di: endiopside; au: augite; fe-au: ferroaugite; sa: salite; fe-sa: ferrosalite; cpx: clinopyroxene; opx: orthopyroxene; ol: olivine, phl: phlogopite. Clinopyroxenes in Dreis lherzolites (Stosch and Seck, 1980), diopside from amphibole lherzolite, endiopside from anhydrous lherzolite.

corroded borders and trains of fluid inclusions. Red mica flakes occur in some sites of corrosion.

Analytical techniques

Mineral analyses were done at the Universities of Reading (FL 27, FL 86, FL 123, FL 251, FL 245) and Western Ontario (FL 15, FL 4, FL 13, FL 14, FL 18, FL 19, FL 17, FL 27, E 48Y) on JEOL 840 and JEOL 8600 model electron microprobes respectively. A 20 kV accelerating voltage and beam current of 10 nA was used for energy-dispersive analyses on the JEOL 840 model, whereas the JEOL 8600 model employed a 15 kV accelerating voltage and a 10 nA beam current for wavelength-dispersive analyses. Replicate analyses suggest that inter-laboratory correspon-

TABLE 6. Representative composition of clinopyroxenes from Gees xenoliths

Composition	Lherzolites:					Harzburgite:		^{5}Ol-rich wehrlite:		^{6}Cpx-^{7}phl dunite:	Phl wehrlites:	
No.	1	2	3	4	5	6	7	8	9	10	11	12
Sample	FL 15	FL 15 core	FL 15 core	FL 7	FL 7	FL 86 ^{4}adj^{3}sp	FL 86 edge	FL 123	FL 123 edge	FL 4	FL 14 high-Mg	FL 14 high-Mg
No. of grains	14	1,small	1,small	1,small,	1,large	4	1	9	1	9	12	1
SiO_2	54.30	53.72	55.04	53.15	53.48	51.93	46.48	53.42	49.54	50.43	53.17	52.20
TiO_2	0.12	0.02	0.06	0.40	0.18	0.08	2.88	0.48	1.60	0.94	0.52	0.18
Al_2O_3	1.32	0.71	1.42	1.40	1.04	3.13	7.25	1.39	4.09	4.53	1.48	1.74
Cr_2O_3	0.67	0.65	1.15	2.40	1.97	2.23	0.25	1.94	0.50	0.94	1.13	1.85
^{1}FeO	3.13	3.00	3.17	2.91	2.94	2.57	5.85	3.08	4.66	4.00	4.15	3.69
MnO	0.06	0.12	n.d.	0.18	0.19	0.09	0.06	0.16	0.01	0.09	0.22	0.12
MgO	18.34	18.16	17.95	17.07	17.38	15.74	12.53	16.88	14.39	15.00	17.26	16.72
CaO	21.37	23.08	21.00	19.82	19.69	21.84	23.91	20.16	24.43	23.71	21.12	21.27
Na_2O	0.70	0.53	0.71	1.15	1.49	0.52	^{2}n.d.	1.24	0.08	0.61	0.74	1.07
TOTAL	100.01	99.99	100.50	98.75	98.34	98.13	99.21	98.76	99.30	100.25	99.79	98.84
						Numbers of ions on the basis of 6 oxygens						
Si	1.976	1.960	1.982	1.957	1.975	1.925	1.737	1.965	1.843	1.890	1.946	1.935
Al	0.033	0.031	0.018	0.043	0.025	0.075	0.263	0.035	0.157	0.110	0.054	0.065
Al	0.023	0.000	0.042	0.018	0.020	0.74	0.056	0.025	0.023	0.079	0.010	0.011
Ti	0.003	0.001	0.002	0.011	0.005	0.001	0.081	0.013	0.045	0.025	0.014	0.005
Cr	0.019	0.019	0.033	0.070	0.057	0.065	0.007	0.056	0.014	0.026	0.033	0.054
Fe	0.095	0.092	0.095	0.090	0.088	0.080	0.183	0.094	0.145	0.119	0.126	0.114
Mn	0.002	0.004	0.000	0.006	0.006	0.003	0.002	0.005	0.000	0.003	0.007	0.004
Mg	0.996	0.988	0.963	0.937	0.957	0.870	0.698	0.931	0.798	0.800	0.948	0.924
Ca	0.829	0.902	0.810	0.782	0.779	0.871	0.957	0.794	0.974	0.903	0.828	0.845
Na	0.049	0.037	0.050	0.082	0.106	0.039	0.000	0.088	0.006	0.042	0.052	0.007
Fs	4.92	4.62	5.11	5.29	5.14	4.54	10.05	5.19	7.56	6.51	6.65	6.08
Wo	43.19	45.54	43.35	43.08	42.57	47.67	52.01	43.65	50.81	49.58	43.53	44.86
En	51.89	49.84	51.55	51.63	52.30	47.80	37.93	51.16	41.63	43.91	49.82	49.06
σ	26	38	36	54	56	33	2	49	8	12	34	42

1: Total Fe expressed as FeO; 2: n.d. = not detected; 3: sp = spinel; 4: adj = adjacent; 5: ol = olivine; 6: cpx = clinopyroxene; 7: phl = phlogopite

dence for all minerals involved is highly acceptable.

Results: Group I xenoliths

Unaltered mantle assemblage

Olivines have Mg/(Mg + Fe_{Total}) (*mg*) values that correlate positively with the proportion of olivine + orthopyroxene in the samples, decreasing with increasing amounts of clinopyroxene + phlogopite (Tables 2 and 3). There is no significant intra-xenolith variation in olivine composition and coarse olivines cannot be differentiated in terms of chemistry (*mg* and minor Ca, Mn, Ni) from adjacent neoblasts (Table 4). In the harzburgite (FL 86) both rounded olivines and those with planar faces are of identical composition which is also indistinguishable from the olivine granules that occur together with clinopyroxene in reaction fringes to enstatite.

Orthopyroxenes: Enstites in lherzolite (FL 15) and harzburgite (FL 86), and bronzites in olivine websterite (FL 245) have *mg* slightly higher than that of the co-existing olivines (Table 3). In FL 7, however, *mg* enstatite ≃*mg* olivine which suggests re-equilibration post co-crystallisation of these two phases. This is consistent with the observation that primary and secondary clinopyroxenes in FL 7 are indistinguishable in terms of chemistry (see *Clinopyroxenes*, below).

The wollastonite component in enstatite from lherzolite (FL 15) is slightly higher than that in enstatite from lherzolite (FL 7) (Table 5, analysis nos. 1, 2; Fig. 4) although the endiopsides in the

TABLE 6. Continued

Composition	Phl wehrlites:					Phl clinopyroxenite		Sp-[8]an clinopyroxenite
No.	13	14	15	16	17	18	19	20
Sample	FL 14 high-Mg	FL 14 low-Mg	FL 14 adj glass	FL 13	FL 251	FL 19 low-Mg	FL 19 high-Mg	FL 17
No. of grains	1	2	1	15	4	12	2	5
SiO_2	52.82	46.92	49.65	50.43	49.84	46.04	54.53	48.14
TiO_2	0.72	0.59	1.85	0.85	1.16	2.19	0.16	0.58
Al_2O_3	1.90	8.32	4.92	3.76	4.28	6.89	1.35	7.65
Cr_2O_3	0.66	0.10	0.44	0.62	0.56	0.02	0.96	0.09
FeO	4.49	6.70	4.30	4.91	4.79	8.18	3.20	7.35
MnO	0.15	0.10	0.01	0.13	0.05	0.12	0.13	0.15
MgO	16.75	12.57	14.85	14.90	14.53	11.68	18.25	12.88
CaO	22.71	24.42	25.20	24.02	23.11	23.46	21.16	24.23
Na_2O	0.83	0.17	n.d.	0.57	0.63	0.88	0.87	0.25
TOTAL	101.03	99.89	101.25	100.19	98.95	99.46	100.61	101.32
	Numbers of ions on the basis of 6 oxygens							
Si	1.922	1.755	1.816	1.864	1.859	1.749	1.967	1.777
Al	0.078	0.245	0.184	0.136	0.141	0.251	0.033	0.223
Al	0.004	0.121	0.028	0.028	0.047	0.057	0.024	0.109
Ti	0.020	0.017	0.051	0.024	0.032	0.062	0.004	0.016
Cr	0.019	0.003	0.013	0.018	0.017	0.001	0.027	0.003
Fe	0.137	0.209	0.132	0.151	0.149	0.259	0.096	0.226
Mn	0.005	0.003	0.000	0.004	0.002	0.004	0.004	0.005
Mg	0.909	0.705	0.809	0.826	0.813	0.665	0.981	0.713
Ca	0.886	0.979	0.987	0.951	0.924	0.955	0.818	0.958
Na	0.059	0.012	0.000	0.041	0.046	0.065	0.060	0.018
Fs	7.08	11.03	6.82	7.84	7.89	13.78	5.10	11.92
Wo	45.86	51.70	51.20	49.32	48.99	50.81	43.14	50.50
En	47.06	37.26	41.98	42.84	43.12	35.41	51.77	37.58
cr	19	1	6	10	8	-	33	1

8: an = anorthite

latter have an equal, or marginally higher enstatite component than the former. Exsolution of diopside was not observed in these enstatites (nor vice-versa) but it cannot be assumed that 'deep-source pyroxenes have not expelled part of their diopside or enstatite components' (Brown *et al.*, 1980). Energy dispersive microprobe analyses of Ca in FL 7 enstatites are not sufficiently accurate to use this minor element for quantitative geothermometry. However, the CaO contents of Gees lherzolite enstatites are very similar to those of enstatites which co-exist with endiopside in Dreis lherzolites lacking amphibole (Type 1b, Table 5, analysis 4) and which are considered to have equilibrated at 1100–1150 °C (Stosch and Seck, 1980).

In harzburgite (FL 86), diopside is a reaction product (see *Harzburgites*) and was not coprecipitated with enstatite which, in this xenolith, has a relatively low wollastonite component (Table 5, analysis 5).

Clinopyroxenes. Coarse endiopsides in lherzolite (FL 15) have lower 100 Cr/(Cr + Al) (*cr*) values than the small secondary endiopsides which frequently enclose Cr-spinels. Otherwise the primary mantle (?) clinopyroxenes (see *Petrography: Unaltered mantle assemblage*) cannot be recognised in terms of chemical composition: En, Wo, Fs and minor Ti, Ca, Mn, Na (Table 6, analysis nos. 1, 2, 3). However the secondary grains display a wider range of wollastonite content, some plotting just inside the diopside field (Table 6, analysis 2). In lherzolite (FL 7) the two generations of clinopyroxene are indistinguishable in terms of *cr*, wollastonite content or any other chemical parameter (Table 6, analysis nos. 4, 5).

In herzburgite (FL 86) the diopside granules which fringe enstatite show significantly lower *m g* than co-existing olivine and enstatite. These features are consistent with a reaction that proceeded at a lower temperature than the equilibration of the primary mantle minerals in the Group I, opx-rich xenoliths. Olivine microlites in the reaction fringe, however, appear to have re-equilibrated with the primary coarse olivine (see *Olivines*, above).

Effects of veining in Group I xenoliths: introduction of clinopyroxene and phlogopite

Vein minerals are clinopyroxenes and phlogopites and point to infiltration of original clinopyroxene-poor, harzburgitic (Group I, opx-rich) and dunitic (Group I, opx-free) mantle by Ca- and K-rich silicate (?) melts. Veins and stringers are one mineral grain or, a few grains wide (Figs. 1 and 3) and local chemical alteration of vein-wall minerals has been identified only adjacent to glass.

The vein minerals are in equilibrium with their host silicates in terms of *m g* (Table 3), which may be a function of resorption by small volume melts of the high-Mg, primary mantle minerals. The Group I xenoliths whose silicates have lowest *m g* levels are opx-free and show the highest proportion of clinopyroxene-rich areas (pervasive alteration) and phlogopite veining (FL 13, FL 251).

Two xenoliths, phlogopite wehrlite (FL 14) (Group I, opx-free) and phlogopite clinopyroxenite (FL 19) (Group II), contain small populations of clinopyroxenes with anomalous *m g* which are in disequilibrium with the other phases (Table 3). In FL 14 the majority of the clinopyroxenes are Cr-rich endiopsides-diopsides (Fig. 4) (Table 6, analysis 11) while two analysed grains prove to be Al-rich and Cr-poor salites (Fig. 4, low-Mg group) (Table 6, analysis 14). In FL 19 a small population (2 grains analysed) of endiopsides (Fig. 4, high-Mg group) (Table 5, analysis 19) occurs with Ti- and Al-rich salites (Fig. 4) which form the bulk of the xenolith clinopyroxene (Table 6, analysis 18). In both FL 14 and FL 19 the anomalous, disequilibrium clinopyroxenes cannot be distinguished petrographically. Their location and further investigation is required, however it is feasible that the low-Mg clinopyroxenes in FL 14 are part of a small vein of low-Ti, high-Al salite similar to that of Group II, feldspar clinopyroxenite (FL 17) (Fig. 5; Table 6, analysis 20). The high-Mg clinopyroxenes in FL 19 are likely a relict or clast of clinopyroxenes from Group I xenolith material (Fig. 4).

Vein diopside in dunite (FL 4), which occurs together with substantial amounts of vein phlogopite (Table 2), is notably richer in Ca than clinopyroxenes in the other olivine-rich, opx-free assemblages (FL 123) and (FL 14) (compare 8, 10 and 11, Table 6). FL 4 diopsides plot together with diopsides from wehrlites (FL 13) and (FL 251) (Fig. 4) which both have diopside-rich areas that are extensively veined by phlogopite. Thus the more Ca-rich clinopyroxenes in Group I, opx-free xenoliths are likely related to the introduction of phlogopite. Wehrlite (FL 14) which has few veins and minor phlogopite contains more magnesian clinopyroxenes which are remarkable for their range in composition (Fig. 4). The clinopyroxenes from wehrlites (FL 14), (FL 13) and (FL 251) have a pervasive distribution and are described further under *Pervasive alteration in Group I xenoliths* (below).

Clinopyroxenes in xenoliths of the opx-free sub-group have higher Ti and Ti : Al contents than those of the opx-rich sub-group. Diopsies in the phlogopite-rich veins of dunite (FL 4), and in the wehrlites substantially veined by phlogopite, tend to show the greatest, though variable, enhancement in Ti (Fig. 5) and conversely the lowest Cr and *cr* contents of the Group I clinopyroxenes (Table 6, analyses 9, 16 and 17). When their Ti : *m g* values are considered they are found to plot within the field of Cr-diopside series xenoliths as defined by Wass (1979, Fig. 2). In terms of $Al^{VI}:Al^{IV}$ (ions per formula unit), however the clinopyroxenes in xenoliths substantially veined by phlogopite plot with marginally lower $Al^{vi}:Al^{iv}$ than those from Cr-diopside series xenoliths. A proportion fall within the field of Al-augite series xenoliths and megacrysts (Wass, 1979, Fig. 3).

Vein phlogopites are titaniferous with fairly restricted Ti contents (Table 7). In xenoliths where phlogopites enclose or are in close proximity to vein spinel, Cr contents are relatively high (Table 7, analyses 1, 4).

TABLE 7. Composition of phlogopites from Gees xenoliths

Composition	Lherzolite	Cpx-Phl dunite	Phl wehrlites				Phl clinopyroxenites	
No.	1	2	3	4	5	6	7	8
Sample	FL 7 adj sp	FL 4	FL 14	FL 14 adj sp	FL 13	FL 251	FL 18	FL 19
No. of grains	1	8	9	1	9	2	8	6
SiO_2	39.38	38.27	38.46	38.39	38.11	37.15	37.47	36.77
TiO_2	4.12	3.63	5.31	5.54	3.85	4.05	3.86	4.18
Al_2O_3	13.26	15.92	14.58	14.06	15.92	15.86	16.91	16.65
Cr_2O_3	2.65	1.02	0.82	2.21	0.63	0.72	0.16	0.15
[1]FeO	3.92	6.61	7.03	6.45	8.41	7.33	9.87	12.24
MnO	[2]n.d.	0.09	0.09	0.08	0.07	0.07	0.10	0.12
MgO	21.69	20.25	19.23	19.42	19.47	19.66	18.12	16.07
CaO	0.44	n.d.	n.d.	n.d.	n.d.	0.26	0.04	0.02
BaO	[3]n.a.	0.70	0.96	0.90	0.64	n.a.	0.82	0.88
Na_2O	0.24	0.28	0.49	0.40	0.26	0.33	0.40	0.49
K_2O	10.69	10.18	9.84	9.96	10.28	10.16	9.40	9.20
TOTAL	96.39	96.95	97.14	97.41	97.64	95.59	97.15	96.77

Numbers of ions on the basis of 22 oxygens

Si	5.596	5.460	5.516	5.481	5.442	5.378	5.391	5.377
Al	2.217	2.540	2.464	2.365	2.558	2.622	2.609	2.623
Al	0.000	0.138	0.000	0.000	0.120	0.080	0.290	0.246
Ti	0.439[4]	0.389	0.572[5]	0.595[6]	0.413	0.440	0.418	0.460
Cr	0.297	0.115	0.092	0.249	0.071	0.082	0.018	0.017
Fe	0.464	0.789	0.843	0.770	1.005	0.884	1.188	1.497
Mn	n.d.	0.011	0.010	0.010	0.008	0.009	0.012	0.015
Mg	4.624	4.306	4.111	4.132	4.144	4.270	3.886	3.502
Ca	0.067	n.d.	n.d.	n.d.	n.d.	0.040	0.005	0.004
Ba	n.a.	0.039	0.540	0.050	0.036	n.a.	0.046	0.051
Na	0.067	0.078	0.135	0.111	0.071	0.092	0.110	0.139
K	1.939	1.853	1.800	1.814	1.871	1.878	1.724	1.715
cr	12	4	4	10	3	3	1	1

1: Total iron expressed as FeO; 2: n.d. = not detected; 3: n.a. = not analysed; 4: 0.187 Ti ions needed to complete Z site occupancy; 5: 0.020 Ti ditto; 6: 0.154 Ti ditto

Abbreviations as for Table 6

Cr-spinels (Table 8) in Group I xenoliths lacking substantial phlogopite veining, and excluding olivine websterite (FL 245), are the more magnesian and have 100. $Fe^{3+} : (Fe^{3+} + Al + Cr)$ (*fe*) of <25 which is consistent with spinels in peridotites (Irvine, 1967; Conrad and Kay, 1984). In the opx-free, Group I xenoliths substantially veined by phlogopite, spinels are generally more iron-rich and have *fe* values which are close to, or exceed 25, with the exception of a core of a zoned spinel in FL 4 (analysis 8, Table 8).

Group I xenoliths substantially veined by phlogopite are all of the opx-free sub-group and contain more aluminous Cr-spinels and clinopyroxenes which have lower *cr* contents (Tables 6 and 8, analyses 9, 16, 17 and 5, 9, 10 respectively).

TiO_2 in spinels from the opx-rich, Group I xenoliths, with the exception of olivine websterite

TABLE 8. Composition of Cr-spinels from Gees xenoliths

Composition	Lherzolites		Harzburgite	Ol-rich wehrlite	Phl-cpx dunite			Phl wehrlite
No.	1	2	3	4	5	6	7	8
Sample	FL 15	FL 7	FL 86	FL 123	FL 4 unzoned	FL 4 core	FL 4 rim	FL 14
No. of grains	5	6	3	2	9	1		5
SiO_2	n.a.	0.27	n.d.	0.29	n.a.	n.a.	n.a.	n.a.
TiO_2	0.84	1.30	0.10	2.07	3.07	1.16	2.91	4.30
Al_2O_3	10.89	7.35	18.14	7.76	19.72	10.35	18.82	8.40
Cr_2O_3	54.01	56.09	45.49	54.46	27.27	49.69	29.52	41.50
$^1FeO_3$	10.39	6.39	17.94	5.92	21.02	6.17	19.00	12.33
^1FeO	12.52	14.29	12.74	16.26	17.80	21.84	17.78	19.44
MnO	1.11	0.27	0.16	0.22	0.78	1.21	0.72	n.a.
MgO	12.97	12.47	13.99	12.01	12.96	11.10	12.58	10.83
CaO	n.a.	0.14	0.05	0.19	n.a.	n.a.	n.a.	n.a.
TOTAL	102.73	98.57	97.89	99.18	102.62	101.52	101.33	96.80
^{2}*mg*	65	61	66	57	57	48	56	50
^{3}*cr*	77	84	63	83	48	76	52	77
^{4}*fe*	12	8	10	8	26	8	24	18

1: ferric and ferrous iron determined assuming an ulvospinel basis; 2: 100.Mg/(Mg+Fe); 3: 100.Cr/(Cr+Al); 4: $100Fe^{3+}/(Fe^{3+}+Al+Cr)$.
Abbreviations as for Table 6

(FL 245), is less than 2 wt.% but ranges from 2.07–6.71 wt.% in the opx-free sub-group. The highest TiO_2 values occur in spinels from wehrlites (FL 13) and (FL 251) (Table 8, analyses 9, 10) which are rich in phlogopite veins.

Summary. Group I xenoliths substantially veined by phlogopite are opx-free. Their clinopyroxenes are relatively enhanced in Fe, Ca and Ti and decreased in *mg* and *cr*, and their Cr-spinels follow a similar pattern: relatively enrichment in Ti and *fe* together with depletion in *mg* and *cr*. The levels of Ti:*mg* in their clinopyroxenes are characteristic of the Cr-diopside suite (Group I of Frey and Prinz, 1978) but $Al^{VI}:Al^{IV}$ values in the clinopyroxenes are appropriate for the Al-augite suite (Group II of Frey and Prinz, 1978).

Effects of glass veining on clinopyroxene composition

Changes in clinopyroxene composition occur in contact with vein-selvage glasses in two Group I xenoliths, one an opx-rich type (harzburgite FL 86) and the other an opx-free type (clinopyroxene dunite, FL 123). In addition two small (*c.* 50 μm across) zoned clinopyroxenes, protruding into vein glass, were identified by electron backscatter imagery within phlogopite wehrlite (FL 14) (Group I, opx-free) and phlogopite clinopyroxenite (FL 19) (Group II). In the Group I xenoliths, the outer zones of clinopyroxenes in contact with vein-selvage glasses and the clinopyroxene microlite protruding into intra-xenolith vein glass, are all diopsides similar in Ti, Al and Cr content (Fig. 5; Table 6, analysees 7, 9, 15). They show decreased Mg (Fig. 4) and Cr (Table 6, analyses 7, 9, 15) and enhanced Ti and Al (Fig. 5) compared with the clinopyroxenes of their host xenoliths.

Group II clinopyroxenes are salites, but the subhedral outer zone of the microlite protruding into vein glass in phlogopite clinopyroxenite (FL 19) is diopside of variable Ti and Al contents (Fig. 5) and has a composition close to that of Group I clinopyroxenes in contact with glass (*c, d* in Figs. 4 and 5).

Thus veining by glass results in clinopyroxenes of similar composition in both Groups I and II xenoliths. Both intra-xenolith and selvage glasses in the Gees xenoliths vary in composition but share a similar signature of high alkalis plus Ti, moderate to high Al together with low Mg and low to moderate Fe and Ca (Edgar *et al.*, 1989).

The intra-xenolith vein glasses in wehrlite (FL 14) (Group I, opx-free) and clinopyroxenite (FL 19) (Group II), when recalculated in terms of pyroxene end-member molecules (Fig. 4), are in the ferroaugite field and it is unlikely that these glasses were in equilibrium with the diopside microlites that protrude into them. The compositions of the Gees xenolith glasses do not appear to be compatible with the suggestion that they represent the residue of a melt from which these clinopyroxenes crystallised (Edgar *et al.*, 1989). Interaction between this melt and the host xenoliths could be responsible. A probable exception to this is the anhedral centre zones of FL 19 clinopyroxene microlite which approach ferroaugite (*a, b* in Fig. 4) and zone a has high Ti and Al (Fig. 5) which is a feature of the glass (Edgar *et al.*, 1989). It is likely that the centre of this small grain is the product of crystallisation, together with partial resorption, from the melt now represented by glass.

Pervasive alteration in Group I (opx-free) xenoliths

In the wehrlites (FL 14, FL 13, FL 251) clinopyroxenes have a pervasive distribution and show considerable compositional variation: mainly intergrain variation in FL 14 (Table 6, analyses 12, 13) and largely attributable to zoning in FL 13. Variation is marked in levels of Ti, Al (Fig. 5) and Cr (Table 6) but is also visible in Mg, Fe and Ca contents (Fig. 4). The effects of veining by phlogopite (*Effects of veining in Group I xenoliths*, above) and glass (*Effects of glass veining on clinopyroxene composition*, above) on clinopyroxene chemistry have been described, and the range in *cr* for FL 14 clinopyroxenes can be attributed to their degree of proximity to Cr-spinels. The wehrlite clinopyroxenes are considered to have crystallised from permeating Ca-rich melts which interacted with the original xenolith mineralogy, namely olivine and spinel, and clinopyroxene crystallisation overlapped with the invasion of phlogopite-precipitating melts which were closely followed by the alkali-felsic melts now represented by glass (Edgar *et al.*, 1989). The heterogeneity of wehrlite clinopyroxenes is likely, then, to be a consequence of crystallisation under the influence of local (micro-scale) chemical conditions which changed during the events described.

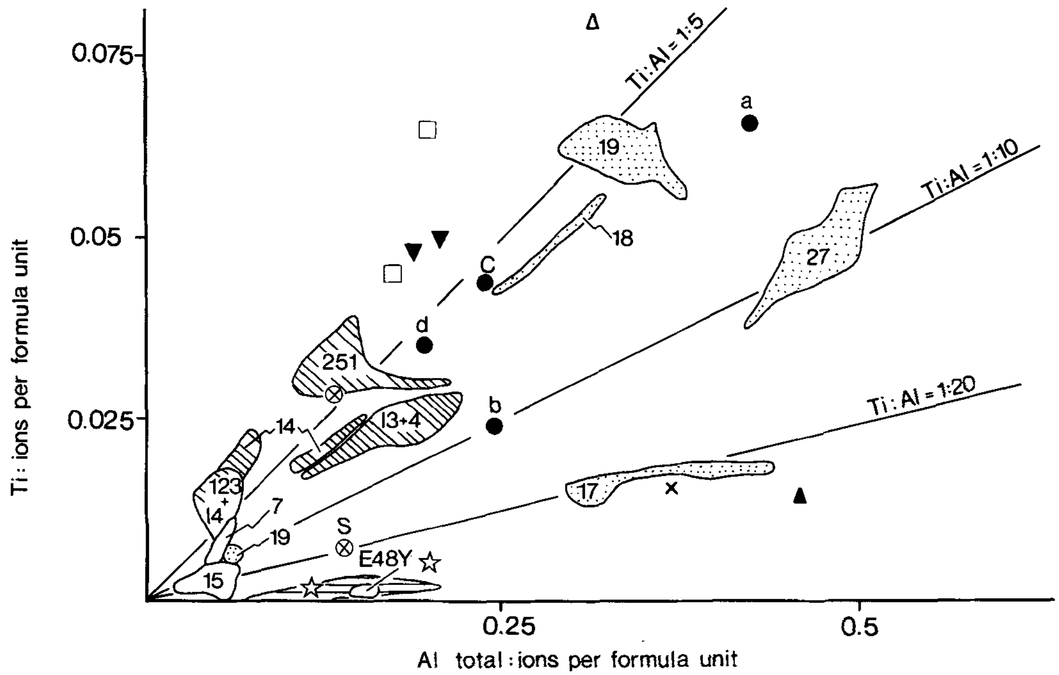

FIG. 5. Ti *vs.* Al for clinopyroxenes. Numbers, symbols and ornamentation of composition fields as for Fig. 4. Smaller 19 field: high-Mg clinopyroxenes from FL 19. More Ti-rich cpx from 245 adjacent to olivine, less Ti-rich adjacent to spinel. 17: spinel-anorthite clinopyroxenite from Dreis; 27: clinopyroxenite from Dreis. Spinel lherzolite clinopyroxene with higher Al and Ti from anhydrous sample, the other from amphibole-bearing sample (Stosch and Seck, 1980; Table 3). Abbreviations of minerals names as for Fig. 4.

Results: Group II xenoliths

Phlogopite clinopyroxenite

There is a compositon 'gap' in terms of Ti, Al and Cr between clinopyroxenes in Group I assemblages and those in Group II phlogopite clinopyroxenites (Fig. 5; Table 6). In addition, Ti-spinels are found in Group II xenoliths but Cr-spinels occur in Group I xenoliths. Thus the chemistry of the clinopyroxenes and spinels does not support the hypothesis: namely that Group II phlogopite clinopyroxenites are the end-products of pervasive introduction of clinopyroxene, coupled with substantial phlogopite veining, in Group I dunitic xenoliths.

Evidence from other localities

Group I, opx-rich xenoliths

Gees lherzolite clinopyroxenes plot between diopside in Dreis amphibole lherzolite and endiopside in Dreis anhydrous lherzolite (Fig. 4) (Stosch and Seck, 1980). Meerfeld amphibole–phlogopite lherzolite (E 48Y) contains diopside comparable to that in Dreis amphibole lherzolite. Diopside in the latter coexists with orthopyroxene that has a lower wollastonite component than orthopyroxene in the anhydrous lherzolites. Pyroxene geothermometry yields an equilibration temperature of 950 °C for the amphibole lherzolite which is 200 °C below that obtained for anhydrous lherzolite (Stosch and Seck, 1980). Pyroxene geochemistry and the absence of amphibole indicates that Gees lherzolites equilibrated at higher temperatures than the Meerfeld lherzolite and the Dreis amphibole lherzolite, but probably not in excess of 1150 °C calculated for anhydrous lherzolites from Dreis.

Clinopyroxenes from Meerfeld and Dreis lherzolites are richer in Al than those from Gees, and they are consistently Ti-poor. The low Al levels of Gees lherzolite clinopyroxenes, which are also seen in orthopyroxenes and spinels from Gees lherzolites (Table 5, analyses 1, 2; Table 8, analyses 1, 2), could be a feature of infiltration by K-rich melts. Clinopyroxenes crystallised from such melts are characterised by low Al (Edgar *et al.*, 1976) and K mafic rocks tend to be poorer in Al than their sodic counterparts (Lloyd, 1972). Gees lherzolite (FL 7), which contains trace phlogopite, has clinopyroxenes that are relatively Ti-enhanced compared with those of Meerfeld and Dreis lherzolites (Fig. 5), and enrichment in Ti and Ti : Al in clinopyroxenes of Gees Group I xenoliths has been shown to be associated with the introduction of phlogopite (*Effects of veining in Group I xenoliths*, above). By contrast, the secondary clinopyroxenes in Meerfeld lherzolite (E 48Y), that are interpreted as a breakdown product of pargasitic amphibole ($Na_2O > K_2O$) (Stosch and Seck, 1980), are strongly enhanced in Al coupled with weak Ti increase ($Ti : Al < 1 : 20$) (Fig. 5) when compared with the clinopyroxenes of the host xenolith.

Group II, clinopyroxenite from Dreis

This xenolith (Fl 27) is comprised from Al-rich salites with Ti : Al ratios *ca.* 1 : 10 (Fig. 5). The salites occur with trace phlogopite, and although the relationship between this Dreis Group II xenolith and Dreis lherzolites is unclear it illustrates the connection between Ti-enrichment of clinopyroxene and the presence of phlogopite.

Discussion

The development of mantle heterogeneity at Gees

Original 'mantle' at Gees is harzburgite with trace clinopyroxene, and has an Al-poor signature which distinguishes it from comparable material (clinopyroxene-poor lherzolites) at Dreis and Meerfeld.

Clinopyroxene enrichment in Group I xenoliths is evident in both opx-rich and opx-free types. In harzburgite this process has occurred at the expense of orthopyroxene, and, by inference, the opx-rich xenoliths can be linked to the opx-free series by the reaction of enstatite to clinopyroxene + olivine recorded in harzburgite. This reaction could be evidence for a metasomatising ephemeral carbonatite melt: calcium carbonate + enstatite = olivine + diopside + CO_2. Green and Wallace (1988) show experimentally that a sodic, dolomitic melt which infiltrates pargasite lherzolite at P 21 kbar and T 950–1050 °C can effect such a de-carbonation reaction, and the rare presence of magmatic carbonate in Eifel volcanism has been documented (Lloyd and Bailey, 1969). However, the more likely agent was a Ca- and alkali-bearing hydrous silicate melt, as evidenced by the presence of an alkali- and silica-rich glass coating spinels, which together with olivine and diopside, form a reaction fringe to enstatite in harzburgite (FL 86).

There is no evidence in the lherzolites for reaction of enstatite to olivine + diopside, and lherzolite enstatite is in equilibrium with 'original' clinopyroxene. Secondary clinopyroxene has been added to the lherzolites by precipitation from interpenetrating Ca-rich silicate melts and such melts have also veined the dunities (opx-free, dunite–wehrlite series) with clinopyroxene.

In the wehrlites, clinopyroxene grains have a more pervasive distribution and they occur in areas of recrystallised olivine, and phlogopite preferentially veins the clinopyroxene-rich areas. Thus clinopyroxene in the wehrlites crystallised from a permeating Ca-rich silicate melt, which was closely followed by a phlogopite-precipitating melt (see *Phlogopite enrichment in Group I xenoliths,* below).

The secondary clinopyroxenes in all Group I xenoliths preferentially enclose lobate to subhedral spinels and there is a positive relationship between *cr* clinopyroxene and *cr* spinel. In the wehrlites spinels and clinopyroxenes are more aluminous than those in the dunites (Tables 6 and 8) and it is unlikely that consumption of spinel provided Al for clinopyroxene and phlogopite formation in the wehrlites. In peridotite xenoliths the common location of spinels at triple junctions and between grain boundaries is well documented (e.g. Mercier and Nicholas, 1975). It is considered to be a consequence of recrystallisation which in the Gees xenoliths is likely to have accompanied the introduction of Ca-rich melts and the precipitation of clinopyroxene.

Phlogopite enrichment in Group I xenoliths closely follows the infiltration of clinopyroxene and provides evidence for the introduction of a Ti-, Al- and K-rich, hydrous silicate melt into Group I xenoliths. This process is best developed in the opx-free, dunite–wehrlite xenolith series and is associated with a significant decrease in *m g* of the wehrlite silicates (Table 3). Early precipitations of clinopyroxene suggests a high Ca activity in the melt which together with continued clinopyroxene crystallisation becomes enriched in Al and K as indicated by the later crystallisation of phlogopite. Clinpyroxene composition was affected by decreasing concentrations of Mg and Cr, and increasing levels of Ti and Al in the melt. Evidence for replacement of clinopyroxene and olivine by phlogopite is rare and introduction of this mineral is almost entirely by interpenetration.

Group II xenoliths: phlogopite clinopyroxenites

One interpretation of this assemblage is that it represents a facies of Ca- and K-bearing melt activity in channel-ways already lined by previously precipitated clinopyroxene and phlogopite. The compositions of such melts would be 'insulated' from mantle dominated by olivine and Cr-spinel.

Olivine websterite

Olivine websterite (FL 245), has a distinctive, relatively Fe-rich and Ca-poor signature (see composition of (i) clinopyroxenes, Fig. 4; (ii) orthopyroxenes, Table 5). There is no relationship between this and other Gees Group I, opx-rich assemblages, apart from the petrographic identification of orthopyroxene reacting to clinopyroxene + olivine which is similar to that recorded for harzburgites, and implies that this websterite has been subject to mantle processes comparable to those identified in other Gees material.

Conclusions

The petrography and clinopyroxene chemistry of Gees lherzolites are consistent with an origin as spinel harzburgites (<5% clinopyroxene), which were subsequently clinpyroxene-enriched by the activity of an infiltrating Ca- and alkali-rich silicate melt, rather than an ephemeral carbonatite melt. This process was likely concommitant with the young uplift of the Rhenish Shield (Stosch and Seck, 1980).

Furthermore opx-free, dunitic mantle beneath Gees has been invaded by Ti-, Al-, Ca- and K-bearing hydrous silicate melts which have transformed dunite into phlogopite-wehrlite. These opx-free, Group I xenoliths can be linked, by inference, to the opx-rich, Group I assemblages via the reaction of enstatite to diopside + olivine which is seen in Gees harzburgite.

The absence of amphibole in all xenoliths may imply that the Gees samples are from deeper mantle than that represented by Dreis and Meerfeld lherzolites. Alternatively, amphibole and phlogopite enrichment may represent distinct mantle events (Kempton *et al.*, 1988).

Alteration of clinopyroxenes in contact with interstitial and selvage glasses, results in clinopyroxenes of similar composition in a variety of Gees xenolith assemblages. This implies the later penetration of heterogeneous mantle by alkali-rich, felsic melts which are now represented by the glasses (Edgar *et al.*, 1989).

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