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ORIGIN OF GLASS IN QUATERNARY MANTLE XENOLITHS FROM MEERFELDERMAAR, WEST EIFEL, GERMANY: IMPLICATIONS FOR ENRICHMENT IN THE LITHOSPHERIC MANTLE

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ABSTRACT

Intraxenolith glasses from twenty-eight mantle-derived spinel-bearing lherzolite, olivine clinopyroxenite, wehrlite, and olivine websterite xenoliths from the Quaternary mafic–ultramafic ash and pyroclastic rocks from Meerfeldermaar, West Eifel, Germany have been petrographically examined and chemically analyzed. On the basis of Al and Cr contents of clinopyroxene in these xenoliths, the majority are Group-I metasomatized types. The abundance of glass is variable. Small amounts of pargasitic amphibole, phlogopitic mica and spinel are associated with glass. Glass occurs along grain boundaries, in pools and vugs, and occasionally as inclusions in spinel. Widely variable compositions of glass depend on their associated minerals and xenolith type. Glasses are not directly related to the host magma. Microlitic olivine grains in the glass are not in equilibrium with melt or fluid. Similarly, the glass cannot be a partial melt of mineral assemblages of the xenoliths, and is an unlikely products of decompression melting of hydrous minerals. In the suite of glass compositions, Ca, Fe and Ti decrease with increasing SiO_2, but there is no correlation between Mg and SiO_2, suggesting that these bodies of glass have a common origin as "frozen" melts or fluids that migrated through the upper mantle and produced the enrichment in the source regions for the kamafugitic magmas. The degree of enrichment of the suite of xenoliths at Meerfeldermaar is not as pronounced as at Gees, only 12 km away, suggesting that metasomatic enrichment was variable within the subcontinental lithosphere underlying this area.

Keywords: glass, mantle xenoliths, metasomatism, Meerfeldermaar, Gees, West Eifel, Germany.

SOMMAIRE

Nous avons analysé le verre qui se trouve à l'intérieur de vingt-huit xénolithes mantelliques de lherzolite à spinelle, de clinopyroxénite à olivine, de wehrlite et de websterite à olivine, découverts dans des cendres mafiques et ultramafiques, et des roches pyroclastiques associées, à Meerfeldermaar, dans le secteur ouest de l'Eifel, en Allemagne. D'après la teneur en Al et Cr du clinopyroxène de ces xénolithes, la majorité de ceux-ci font partie du Groupe I, et sont métasomatisés. La proportion de verre y est variable. Lui sont associés de petites quantités d'amphibole pargasitique, de phlogopite et de spinelle. Le verre se trouve en liserés le long des grains, en amas et dans des cavités ou, plus rarement, inclus dans le spinelle. Les compositions très variables du verre dépendent de la composition des minéraux associés et du type de xénolithe. Le verre ne semble pas lié au magma responsable de la montée des xénolithes. Les microgermes d'olivine dans le verre ne sont pas en équilibre avec le liquide ou une phase fluide. De même, le verre ne pourrait s'être formé par fusion partielle de l'assemblage des minéraux des xénolithes, et non plus par fusion des minéraux hydratés lors de la décompression. Dans tous les cas, le verre montre une diminution des teneurs en Ca, Fe et Ti avec augmentation de SiO_2, mais ne montre aucune corrélation entre teneurs en Mg et en SiO_2, ce qui fait penser qu'il s'agit de liquides "figés" ou fluides en migration dans le manteau supérieur, responsables de l'enrichissement géochimique dans les régions d'où viennent les magmas kamafugitiques. Le degré d'enrichissement indiqué dans la suite de xénolithes à Meerfeldermaar n'atteint pas celui que nous voyons à Gees, seulement 12 km plus loin, ce qui témoignerait de la variabilité de l'intensité de l'enrichissement métasomatique dans le manteau subcontinental sous cette région.

(Traduit par la Rédaction)

Mots-clés: verre, xénolithes mantelliques, métasomatose, Meerfeldermaar, Gees, Eifel, Allemagne.

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INTRODUCTION

Metasomatic processes occur in the continental lithospheric mantle and enrich sources that are subsequently partially melted to give a wide range of magmas with abundant incompatible and LIL (large-ion lithophile) elements (*cf.* Menzies & Hawkesworth 1987, Lloyd 1987, Peccerillo & Foley 1992). Evidence of such process of enrichment in the mantle is based on petrography and mineralogy of mantle xenoliths (Bailey 1982, Lloyd 1987), experiments at mantle pressures (*cf.* Edgar & Vukadinovic 1992) and isotope geochemistry (*cf.* Menzies & Hawkesworth 1987). From these studies, the nature of the metasomatizing melts or fluids may be inferred.

Edgar *et al.* (1989) proposed that intraxenolith silicate glass from six different types of mantle xenoliths from Gees, West Eifel, Germany represent "fossil" melts or fluids that migrated through the mantle and were responsible for its heterogeneity. Similar proposals for the origin of glass from other xenolith localities have been suggested (Gamble & Kyle 1987, Lloyd *et al.* 1991, Schiano & Clocchiatti 1994, Schiano *et al.* 1994). This study compares the glass in mantle-derived xenoliths at Meerfeldermaar with the glass in xenoliths at Gees, 12 km northeast of the site of the present study, in the West Eifel region (Edgar *et al.* 1989, Lloyd *et al.* 1991, Fenwick 1991).

The Quaternary (<0.7 Ma) alkaline mafic–ultramafic lavas and pyroclastic rocks of the West Eifel consist principally of kamafugite (*cf.* Foley *et al.* 1987) and host a wide variety of mantle xenoliths from about 240 eruptive centers within a restricted area (Frechen 1948, 1963, Lloyd & Bailey 1975, Stosch & Seck 1980, Lloyd 1987, Edgar *et al.* 1989, Lloyd *et al.* 1991). These xenoliths consist of depleted anhydrous lherzolite (Stosch & Lugmair 1986), enriched phlogopite wehrlite and highly anomalous, mica- and amphibole-rich clinopyroxenite. In this paper, we characterize the intraxenolith glass found in 28 of 30 samples of the suite of ultramafic xenoliths from the stratified ash of the maar deposits in a quarry near Meerfeldermaar Lake, West Eifel, Germany, and compare these glasses with those in the Gees xenoliths.

GEOLOGY, PETROGRAPHY AND CLASSIFICATION OF XENOLITHS

The xenoliths from the West Eifel region are part of the continental lithosphere of the Rhenish Massif uplifted to form the Rhine Rift (Illies & Fuchs 1983). Volcanic rocks include nephelinite, leucitite and basanite, which form scoria cones near ash-flow deposits, and lava flows (Schmincke *et al.* 1983) with a total volume of 1.5 km^3. The xenoliths from Meerfeldermaar, classified according to Streckeisen (1976), consist mainly of spinel lherzolite. Spinel wehrlite, olivine websterite and clinopyroxenite are less common and occur in lava bombs. Stosch & Lugmair (1986) suggested a similarity between a single xenolith from Meerfeldermaar and those from the classic Dreiser Weiher locality. The present study forms the initial part of an investigation designed to determine the extent of heterogeneity in the West Eifel lithospheric mantle by comparing the variability of the xenoliths at Meerfeldermaar with those found at Gees (Edgar *et al.* 1989, Lloyd *et al.* 1991).

All of the xenoliths collected from Meerfeldermaar

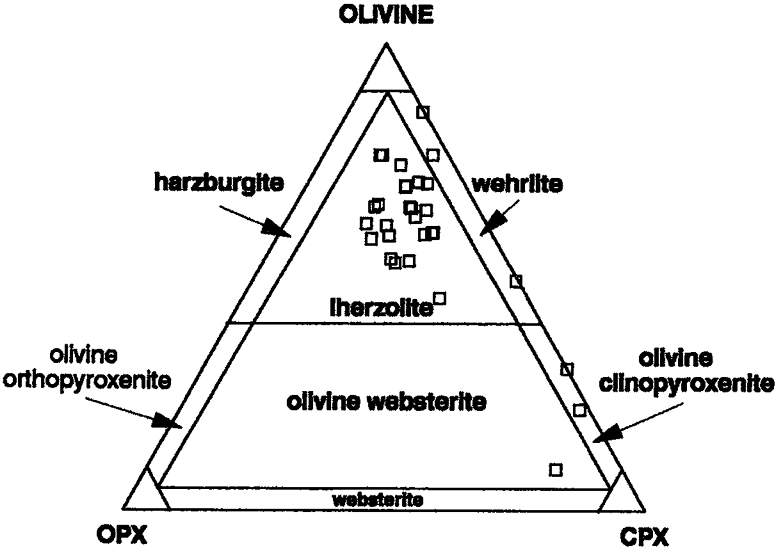

FIG. 1. Classification of mantle xenoliths at Meerfeldermaar in terms of modal proportions of olivine – orthopyroxene – clinopyroxene (after Streckeisen 1976).

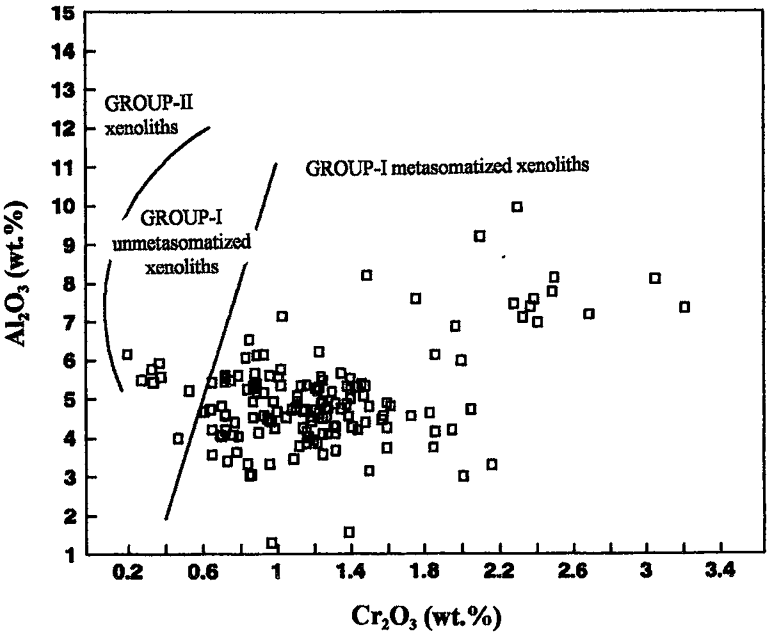

FIG. 2. Plot of Cr_2O_3 *versus* Al_2O_3 in clinopyroxene in the Meerfeldermaar xenoliths (fields after Kempton *et al.* 1984).

were modally analyzed, and classified by the method of Frey & Prinz (1978), as modified by Lloyd (1987), based upon their mineralogy (Fig. 1) and mineral chemistry (Fig. 2). The majority of the xenoliths are metasomatized.

Spinel lherzolite comprises 80% of the xenolith suite; spinel wehrlite (10%), olivine clinopyroxenite (6.7%) and olivine websterite account for the rest (Fig. 1). Both lherzolite and wehrlite xenoliths range from anhydrous glass-free to amphibole–phlogopite-bearing with minor glass. The textures are similar in both types of xenoliths.

With the exception of a single xenolith of phlogopite lherzolite with a foliation suggesting a metamorphic overprint, all lherzolite and wehrlite samples are equigranular and dominated by olivine grains that tend to be smaller than the grains of pyroxene. Volatile-bearing phases (phlogopite, pargasite, edenite, glass) are present in 26 of the 30 xenoliths. The amounts are quite variable, ranging from a trace to 11.1% amphibole, with up to 4.4% mica and trace to 2.6% glass.

Glass is found as light yellow to reddish brown microlite-rich pools or as a lining of vugs (up to 1 mm across). This intraxenolith glass has bubble-like voids between and in some cases within its margins (Fig. 3a), suggestive of a former higher content of volatiles, possibly removed during degassing. All glass in contact with surrounding minerals shows a meniscus represented by a slightly curved boundary between minerals inherent to the xenolith and veins of glass (see Fig. 3a). This is likely caused by a surface-tension phenomenon when in a liquid state.

Pools of glass and microlites are commonly associated with yellow to tan brown, slightly pleochroic amphibole in various stages of degradation (Fig. 3a). It cannot be determined whether this is a primary mineral, or whether degradation is a result of reaction of the liquid with the amphibole to form the vugs and microlites (olivine, spinel, clinopyroxene, carbonate, and rare rhönite). The presence of carbonate may indicate a reaction in the presence of CO_2, or simply a post-reaction alteration.

In several of the lherzolite and wehrlite samples, glass occurs along grain boundaries, forming branching networks that in some cases coalesce as "veins" that connect with glass in vug linings and pools of glass (Fig. 3b). In two of the wehrlite samples and in one of lherzolite, anhedral clinopyroxene is present in the "veins". Rarely, the glass is associated with large partially melted crystals (1 mm) of chromian spinel (Fig. 3c), and it also occurs as inclusions in spinel.

Unlike amphibole, the phlogopite in all xenoliths is fresh. "Vein" glass may surround phlogopite, suggesting that the phlogopite formed from a melt that moved along the vein. Except in the foliated lherzolite, phlogopite shows no preferred orientation.

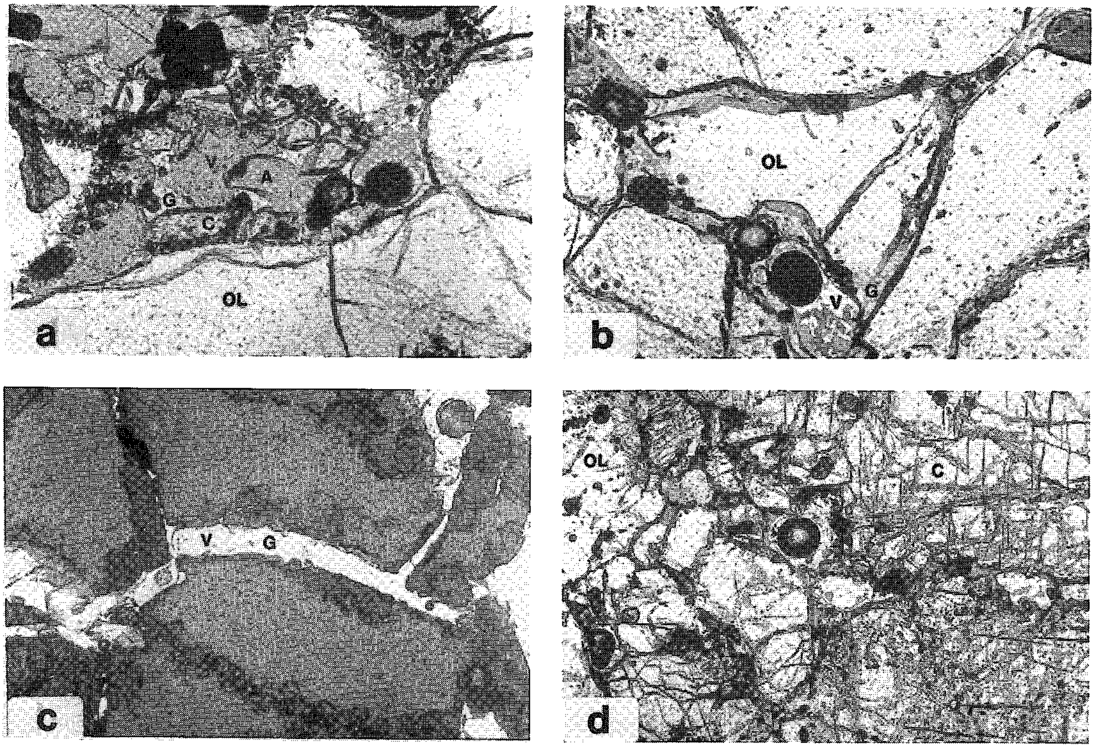

FIG. 3. a. Photomicrograph of amphibole lherzolite with amphibole degradation. Small central grain of amphibole (A) surrounded by clinopyroxene crystals (C), glass (G) and small dark spinel crystal; Ol: olivine, V: void. b. Photomicrograph (plane-polarized light) of spinel lherzolite with a network of brown glass-filled veinlets (G) along grain boundaries of light olivine (Ol) and darker clinopyroxene; V: void. c. Photomicrograph of spinel lherzolite with large brown spinel crystal fractured by glass- (G) and void-filled veinlets (V). Note the development of subgrains in the spinel exposed along veinlets and circular bubble between areas of glass. d. Photomicrograph of olivine clinopyroxenite (plane-polarized light) showing coarse-grained clinopyroxene (C) and olivine (Ol) infiltrated by a network of veinlets of dark brown and black glass. In all cases, the field of view measures 1.5 mm diagonally across.

In the websterite and clinopyroxenite, dark brown to black glass occurs within the voids of these very coarse-grained rocks (Fig. 3d). This glass has the same appearance as the matrix material of the porphyritic volcanic rind that encrusts many xenoliths at Meerfeldermaar. This glass also occurs proximal to the rims of these xenoliths. Both the mode of occurrence and the chemistry of the glass (see below) suggest that the black glass represents silicate melt that infiltrated these xenoliths during ascent.

Likewise, clinopyroxene also is fractured, but glass occurs only along the large fractures as "vein" glass (Fig. 3b). Some of the larger grains of clinopyroxene appear to have reacted with the glass. For example, the larger darker clinopyroxene grain along the top edge in Figure 3b shows some small embayments that might be the result of such a reaction.

ANALYTICAL TECHNIQUES

Compositions of minerals and glasses were determined using a four-spectrometer JEOL 8600 electron microprobe with wavelength-dispersion spectrometry (WDS), energy-dispersion spectrometry (EDS) and light-element capabilities. Mineral analyses were done with a beam diameter of 1 μm at 15 kV and a beam current of 10 nA. Analyses of glass and carbonate were made with a defocussed beam 5 μm in diameter in order to minimize loss of Na and K due to volatilization.

Problems of erroneous results in microprobe analyses of glass and even minerals with high Na and K contents have long been recognized (*cf.* Hunter & Taylor 1982, Spray & Rae 1995). Nielsen & Sigurdsson (1981) developed an empirical, cryogenic method of minimizing Na loss by cooling the sample, thus preventing loss to volatilization. These methods have not been widely accepted because errors introduced during extrapolation are not well constrained. A survey of 20 published studies involving microprobe analyses of K- and Na-bearing glasses showed that only two authors used Nielsen's & Sigurdsson's method. The loss of K due to volatilization is of much less importance than for Na (see Nielson & Sigurdsson 1981; Fig. 1). Our study involves glass (containing Na and K) in K-rich rocks and compares its composition with that of glass in similar rocks. For these reasons, we believe that the use of corrective measures such as suggested by Nielsen & Sigurdsson (1981) is not justified. Furthermore, current studies of synthetic glasses with much higher levels of K (approximately 25 wt% K_2O) and Na (approximately 10 wt% Na_2O) do not show the losses claimed by some earlier investigators.

Data reduction was carried out using a ZAF program with a Tracor Northern reduction system. Back-scatter electron imagery was used extensively to document the various textures observed optically.

RESULTS

Glass

Variations in mineral and glass compositions were observed both between and within individual xenoliths. The dark, black glass in the olivine websterite and olivine clinopyroxenite (Table 1, anal. 2, 3) compares with the composition of the host lava (Table 1, anal. 1) except for its much lower Mg, Fe and Ca, and higher Al and P. This suggests that the black glass does not represent the host magma but might be related to it by crystallization of mafic minerals (olivine and pyroxene) and, possibly, plagioclase. Alternatively, the black glass may represent a liquid modified by mixing with other infiltrated melts that form along fractures. Black glass is absent in the lherzolite xenoliths, and the network glass in these xenoliths (Fig. 3b) is chemically different from the black glass. The black glass composition is not plotted in Figure 4.

The chemistry of other intraxenolith glasses is extremely variable (Table 1) and, to some degree, can be related to the type of xenolith, to the mode of occurrence of glass, and to its association with various minerals within the xenolith. For example, glass from "anhydrous" xenoliths (*i.e.*, lacking mica and amphibole) (Table 1, anal. 4) has a mg# [= Mg/(Mg+Fe), molar basis] of greater than 0.50, and high SiO_2 (greater than 52 wt%). In contrast, xenoliths with lower modal olivine, such as the olivine websterite and clinopyroxenite (Table 1, anal. 2, 3) contain glass with a low mg# (less than 0.5) and low SiO_2 (less than 46 wt%).

The relationship between SiO_2 and iron contents of glass in mantle-derived xenoliths, particularly in olivine-poor and olivine-rich glasses, has been noted by Francis (1991), who studied composite mantle-derived xenoliths from Nunivak, Alaska. He found a general increase in SiO_2 and decrease in iron in glasses from amphibole-bearing, olivine-poor xenoliths of clinopyroxenite compared to the SiO_2 and iron in olivine-rich lherzolite and harzburgite xenoliths. Table 1 shows that glass in the Meerfeldermaar xenoliths is generally higher in SiO_2 in lherzolite than in olivine-poor xenoliths such as websterite and clinopyroxenite (*cf.* Table 1, anal. 4, 6–10 with anal. 2, 3). Similarly, there is a general decrease in Fe in glasses from the olivine-poor to the olivine-rich

TABLE 1. SELECTED COMPOSITIONS OF GLASS FROM XENOLITHS AND HOST LAVA, MEERFELDERMAAR

wt %	1	2	3	4	5	6	7	8	9	10
SiO_2	43.63	45.54	45.89	60.88	45.72	53.36	55.26	53.34	40.64	59.89
TiO_2	2.64	3.05	3.03	1.16	1.73	0.99	1.87	1.51	8.82	2.42
Al_2O_3	13.01	19.52	18.91	17.60	17.19	13.51	20.29	21.06	14.36	17.54
FeO	9.27	6.14	5.95	2.57	8.12	2.64	2.60	4.92	12.19	3.85
MnO	0.21	0.20	0.14	0.08	0.13	0.03	0.04	0.08	0.19	0.19
MgO	8.21	1.17	1.16	2.30	5.51	1.66	3.66	3.63	11.56	3.31
CaO	14.57	12.31	14.02	3.82	11.08	6.42	0.24	3.41	9.87	3.44
BaO	na	0.20	0.23	0.03	0.07	na	0.35	0.02	0.02	0.09
K_2O	2.31	3.28	1.98	3.70	5.53	3.11	3.61	3.92	1.61	3.11
Na_2O	3.90	4.27	3.97	3.13	2.92	7.11	3.99	3.32	2.94	2.35
P_2O_5	0.27	1.43	1.24	0.27	0.07	0.06	0.38	0.14	nd	0.87
F	na	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cl	na	0.38	0.32	0.16	0.21	0.15	0.17	0.09	nd	0.17
Cr_2O_3	na	na	na	na	0.08	0.01	na	0.00	nd	na
Total	98.47	96.41	95.60	95.43	92.76	88.99	96.46	97.50	99.20	98.20
mg#	0.61	0.25	0.27	0.60	0.55	0.53	0.72	0.57	0.64	0.60

1. Host lava, Meerfeldermaar; 2. Olivine websterite, black; 3. Olivine clinopyroxenite, black; 4. "Anhydrous" spinel lherzolite; 5. With phlogopite from phlogopite lherzolite; 6. With amphibole from amphibole lherzolite; 7. With amphibole from amphibole - phlogopite lherzolite; 8. As pools associated with spinel and trace amphibole in spinel lherzolite; 9. Glass as inclusions and embayments in spinel lherzolite; 10. Glass associated with carbonated spinel lherzolite. na: not analyzed; nd: not detectable.

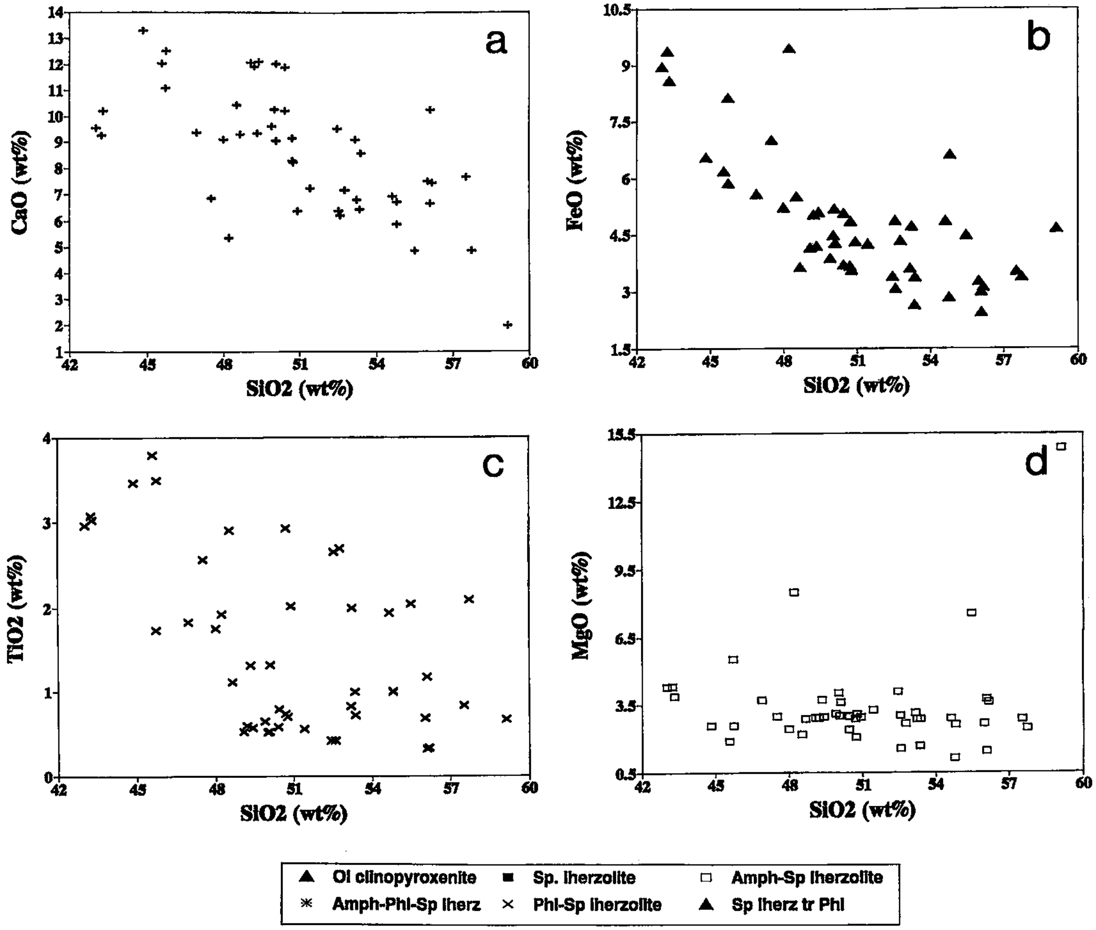

FIG. 4. Glass compositions by rock type: a. SiO_2 *versus* CaO (wt%), b. SiO_2 *versus* FeO (wt%), c. SiO_2 *versus* TiO_2 (wt%), d. SiO_2 *versus* MgO (wt%).

xenoliths (Table 1). The composition of glass presented in Table 1 from inclusions and embayments in a spinel lherzolite (anal. 9) has very low SiO_2 and high iron content.

The composition of glass in individual xenoliths is influenced by its proximity to mica, amphibole, and spinel. If phlogopite is the only associated mineral, the composition of glass (Table 1, anal. 5) is characterized by K greater than Na, high Ti and Ca, and low SiO_2 relative to glass in other environments. Glass associated with amphibole as the only hydrous phase has K less than Na, low Ti, and lower Ca and higher SiO_2 (Table 1, anal. 6) than glass associated only with phlogopite (Table 1, anal. 5). Glass domains analyzed from phlogopite–amphibole-bearing xenoliths all have very low totals (Table 1), possibly a reflection of higher proportions of Fe_2O_3 (determined as FeO), higher contents of volatiles, or to some undetected elements. Natural glasses with similar low totals are known (*e.g.*, Mitchell *et al.* 1987).

Glass within xenoliths with both phlogopite and amphibole as hydrous phases (Table 1, anal. 7) has a composition similar to that of glass associated with amphibole in amphibole lherzolite (Table 1, anal. 6), but has higher Al and Mg and lower K and Ca. Glass in pools associated with spinel and trace amounts of amphibole (Table 1, anal. 8) is comparable in composition to glass in other hydrous-mineral-bearing xenoliths (Table 1, anal. 6, 7). In contrast, glass-forming inclusions and embayments in spinel from the same xenoliths (Table 1, anal. 9) has lower SiO_2, slightly less Na and K, but much lower Al, Mg and Fe. Glass associated with carbonate minerals may occur in the same xenoliths as glass that has no such associations.

TABLE 2. SELECTED COMPOSITIONS OF CLINOPYROXENE AND ORTHOPYROXENE, MEERFELDERMAAR

wt %	1	2	3	4	5	6	7	8	9	10	11
SiO_2	50.17	51.25	50.92	51.63	51.07	51.97	51.56	54.15	53.61	54.49	54.62
TiO_2	1.58	1.11	0.86	0.71	0.55	0.24	0.60	0.10	0.08	0.05	0.01
Al_2O_3	4.75	4.00	5.23	5.02	3.16	4.29	4.59	5.23	4.14	4.16	2.17
Cr_2O_3	0.64	0.47	0.53	1.40	1.50	1.41	0.93	0.48	0.87	0.82	0.57
MnO	0.04	0.06	0.12	0.16	0.12	0.07	0.13	0.22	0.14	0.19	0.06
FeO	3.67	3.64	4.70	3.84	4.47	2.62	3.90	5.72	5.57	5.47	5.37
MgO	15.83	16.38	15.64	17.52	19.09	16.73	16.25	32.12	32.67	33.22	34.49
CaO	23.28	22.63	21.31	19.09	18.13	21.73	20.54	1.31	1.63	1.26	0.81
K_2O	nd	nd	nd	0.01	0.02	0.03	0.01	0.02	nd	nd	0.05
Na_2O	nd	nd	0.93	0.96	0.89	0.70	0.85	0.10	0.12	0.11	0.13
Total	99.96	99.78	100.25	100.35	99.01	99.77	99.37	99.43	98.83	99.77	98.28
mg#	0.89	0.89	0.86	0.89	0.88	0.92	0.88	0.91	0.92	0.92	0.92

1. Xenolith from phlogopite lherzolite; 2. Microlite in glass from phlogopite lherzolite; 3. Xenolith from olivine clinopyroxenite; 4. Xenolith from spinel lherzolite; 5. Microlite from spinel lherzolite; 6. Xenolith from amphibole-phlogopite lherzolite; 7. Xenolith from olivine clinopyroxenite; 8. Orthopyroxene core to clinopyroxene microlite in spinel lherzolite; 9. Xenolith from spinel lherzolite; 10. Orthopyroxene core to clinopyroxene microlite in hydrous lherzolite. 11. Orthopyroxene core to clinopyroxene microlite in hydrated lherzolite. nd: not detectable. Columns 1 to 7: clinopyroxene; columns 8 to 11: orthopyroxene. Total Fe is reported as FeO.

However, such carbonate-associated glass (Table 1, anal. 10) has high SiO_2, Al, K greater than Na, and lower Fe and Mg. The higher SiO_2 suggests that carbonate is not related to glass because such a relationship would result in a lower-SiO_2 glass.

Pyroxenes

Table 2 shows that the ranges in compositions of orthopyroxene and clinopyroxene are constant within and between xenoliths. The clinopyroxene is a chromian diopside with high mg# (about 0.89) and low levels of Ti and Al. In contrast, the clinopyroxene that forms microlites associated with glass (Table 2, anal. 5) has a slightly lower mg# (about 0.88), and lower levels of Ti and Al. Orthopyroxene is present as an essential mineral in the xenoliths and is also found as a core in clinopyroxene and amphibole in microlites. The composition of the orthopyroxene fractions is similar (Table 2, anal. 8–11), suggesting that the clinopyroxene and amphibole microlites formed as a rim around the orthopyroxene. Both pyroxenes are comparable in composition to those found in the xenoliths at Gees (Edgar *et al.* 1989, Lloyd *et al.* 1991) and to those from other examples of enriched mantle xenoliths (Nixon 1987).

Spinel

The chemistry of spinel varies systematically with xenolith type and mode of occurrence. The spinel belongs to the Cr–Al series, with a small range of Fe_2O_3 (calculated) and low TiO_2 (Table 3). In amphibole-bearing xenoliths (Table 3), the spinel is

TABLE 3. SELECTED COMPOSITIONS OF SPINEL, MEERFELDERMAAR

wt %	1	2	3	4	5	6	7
SiO_2	0.10	nd	0.02	0.05	0.06	0.07	0.04
TiO_2	1.76	0.12	0.05	0.00	0.80	0.63	0.09
Al_2O_3	21.67	31.84	42.08	41.77	30.66	24.16	40.88
Cr_2O_3	39.61	33.70	25.53	25.20	34.81	41.96	25.55
Fe_2O_3	8.65	6.58	3.64	4.04	4.60	5.29	4.20
FeO	13.72	11.66	11.33	11.35	11.01	13.59	8.17
MnO	0.21	0.24	0.13	0.14	0.22	0.27	0.23
MgO	15.35	16.63	17.97	17.84	17.10	14.97	19.43
Total	101.07	100.77	100.75	100.39	99.26	100.94	98.59
mg#	0.70	0.72	0.74	0.74	0.73	0.81	0.72

1. Spinel from phlogopite lherzolite; 2. Spinel inclusion in amphibole from amphibole lherzolite; 3. Core composition of spinel from amphibole lherzolite associated with glass; 4. Rim composition of same grain of spinel from amphibole lherzolite; 5. Spinel from spinel wehrlite; 6. Spinel from amphibole lherzolite with trace phlogopite; 7. Core composition of spinel from spinel lherzolite. nd: not detectable. Proportion of total iron assigned to Fe_2O_3 determined by stoichiometry.

TABLE 4. SELECTED COMPOSITIONS OF AMPHIBOLE AND PHLOGOPITE, MEERFELDERMAAR

wt %	1	2	3	4	5	6	7	8
SiO_2	42.97	43.48	39.82	44.28	38.16	39.60	38.34	39.58
TiO_2	0.68	1.31	5.82	0.53	5.08	0.72	3.24	0.91
Al_2O_3	13.82	14.33	15.61	12.69	15.86	17.10	16.08	17.09
Cr_2O_3	2.28	1.84	0.39	2.00	2.32	1.33	1.24	1.96
MnO	nd	0.05	nd	nd	0.07	nd	0.06	nd
FeO	3.83	3.91	4.92	3.79	3.99	4.39	5.89	3.44
MgO	18.44	18.29	15.44	18.58	20.53	23.02	21.38	22.96
CaO	11.10	11.08	13.06	11.43	0.05	nd	0.02	0.01
BaO	na	na	na	na	0.49	0.50	0.30	0.76
K_2O	1.41	0.73	0.46	1.32	9.86	9.01	9.19	8.72
Na_2O	3.22	3.34	2.64	3.01	0.30	1.10	0.85	1.06
F	nd	nd	0.54	0.02	0.28	0.16	0.22	0.11
Cl	0.10	0.04	0.06	0.07	nd	0.09	0.05	0.08
Total	97.85	98.40	98.52	97.72	96.99	97.02	96.86	96.68
mg#	0.90	0.89	0.89	0.90	0.90	0.90	0.87	0.92

1. Amphibole from amphibole lherzolite; 2. Core of amphibole from phlogopite lherzolite with trace amphibole; 3. Rim of amphibole; 4. Amphibole from amphibole lherzolite; 5. Phlogopite rimming spinel from phlogopite lherzolite; 6. Phlogopite from amphibole - phlogopite - spinel lherzolite; 7. Phlogopite from amphibole-phlogopite lherzolite; 8. Phlogopite from amphibole-phlogopite lherzolite. na: not analyzed, nd: not detectable. Total Fe is expressed as FeO.

enriched in Al and has lower Cr than spinel in amphibole- and phlogopite-poor xenoliths. Where spinel is associated with intraxenolith glass (Table 3, anal. 3), it has low Cr and high Mg contents, whereas if it occurs as inclusions within amphibole and phlogopite, it has higher Cr and lower Mg values (Table 3, anal. 6) than primary spinel in the xenoliths.

Amphibole

All amphibole crystals in the Meerfeldermaar xenoliths have very constant composition (Table 4). Core-to-rim analyses indicate enrichment in alkalis, Cr and Mg in the core, with enrichment in Ca and Ti in the rim.

Phlogopite

Except for Ti, the composition of the phlogopite is constant (Table 4, anal. 5–8). The most Ti-rich phlogopite (greater than 5.0 wt% TiO_2) occurs as a rim on spinel (Table 4, anal. 5), whereas the lowest Ti (less than 1.0 wt%) is found in phlogopite from an amphibole–phlogopite spinel wehrlite (Table 4, anal. 6, 8). If most of the phlogopite in the Meerfeldermaar suite of xenoliths is of metasomatic origin, the low- to high-Ti values (Table 4) may reflect the compositions of a range of metasomatizing melts or fluids. Whether or not the phlogopite is of metasomatic origin, the variable Ti contents also may reflect the protolith it replaces. The range of Ti in the phlogopite in the Meerfeldermaar xenoliths (Table 4) is much greater than that in the phlogopite in the Gees suite (Lloyd *et al.* 1991), in which the Ti values are consistent, lying in the upper range of those in the Meerfeldermaar suite.

In common with phlogopite compositions in the metasomatized xenoliths from southwestern Uganda and those of other West Eifel xenoliths (Edgar *et al.* 1994), the phlogopite and amphibole in the Meerfeldermaar xenoliths have very low F and Cl contents relative to the mica in the host rocks (Table 4).

Olivine

In olivine-rich xenoliths (lherzolite), the olivine has a mg# greater than 0.90, and the Ni content is greater than 0.32 wt% NiO (Table 5, anal. 1, 2, and 6), whereas in the olivine-poor xenoliths (olivine websterite and olivine clinopyroxenite), the olivine has lower mg# and Ni content (Table 5, anal. 3, 4). Olivine associated with veins or pools of intraxenolithic glass (Table 5, anal. 7, 8) is more Mg-rich (mg# greater than 0.92) than the essential olivine in the xenoliths.

Calcite

A high-Mg calcite (up to 2.69 wt% MgO) is associated with intraxenolith glass in the amphibole lherzolite and spinel lherzolite with trace amphibole.

TABLE 5. SELECTED COMPOSITIONS OF OLIVINE, MEERFELDERMAAR

wt %	1	2	3	4	5	6	7	8
SiO_2	39.99	40.41	40.96	40.04	40.11	40.23	40.94	39.99
TiO_2	0.01	0.01	0.03	0.03	0.03	nd	nd	nd
Al_2O_3	nd	0.01	0.04	7.00	0.05	0.01	0.03	0.06
Cr_2O_3	0.06	nd	0.03	nd	0.04	nd	0.05	0.12
FeO	9.53	8.92	10.48	12.44	9.95	9.23	7.20	6.06
MnO	0.15	0.10	0.20	0.19	0.08	0.14	0.05	0.04
MgO	49.77	50.10	48.07	47.31	47.96	49.72	51.30	53.38
CaO	0.09	0.10	0.19	0.19	0.21	0.06	0.16	0.18
K_2O	nd	0.03	0.02	nd	0.03	nd	0.01	0.13
Na_2O	nd	0.18	0.02	0.03	0.01	0.04	0.02	0.24
NiO	0.37	0.37	0.19	nd	0.23	0.33	0.17	0.37
Total	99.97	100.23	100.23	100.30	98.70	99.76	99.93	100.57
mg#	0.90	0.91	0.89	0.87	0.89	0.91	0.93	0.94

1. Xenolith olivine from phlogopite lherzolite; 2. Xenolith olivine from amphibole lherzolite; 3. Xenolith olivine from olivine websterite; 4. Xenolith olivine from olivine clinopyroxenite; 5. Xenolith olivine from olivine clinopyroxenite; 6. Xenolith olivine from amphibole lherzolite; 7. Microlite olivine from same amphibole lherzolite; 8. Microlite olivine in glass from amphibole-phlogopite lherzolite. nd: not detectable. Total Fe is expressed as FeO.

ORIGIN OF THE INTRAXENOLITH GLASS

Several origins have been proposed for intraxenolith glass. These include: (1) infiltration of host lava (Edgar *et al.* 1989), (2) liquid formed and trapped during partial melting of the xenolith (Moreva-Peralkalina 1985, Aranda-Gomez & Ortega-Guttierrez 1987), (3) partial melting of hydrous minerals due to (a) decompression (Green *et al.* 1968, Francis 1987) or (b) heat from the host magma (Nicolas *et al.* 1987), (4) migration of fluid through the upper mantle (Nielson & Noller 1987, Edgar *et al.* 1989), (5) partial melting of xenolith by a carbonate melt (Ionov *et al.* 1993), and (6) mixing of melt derived from preferential melting of veins of amphibole-bearing pyroxenite with high-SiO_2 melt from lherzolite (Francis 1991).

Some indications of which process has produced the glass may be made on the basis of its chemical variations and textures. At Meerfeldermaar, veins and networks of glass (Fig. 3b) can be traced from the outer edge to within the xenolith.

Infiltration

The glass in the Meerfeldermaar xenoliths has a very wide compositional range that incorporates that of the host lava and the black glass. In terms of weight %, these ranges are: SiO_2 (xenolith) 39.95–61.24, host 49.63; TiO_2 (xenolith) 0.31–6.82, host 2.64; Al_2O_3 (xenolith) 11.99–24.17, host 13.01; CaO (xenolith) 1.97–14.71, host 14.57; K_2O (xenolith) 1.2–7.31, host 2.31; Na_2O (xenolith) 1.26–7.88, host 3.9; mg# (xenolith) 0.25–0.69, host 0.61. These glass compositions suggest that intraxenolith glass cannot represent direct infiltration of the host lava during magma ascent, but could be the product of mixing of liquids, as suggested by Francis (1991) (mechanism 6 above). If the glass compositions are related to infiltration, then they may represent compositions buffered by minerals in the host xenolith. Furthermore, the host lava has a SiO_2 content that is at the lower end of the range of SiO_2 in xenolith glasses, and hence could be a potential parental liquid for the other glass compositions in terms of a SiO_2 *versus* oxide liquid-line-of-descent diagram. However, plots of Ca, Fe, Ti and Mg *versus* SiO_2 diagrams (Fig. 4) show 1) no correlation with Mg, and 2) trends of decreasing Ca, Fe and Ti with increasing SiO_2 rather than the more continuous change in all of these elements that would be expected if fractional crystallization of the host lava formed the intraxenolith glass.

Compositional relationships between intraxenolith glass and host lava can be assessed by examining the compositions of olivine microlites in the intraxenolith glass. In all xenoliths, microlites of olivine have a mg# greater than 0.90 (Table 5), the clinopyroxene, a mg# greater than 0.87 (Table 2), and the spinel, a mg# in the range 0.70–0.81 (Table 3). These results can be used to determine the mg# of liquid with which they may have equilibrated and to compare it with the mg#

of the host lava.

In some cases, the intraxenolith glass contains randomly distributed microlites of olivine as the first mineral to crystallize. The variable distribution of glass and of olivine (Fig. 1) precludes relating olivine abundance in the glass to that in the rock. On the basis of the temperature–pressure-independent partition coefficient of Mg and Fe between olivine and liquid (Roeder & Emslie 1970), it can be shown that olivine with a typical mg# of approximately 0.91 (Table 5) must be in equilibrium with a liquid of mg# approximately 0.77. This mg# is comparable to that of intraxenolith glass, with a mg# of about 0.72 (Table 1, anal. 7), in which olivine is the early microlite to form. Such olivine, however, cannot have equilibrated with a liquid of the composition of the host lava, with a mg# of 0.61 (Table 1, anal. 1). Recently, Ionov *et al.* (1993) have reported that high mg# are typical of phases produced by interaction of carbonate melts with silicates.

Glass represents partial melt of xenolith minerals

Olivine-poor microlite-bearing glass (with mg# approximately 0.57 (*e.g.*, Table 1, anal. 8), found in pools, veinlets, stringers and along grain boundaries (Fig. 3b), cannot be in equilibrium with primary xenolithic olivine with a mg# in the range 0.87–0.90 (Table 5), on the basis of the partition coefficient of Mg and Fe in olivine and liquid (Roeder & Emslie 1970). This indicates that the liquid in equilibrium with such olivine should have a mg# of about 0.74–0.76. Hence, this glass is not likely to have been formed by partial melting of the primary olivine of the xenolith. These glasses have higher SiO_2 contents (approximately 52 wt%: see Table 1, anal. 8, 10) than glass in the olivine-poor xenoliths (Table 1). For glass in xenoliths from Alaska, Francis (1991) proposed that mixing of the high-SiO_2 glass with low-SiO_2 glass from olivine-poor xenoliths produced intraxenolith glass compositions. Such a process is considered unlikely for the glass in the Meerfeldermaar xenoliths, even if the glass in the xenoliths represents a "eutectic"-like melt of olivine, orthopyroxene and clinopyroxene. Such a melt would be SiO_2-rich, but in the absence of textural evidence for the paragenetic sequence of crystallization, no determinations of the mg# of the liquid can be made. The absence of composite lherzolite and amphibole–pyroxenite xenoliths at Meerfeldermaar, similar to those described by Francis (1991) from Nunivak, makes assessment of the possible mixing of SiO_2-poor and SiO_2-rich liquids difficult.

Glasses from olivine-poor xenoliths have the lowest mg# (0.25–0.27) and the lowest SiO_2 (less than 45 wt%) (Table 1). Such glasses can only be produced by partial melting of an Al-rich pyroxene source. Pyroxene compositions (Table 2) do not indicate such Al enrichment.

Olivine grains with a serrated rim that show a subhedral boundary adjacent to glass imply interaction with the melt. Partition coefficients of Mg and Fe between olivine and melt suggest that this has not occurred, or it is only of minor extent, insufficient to produce the overall observed composition of the glass.

Glass produced by partial melting of phlogopite and amphibole

During ascent, xenoliths may undergo decompression that may result in partial melting of hydrous minerals such as phlogopite or amphibole, or the decomposition of these minerals may result from heat from the host magma (Jones *et al.* 1983a, b). The compositions of melts caused by high pressure – high temperature decomposition are well known (Yoder & Kushiro 1969, Stosch & Seck 1980), and hence examination of the compositions of glass adjacent to phlogopite (Table 1, anal. 5) may indicate if the glasses associated with these minerals are a result of decompression melting or heating.

Table 4 shows the composition of phlogopite that surrounds glass (Table 1, anal. 5) in a xenolith in which phlogopite is the only hydrous mineral. Breakdown of phlogopite produces olivine + liquid. The resulting liquid consists of K_2O:Al_2O_3:SiO_2 in the calculated proportions of 25:27:48 by weight. Table 1 (anal. 5) shows that the average composition of glass associated with phlogopite is quite different from the calculated proportions. In addition, the analyzed glass (Table 1, anal. 5) has a large amount of Ca and Na, and lower amounts of Mg and a lower mg# than the phlogopite. These results suggest that the composition of this glass is unlikely to be the result solely of partial melting of the phlogopite. Although this is likely the source of K in the glass, the source of Ca, Na and Si cannot be explained by melting any other mineral or combination of minerals present in the xenoliths. The composition of melt formed from the partial melting of pargasitic amphibole (Table 4, anal. 4) is more difficult to assess. The products of dissociation of pargasite, a process of incongruent melting, are spinel + clinopyroxene + olivine + glass (Stosch & Seck 1980). Hence, initial melting of such an amphibole may form clinopyroxene and a melt depleted in SiO_2, Ca, Mg, and Fe, and enriched in Al, K, and Na. Examination of the average pargasite in veins (Table 4, anal. 4) and associated glass (Table 1, anal. 6) from a xenolith in which amphibole is the only hydrous mineral present shows that the glass has some of these predicted characteristics. The most significant exceptions are the excess SiO_2 and comparable Al. Combined partial melting of amphibole and phlogopite cannot account for the composition of this glass.

If pargasitic amphibole is completely melted during decompression, in a way analogous to congruent melting, or by other mechanisms, the resulting glass would have high Al, Ca, Mg, Fe values, comparable to the original composition of pargasite (Table 4, anal. 1, 3). Comparison of the glass composition (Table 1, anal. 8) associated with only a trace of pargasite shows that this is not the case with respect to Ca, Mg and Fe.

Table 1 (anal. 8) represents glass from a xenolith with the assemblage of breakdown minerals and a trace of amphibole. The composition of glass is close to that predicted from the breakdown scheme for all elements except Al, which is much higher than that of amphiboles (Table 4) and hence suggests that partial breakdown of amphibole has not occurred. In a survey of glass compositions from lherzolite and harzburgite exhibiting some form of metasomatism, Schiano & Clocchiatti (1994) showed that high Al contents are characteristic.

Glass representing melt or fluid migrating through the upper mantle

In common with the glass in the mantle xenoliths at Gees (Edgar *et al.* 1989), glasses in the Meerfeldermaar xenoliths are unlikely to represent material infiltrated from the host magma, by mechanisms involving fractionation with and without decompression, or by processes of decompression melting and mixing (*e.g.*, Francis 1991). This conclusion is based upon the petrography, mineralogy and chemistry of xenoliths.

The West Eifel region has long been recognized as an area of enriched mantle (Lloyd & Bailey 1975) and volcanism dominated by mantle-derived magmas. Both facts suggest that an elevated geotherm (Stosch & Seck 1980) due to mantle diapirism (Fuchs & Wedepohl 1983) was present in this area. Stosch & Seck (1980) estimated temperatures as high as 1150°C at depths equivalent to 30 kbar. Edgar *et al.* (1989) and Thibault *et al.* (1992) have suggested that these elevated temperatures may be responsible for the upward migration of mantle melts or fluids.

Based on distribution-coefficient data, it is very unlikely that the microlites of olivine were in equilibrium with a melt of a composition comparable to that of the associated glass. Furthermore, the calculated mg# of this glass cannot represent a primitive magmatic melt or fluid from an unenriched source in the mantle. This conclusion is supported by the disequilibrium textures, such as a serrated rim on olivine along glassy veins, and euhedral clinopyroxene and spinel adjacent to glass (Fig. 3b), which suggest a partial melting reaction that maximizes surface areas. Such textures also suggest that melt or fluid may have been present for a significant period of time in order to form the veins and networks of veins, pools and glass-filled vugs. These features may have allowed the metasomatizing melt or fluid to migrate through the mantle.

Other features associated with glass in the Meerfeldermaar xenoliths support the concept that the glass represents a metasomatizing melt or fluid. Compositions of glass inclusions within spinel in spinel lherzolite (Table 1, anal. 9) are generally similar to the host lava (Table 1, anal. 1), and glass in embayments also has similar SiO_2, Al, and alkali contents but different Fe, Mg, Ti and Ca values. Hence, neither the glass as included in the spinel nor the embayed glass seems to represent infiltrated host-magma or a partial melt of spinel. The ophitic relationship of a large grain of spinel with phlogopite (Fig. 3c), in which spinel is an essential mineral in the xenolith, is associated with a feeder vein, suggesting that phlogopite crystallized from a liquid in the void created by partial melting of spinel.

The trends in Ca and Fe relative to SiO_2 for the Meerfeldermaar glass compositions (Figs. 4a, b) are similar to, but not as distinctive as, those for the glasses from the Gees xenoliths (Edgar *et al.* 1989, Fig. 1). In contrast to the glass in the Gees xenoliths, plots of Ca and Fe *versus* SiO_2 for the glasses of Meerfeldermaar show a poor correlation (Figs. 4a, b), and no correlation in TiO_2 and MgO with SiO_2 (Figs. 4c, d). These relationships preclude fractionation of any common ferromagnesian minerals in the host magma that infiltrated the xenoliths.

Abundant cavities and vesicles in the glass pools, vugs and veinlets (Figs. 3b, c) indicate the volatile-rich nature of the melt or fluid. The occurrence of carbonate-rich spherules in some Meerfeldermaar xenoliths implies the presence of CO_2, the dominant fluid-inclusion phase in minerals from metasomatized mantle-derived xenoliths (Pasteris 1987).

Figure 4a shows that glass in the Meerfeldermaar xenolith suite has a trend of decreasing Ca with increasing SiO_2. The experimental modeling of a reaction of dolomitic carbonatite melt with amphibole lherzolite (Green & Wallace 1988) indicates that both Ca and SiO_2 and Mg and SiO_2 change. The decrease in Ca with increase in SiO_2 (Fig. 4a) may be produced by reaction of a carbonate melt ($CaCO_3$-rich) with SiO_2-rich minerals. The occurrence of clinopyroxene in glassy veins and in veinlets (Fig. 3d) may imply that such a process has occurred. After crystallization of clinopyroxene, the activity of K and Na increased and that of Si decreased, promoting the crystallization of phlogopite.

In contrast to Ca, variation in Mg with increasing SiO_2 in the xenolithic glasses at Meerfeldermaar is negligible and cannot be attributed to the same processes that produce the Ca *versus* SiO_2 trend (Fig. 4a). Magnesium may have been buffered in these glasses by any of the xenolith-forming minerals (olivine, clinopyroxene, orthopyroxene, spinel ± amphibole ± phlogopite) in contact with glass, or those minerals crystallized from the glass as microlites.

Comparison with processes of mantle enrichment at Gees

Based upon the assemblages of mantle xenoliths and the intraxenolith glasses, the degree of enrichment in the lithospheric mantle underlying Gees appears to be more extensive than that underlying Meerfeldermaar. The Gees xenoliths of both groups I and II (wehrlite, harzburgite, clinopyroxenite) have greater amounts of patent metasomatic phlogopite, but no amphibole, and some of the Gees xenoliths have been altered to glimmerite. In contrast, xenoliths at Meerfeldermaar are mainly lherzolite, have lower modal percentages of phlogopite, and are devoid of glimmeritic material. The presence of metasomatic amphibole in the xenoliths at Meerfeldermaar, but not at Gees, suggests that the compositions of metasomatizing melts or fluids differed somewhat in each locality. This is shown in Figure 4 and discussed above.

If the intraxenolith glasses at Gees and Meerfeldermaar represent enriching (metasomatizing) melts and fluids migrating through the West Eifel lithospheric mantle contemporaneously, the xenoliths in these neighboring localities may have been enriched by the same set of enriching melts or fluids but at different stages of evolution, or at different depths, or by a different set of enriching melts or fluids generated at different times.

The possibility that the enrichment took place at different depths in the mantle is difficult to assess. The suite of xenoliths at both localities contains spinel rather than pyrope, implying that enrichment took place within the 25–70 km depth range of the upper mantle, based upon experiments on modal pyrolite mantle (Ringwood 1974). The presence of metasomatic amphibole of pargasitic composition in the Meerfeldermaar xenoliths further constrains the metasomatism to this part of the mantle because such amphibole is not stable at deeper levels.

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