

New varieties of mantle xenolith from the Massif Central, France

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ABSTRACT: Spinel lherzolite xenoliths from two localities in the Massif Central are undepleted in Al_2O_3 , CaO, and Na_2O . One suite from Tarreyres, is K_2O depleted and amphibole-bearing whereas the other, from Monistrol d'Allier some 18 km away, is amphibole-free and has a higher mean K_2O content of 0.035 wt. %. We present bulk major and minor element abundances in a harzburgite and a lherzolite from each locality and microprobe analyses of their constituent phases. Amphibole-bearing lherzolite and its pyroxenes are light-rare earth element (*LREE*) depleted, whereas amphibole-free lherzolite and its pyroxenes are *LREE* enriched. Both harzburgites and their pyroxenes are *LREE* enriched and one rock contains *LREE* enriched glass. The harzburgites are like harzburgite xenoliths from elsewhere but each lherzolite represents a previously unrecognized type of mantle in terms of the mineralogy and *REE* content. The implication for basalt genesis are briefly discussed.

KEYWORDS: xenoliths, lherzolite, upper mantle, Massif Central, France.

HETEROGENEITIES within the upper mantle continue to be studied and debated (Frey and Prinz, 1978; Kurat *et al.*, 1980; Menzies, 1983). They are important in understanding the generation of magmas with various trace element and isotopic signatures. To further this understanding it is necessary to establish the chemical and mineralogical diversity of the upper mantle; this paper is a contribution towards that goal.

Hutchison *et al.* (1975) concluded that the upper mantle underlying the Massif Central is laterally heterogeneous. One aspect of this heterogeneity is the occurrence of spinel lherzolite xenoliths of differing compositions in two localities separated by a few kilometres. Some of the xenoliths have a composition that can be considered to be 'undepleted' in that a source region of the same composition could yield up to 12% of mid-ocean ridge basalt (MORB) on partial melting. 'Depleted'

xenoliths also occur in these localities. 'Undepleted' xenoliths from scoria at Tarreyres, 7 km SSW of Le Puy, have a mean K_2O content of 0.006 wt. %, compared with 0.035 wt. % in those from the flow of the Basalte du Rocher du Lion, Monistrol d'Allier, 18 km to the west (fig. 1). Tarreyres xenoliths generally have amphibole as an accessory phase (Hutchison *et al.*, 1975), which, in previously described mantle rocks, is associated with K enrichment and metasomatism (Menzies, 1983). Thus, the association of amphibole with K impoverishment in the Tarreyres suite marks it as most unusual.

This paper examines the abundances of K_2O and the *REE*, and other major and minor element oxides, in four xenoliths from the two localities. Our data are compared with data on xenoliths from elsewhere and some implications for basalt genesis are discussed.

Sampling and analytical techniques. Two xenoliths from Tarreyres (TA) and two from Monistrol d'Allier (MS) were selected as representatives of depleted and undepleted types as discussed by Hutchison *et al.* (1975). Clean, interior chips from each were used for the determination of the *REE* in whole-rocks. Other similar material was crushed and pure concentrates of brown orthopyroxene and green diopside were hand-picked. The phases in the rocks were analysed by electron microprobe using an energy dispersive technique, and *REE* were determined in the pyroxene separates by INAA. Cr, Fe, Ni and Na were also determined by INAA in whole rocks for comparison with the analyses of Hutchison *et al.* (1975), or in mineral separates for comparison with the microprobe data. The *REE* were determined by ion microprobe in the diopsides of two xenoliths and in a major glass phase in a third.

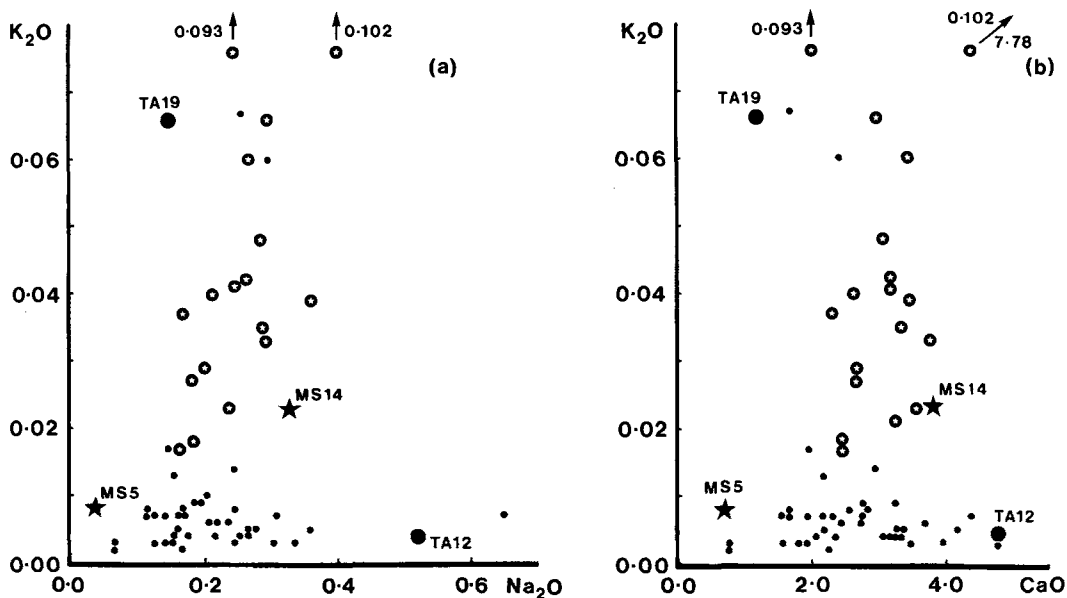


FIG. 1. (a) K_2O vs. Na_2O in all analysed ultramafic xenoliths from Tarreyres (dots) and Monistrol d'Allier (enclosed stars). The xenoliths selected for the present study are indicated by larger symbols. K_2O was determined by RH or Dr D. K. Paul by XRF using undiluted, pelleted samples. Precision (2σ) was 10% at 400 ppm K_2O , and 20% at 100 ppm, indicative of a detection limit of about 40 ppm. Na_2O was determined by Dr D. K. Paul using an INAA technique (Hutchison *et al.*, 1975). Because of failure of some capsules during the INAA work, only 41 (Tarreyres) and 19 (Monistrol d'Allier) measurements were successful, compared with 42 and 20, for K_2O and CaO . (b) K_2O vs. CaO for the same suites of xenoliths. Analysts R. H. and Dr D. K. Paul (Hutchison *et al.*, 1975).

Major and minor elemental abundances (Table I) are from previously unpublished data of Hutchison *et al.* (1975). The INAA technique used was that of Henderson and Williams (1981), with the addition of a Ge(Li) detector in the determination of La. BCR-1 was analysed in two separate runs. Our mean values were within 5% of the 'usable' values of Abbey (1983) except for Sm, our figure being 7.10 ppm and Abbey's 6.5 ppm.

Bulk chemistry. Bulk analyses of the four xenoliths are presented (Table I). The high MgO coupled with low abundances of Na_2O , CaO , and Al_2O_3 distinguish MS5 and TA19 from MS14 and TA12. The latter two have similar compositions except that TA12 has roughly one-sixth of the K_2O content of MS14.

The four xenoliths conform to the relationship of a positive correlation between heavy-REE (*HREE*) abundances and Al_2O_3 and CaO contents as reported for spinel peridotite xenoliths in basalts from world-wide localities (Frey, 1984). The chondrite-normalized La/Yb ratios of TA19 (7.0) and MS5 (12.9) are typical of harzburgitic xenoliths from elsewhere, enrichment in *LREE* being coupled with low levels of Al_2O_3 , CaO , and Na_2O

(Frey, 1984). However, unlike xenoliths from other localities, including Tarreyres, the two xenoliths from Monistrol d'Allier do not exhibit a negative correlation between *LREE* and CaO ; MS14 has a higher content of *LREE* than MS5 which has only 0.7 wt. % CaO . The relative depletion or enrichment in *LREE* is illustrated by the chondrite-normalized La/Yb ratios: < 0.32 and 3.4 of TA12 and MS14, respectively (fig. 2).

Mineral chemistry. Each xenolith contains olivine, orthopyroxene, diopside, and spinel, but, in addition, the undepleted xenolith, TA12 has rare aluminous amphibole, and the depleted one, TA19, has a few volume per cent of red-brown glass. Microprobe analyses of these phases appear in Tables II and III. The mineralogical composition of each rock was calculated from the bulk analysis (Table I); MS5 and TA19 are spinel harzburgites, whereas MS14 and TA12 are spinel lherzolites. There is good agreement between the calculated compositions and modes for MS5, MS14, and TA19; both thin-sections of TA12 suffered plucking, so the mode could not be determined. The MS5 pyroxenes are distinguished by their low TiO_2 , Al_2O_3 , FeO , and Na_2O , and high MgO contents.

Table I. Bulk analyses of ultramafic xenoliths

	MS5	MS5*	MS14	MS14*	TA12	TA12*	TA19	TA19*
SiO ₂	44.2	44.5	44.7	44.2	45.2	45.5	43.8	44.1
TiO ₂	0.005	0.01	0.096	0.12	0.11	0.22	0.08	0.03
Al ₂ O ₃	0.88	0.72	4.10	3.02	4.70	4.54	1.58	1.44
Cr ₂ O ₃	0.45	0.53	0.50	0.53	0.42	0.45	0.31	0.36
FeO	7.73	8.10	7.59	8.60	7.39	7.81	7.97	7.80
NiO	0.32	0.34	0.25	0.18	0.20	0.25	0.29	0.32
MnO	0.11	0.12	0.11	0.10	0.11	0.16	0.11	0.13
MgO	44.6	44.6	37.2	38.3	35.8	35.8	43.6	43.8
CaO	0.70	0.80	3.78	3.90	4.74	4.58	1.16	1.15
Na ₂ O	0.04	0.04	0.32	0.27	0.52	0.45	0.15	0.09
K ₂ O	0.008	-	0.023	0.01	0.004	0.002	0.07	-
SUM	99.0	99.8	98.7	99.2	99.2	99.8	99.1	99.2
La	0.60	0.20	1.05	2.25	<0.25	-	2.37	0.73
Ce	0.81	0.32	2.46	4.36	0.50	0.57	4.64	1.50
Nd	<0.5	0.14	1.37	2.47	0.90	0.80	1.56	0.54
Sm	0.07	0.04	0.40	0.72	0.37	0.38	0.34	0.12
Eu	0.02	0.01	0.13	0.23	0.17	0.16	0.13	0.04
Tb	0.01	0.006	0.06	0.12	0.11	0.11	0.06	0.03
Ho	-	-	0.08	0.18	0.17	0.15	0.08	0.03
Tm	<0.01	0.002	0.03	0.07	0.07	0.06	0.04	0.02
Yb	0.03	0.01	0.20	0.47	0.50	0.49	0.22	0.10
Lu	<0.01	0.001	0.03	0.07	0.07	0.07	0.04	0.02
Th	<0.08	0.02	<0.003	0.10	<0.1	-	0.24	0.07

MS5* Bulk calculated from 3% CPX, 20% OPX, 1% SP and 76% OL, based on bulk and mineral chemistry. C.f. mode, 3% CPX, 20% OPX, 1.5% SP and 76% OL.

MS14* Bulk calculated from 18% CPX, 20% OPX, 2% SP and 60% OL. C.f. mode, 17% CPX, 27% OPX, 1.5% SP and 55% OL.

TA12* Bulk calculated from 20% CPX, 30% OPX, 2% AMPH, 3% SP and 45% OL.

TA19* Bulk calculated from 5% CPX, 20% OPX, 1% SP and 74% OL, ignoring the minor glass content, so the CPX content is a maximum. C.f. mode, 8% CPX, 14% OPX, 2% SP, 74% OL, 1% glass.

MS5, MS14, TA12, TA19, previously unpublished analyses by X-ray fluorescence, except Na₂O, by neutron activation (Hutchison *et al.*, 1975). REE and Th, new analyses by INAA, figures in ppm.

The undepleted xenoliths MS14 and TA12 have olivines with significantly less forsterite than those of MS5 and TA19; the former also have more aluminous and less chromian spinels than the latter, depleted xenoliths (Table III). The TA12 amphibole is pargasitic, with 2.66 wt. % TiO₂ and 2.79% Na₂O, so although of low modal abundance it is a significant contributor of these oxides to the bulk composition.

Various REE were determined in the pyroxenes separates (Table II). In each pyroxene pair the REE are concentrated in the diopside, so the REE pattern of each bulk xenolith is a reflection of the pattern in its diopside (fig. 2a, b). In TA12 and TA19 orthopyroxenes the REE patterns are similar to those of the coexisting diopsides, but at lower

concentrations; this is probably true also for MS5 and MS14. Both undepleted xenoliths have diopsides with HREE of about ten times chondritic, but in MS14 the abundance rises to 36 times chondritic at La, whereas in TA12 it falls to less than two times chondritic. In spinel peridotite xenoliths from Victoria (Frey and Green, 1974) and San Carlos (Frey and Prinz, 1978) LREE enrichment is most extreme in the diopsides that constitute the lowest modal proportions of their bulk rocks. This holds for the two xenoliths from Monistrol d'Allier, the diopside of the harzburgite, MS5, having a chondrite-normalized La/Yb ratio of 10.7 compared with 3.6 in MS14 which is richer in bulk REE, including La.

Ion microprobe analysis confirms that the

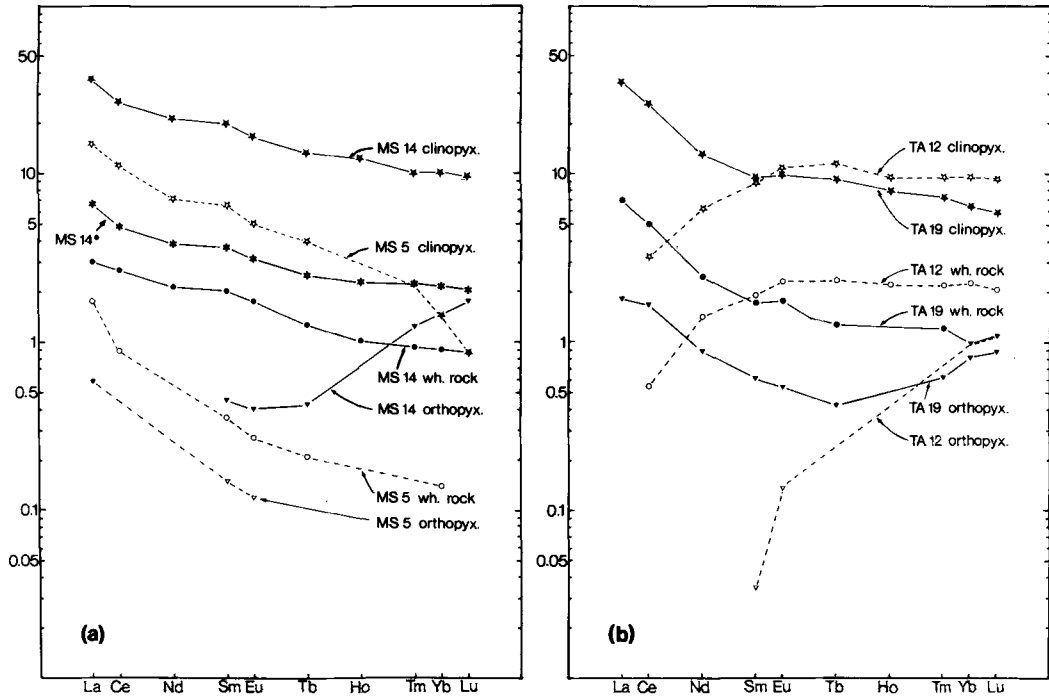


FIG. 2. Chondrite-normalized REE abundance patterns of whole rocks and pyroxenes from (a) Monistrol d'Allier and (b) Tarreyres. Abundances in chondrites were taken from Wakita *et al.* (1971).

Table II. Analyses of pyroxenes

	MS5		MS14		TA12		TA19	
	CPX	OPX	CPX	OPX	CPX	OPX	CPX	OPX
SiO ₂	54.1	57.3	51.1	54.4	51.2	54.6	53.7	55.3
TiO ₂	0.08	0.05	0.45	0.15	0.63	0.15	0.46	0.05
Al ₂ O ₃	2.59	1.8	6.50	3.97	7.10	3.56	5.34	3.60
Cr ₂ O ₃	1.27	0.4	0.92	0.38	0.71	0.24	0.94	0.50
FeO	2.73	5.8	3.60	6.90	2.90	6.89	2.60	5.91
NiO	(0.05)	(0.10)	-	(0.19)	(0.04)	(0.09)	(0.05)	(0.10)
MnO	0.05	0.19	0.20	0.16	0.08	0.20	0.10	0.13
MgO	16.8	33.9	15.3	31.8	14.4	33.3	16.2	32.7
CaO	22.0	0.6	20.4	0.90	20.7	0.62	20.0	0.74
Na ₂ O	1.00	(0.07)	1.40	(0.11)	1.80	(0.11)	1.21	(0.16)
K ₂ O	-	-	0.03	0.00	-	-	-	-
SUM	100.7	100.2	99.9	99.0	99.6	99.8	100.6	99.2
La	5.3	0.20	12.5	<0.5	<0.8	<0.06	12.2	0.62
Ce	10.5	<0.6	24.2	<0.5	2.85	<0.3	23.9	1.54
Nd	4.6	<0.7	13.7	<0.6	4.0	<0.3	8.44	0.57
Sm	1.27	0.03	3.90	0.09	1.89	0.007	1.88	0.12
Eu	0.37	0.009	1.23	0.03	0.80	0.01	0.71	0.04
Tb	0.19	<0.02	0.64	0.02	0.54	<0.3	0.44	0.02
Ho	<0.3	<0.1	0.98	<0.1	0.75	<0.05	0.6	<0.1
Tm	0.07	<0.02	0.32	0.04	0.31	<0.02	0.23	0.02
Yb	0.32	<0.05	2.24	0.32	2.10	0.22	1.26	0.18
Lu	0.03	<0.01	0.33	0.06	0.32	0.03	0.19	0.03
Th	0.70	<0.08	0.56	<0.1	<0.3	<0.1	0.87	0.13

REE in ppm. Figures in brackets by INAA, the remainder by microprobe.

Table III. Microprobe analyses of minerals

	Olivine				Spinel				Amph
	MS5	MS14	TA12	TA19	MS5	MS14	TA12	TA19	TA12
SiO ₂	41.3	40.2	40.1	41.0	-	-	-	-	42.2
TiO ₂	-	-	-	-	0.06	0.23	0.10	0.12	2.66
Al ₂ O ₃	-	-	-	-	28.0	52.7	59.1	44.8	13.8
Cr ₂ O ₃	-	-	-	-	41.0	14.4	7.43	21.2	0.77
FeO	8.8	10.5	10.5	8.6	17.0	13.8	11.4	12.0	4.60
NiO	0.42	0.23	0.43	0.40	0.15	0.25	0.58	0.25	-
MnO	0.10	0.15	0.18	0.13	0.22	0.01	0.13	-	-
MgO	48.9	48.0	48.7	49.0	15.6	18.8	21.5	19.5	17.0
CaO	0.03	0.08	0.10	-	-	-	-	-	10.3
Na ₂ O	-	-	-	-	-	-	-	-	2.79
K ₂ O	-	-	-	-	-	-	-	-	0.10
SUM	99.6	99.2	100.0	99.1	102.0	100.2	100.2	97.9	94.2
Fo	90.7	88.9	89.0	90.9					

diopside in MS14 is *LREE* enriched and indicates that *LREE* are uniformly distributed within crystals and present in the structure, so eliminating the need to invoke minor phases as the host for *REE*. This supports earlier work using leaching techniques (Grey and Prinz, 1978) which are less specific. In TA12 *LREE* were undetected by ion probe in the diopside.

Mass balance calculations. Mass balance calculations were made (Table I) to determine whether all elements in each bulk rock are contributed solely from the analysed phases. Good agreement was obtained for major and minor elements for all four rocks (Table I), but there is a discrepancy with MS14 if the mineralogical composition is based on the Na₂O and CaO contents, 0.20 and 2.16 wt. %, respectively, of the sample prepared for INAA. However, there is good agreement between the mode and the original analysis and it is concluded that the small sample used for INAA is abnormally poor in diopside. Thus the *REE* abundances calculated from the contribution from the pyroxenes (MS14*, Table I) are more likely representatives of the rock than those measured directly. Mass balance is obtained between the *REE* abundances in the bulk and the calculated contribution from the TA12 pyroxenes, so amphibole is not a significant contributor of *REE*.

Mass balance is not obtained from the *REE* in either of the depleted xenoliths. For MS5 we can eliminate sampling as the cause, and conclude from the compositions of the pyroxenes that the rock is a residue after basalt extraction and that the *REE* are concentrated in a minor phase along grain boundaries, as inferred by Frey and Green (1974)

for some Victorian xenoliths. A harzburgite xenolith from Kafenstein (Ka167, Kurat *et al.*, 1980), chemically similar to MS5, was interpreted as depleted mantle contaminated by a phase rich in *LREE*, but MS5 requires some *HREE* also. In TA19, *REE*, TiO₂, Na₂O, and K₂O are over abundant relative to their contribution from the pyroxenes (TA19*). These elements and oxides were probably contributed by the glass which is essentially homogeneous and of composition: SiO₂, 55.0; TiO₂, 2.62; Al₂O₃, 16.8; Cr₂O₃, 0.16; 'FeO', 3.83; MnO, 0.09; MgO, 4.57; CaO, 8.62; Na₂O, 2.95; K₂O, 1.75; P₂O₅, 1.00; Sum, 97.4 (mean of five microprobe analyses). The difference between TA19 and TA19* (Table I) indicates that the glass is *LREE* enriched. This conclusion was confirmed by ion-microprobe analysis in which selected isotopes from La to Dy were measured using *REE*-doped Ca-Al-silicate glass standards (Reed, 1981). Interferences from *LREE* oxides affecting *HREE* from Gd upwards were avoided by using *HREE* oxide peaks, and a correction was applied where examination of peaks at high resolution revealed significant interference from matrix molecules. Estimates of the abundances of *REE* in the glass range from more than 150 times chondritic at La and Ce to less than 50 times for Gd, Tb, and Dy, and although there may be some uncertainty, *LREE* enrichment is clearly demonstrated.

Discussion. All four xenoliths of this study have chrome diopside so they belong to the Group I category of Frey and Prinz (1978). Frey and Green (1974) interpreted Victorian xenoliths (of Group I) as mixtures of two components: a primitive, residual 'component A' contributes major elements

and *HREE*, while 'component B' contributes K and *LREE*. Component B in some cases could be a fractionated magmatic liquid (Frey and Green, 1974) while in others it could be a metasomatic fluid (Frey and Prinz, 1978). Both MS5 and TA19 are consistent with this interpretation, and in the latter xenolith component B is identifiable as the red-brown glass, the presence of 2–3 wt. % of which can account for the *REE*, TiO_2 , Na_2O , and K_2O measured in bulk TA19. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio, with a value of 2, in the glass is not commensurate with a single mineral as its source, unlike glasses in Victorian xenoliths (Frey and Green, 1974) or in amphibole-bearing xenoliths from Dreiser Weiher (Stosch and Seck, 1980). Furthermore, the glass has 9.4 mol. % normative quartz and the composition of an andesite with abnormally low $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio (0.32), so it cannot be related to the nepheline normative host basalt (Hutchison *et al.*, 1975). The FeO/MgO ratio in coexisting olivine and glass are consistent with the K_D of Roeder and Emslie (1970), indicating that the two phases were in equilibrium. Thus the glass was intruded as a liquid into the harzburgite within the upper mantle.

In a review, Menzies (1983) subdivided Group I into Type 1A, comprising xenoliths of which the diopside is *LREE* depleted (like component A), and Type 1B, of which the diopside is *LREE* enriched. Clearly, TA12 belongs in Type 1A, and MS14 in Type 1B. However, by Menzies' (1983) definition, amphibole in TA12 indicates that the rock is metasomatized, but diopsides of previously described, metasomatized Type 1A xenoliths are *LREE* enriched, in contrast to TA12, which therefore represents component A upper mantle hydrated by an aqueous fluid without the addition of *LREE*.

MS5 and MS14, by Menzies' definition, belong to the Type 1B 'unmetasomatized' category. The former xenolith is normal in that its high degree of *LREE* enrichment relative to *HREE*, is coupled with low Al_2O_3 , CaO and Na_2O contents. MS5 is therefore consistent with the statement of Frey (1984) that in spinel peridotite xenoliths from world-wide localities, *LREE* abundances negatively correlate with CaO. A corollary of this is that *LREE* enrichment is most extreme in the diopsides that constitute the lowest modal proportions of their bulk rocks (Frey and Green, 1974; Frey and Prinz, 1978). This clearly holds for MS5 and MS14, the diopside of the harzburgite, MS5, having a chondrite-normalized La/Yb ratio of 10.7 compared with 3.6 in the lherzolite, although the latter is richer in bulk *REE*, including La. Furthermore, bulk MS14 is, we believe, unique among all unmetasomatized spinel peridotite xenoliths studied to date in that it combines high Al_2O_3 , CaO, Na_2O , and *HREE* contents with *LREE* enrichment. Here

is a rock significantly enriched in component B but with essentially undepleted component A. The closest similarity is perhaps with an Ethiopian xenolith, 3G17, but this has only about half the CaO, La, and Yb contents (Ottonello, 1980) actually measured in bulk MS14.

Chemically, TA12 and MS14 differ significantly only in their K_2O and *LREE* contents, so, if TA12 essentially represents component A, and MS14 represents TA12 plus some component B, then component B must consist predominantly of these elements. In this case component B cannot have been magmatic but was presumably a metasomatic fluid. Interaction between the fluid and component A, followed by dehydration and recrystallization, would have incorporated the *LREE* into diopside, as suggested for other xenoliths (Frey and Prinz, 1978; Menzies, 1983). MS14, then, is a sample of anhydrous mantle enriched in *LREE* and K_2O , while TA12 is, in contrast, a sample of hydrous mantle depleted in these elements. Apart from a few occurrences within a few millimetres of the margin of TA12 the amphibole is clear and shows no reaction relationship, indicating that hydration and growth of amphibole preceded incorporation of the rock as a xenolith into basalt. A further possibility is that 'primitive' mantle neither enriched nor depleted in K_2O or *LREE* has experienced a redistribution of these elements to produce some parts (e.g. MS14) relatively enriched in *LREE* and K_2O and others (e.g. TA12) relatively depleted.

We essentially discuss only two rocks so their significance for mantle chemistry in general may be questionable. However, we cannot estimate the volumetric proportions in the mantle of rock types represented in suites of xenoliths brought up by basaltic magmas. Each of the two rocks has a mineral assemblage consistent with crystallization in the upper mantle and their different trace element signatures must have been established there. Thus the properties of only two rocks may be instructive in elucidating the processes that controlled mantle chemistry. Furthermore, abundances of CaO, Na_2O , and K_2O in the suites of xenoliths from Tarreyres and Monistrol d'Allier (fig. 1) and the evidence for coupling between K_2O and *LREE* in spinel peridotites of Group I (Type 1) from world-wide localities (Frey, 1984) indicate that TA12 and MS14 are probably typical of their respective suites. We are still left with the problem that the scale of depletion and enrichment is unknown: is it tens of centimetres, tens of metres, or tens of kilometres? Whatever the answer, MS14 and TA12 yield new and important results. Enrichment in *LREE* occurred in a dry mantle sample rich in Al_2O_3 , CaO, Na_2O , and *HREE*, and depletion in

K₂O and *LREE* occurred in a sample, with high Al₂O₃, CaO, Na₂O, and *HREE*, that is now hydrated.

The chemical compositions of TA12 may be significant for theories of the production of basaltic magmas. TA12 has a composition like that inferred for the source material of MORB-type liquids (Menzies, 1983) which by its hydrous nature could yield MORB magma at a lower temperature than could material equivalent to unmetasomatized Type IA xenoliths. In contrast, dry mantle with the composition of MS14 (for REE, MS14* in Table I) could yield 5–6% of *LREE*-enriched but volatile-free alkalic basalt. These compositions may be of relevance to the magma source beneath the Isle of Skye, in north-west Scotland. Here there is a Main Lava Series of alkalic to transitional basaltic flows lacking a significant pyroclastic component. Thompson *et al.* (1980) suggested that the magnesian basalt parent of this series was produced by partial melting of spinel lherzolite at 16–20 kbar pressure. The parent, with *LREE* enrichment, a TiO₂ content of 1.77 wt. %, and some normative nepheline, could represent a 5% partial melt from mantle of MS14 composition. Associated with the Main Lava Series are basalts (Preshal Mhor type) that have affinities with MORB and could have been derived from mantle with the composition of TA12. The close spatial relationship inferred for the two mantle sources beneath the Isle of Skye is mirrored by the occurrence of the two suites of mantle xenoliths only 18 km apart in the Massif Central. However, MS14 could not represent the source of many lavas of the Massif Central because some combine a high enrichment in *LREE* with a modest depletion in *HREE* (Chauvel and Jahn, 1984) relative to MS14 diopside. This would require either that the partition coefficient of Yb between diopside and liquid was greater than unity, or that garnet was in the source.

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