

Geochemistry of ultramafic xenoliths and their host alkali basalts from Tallante, southern Spain

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ABSTRACT. Ultramafic xenoliths enclosed in Plio-Quaternary alkali basalts from Tallante near Cartagne (southern Spain) are composed mainly of spinel lherzolites which are probably upper mantle residues. In many xenoliths, the spinel lherzolite is cut by pyroxenite or gabbroic anorthosite veinlets generally 0.2-3 cm thick. The clinopyroxenite veinlets were formed by high-pressure crystal-liquid segregation from alkali basalt magmas formed earlier than the host basalts, whereas mantle metasomatism played a role in the genesis of gabbroic anorthosites. Close to the contact with the veinlets, the spinel lherzolites are enriched in Ca, Fe, and some incompatible elements including light *REE* due to the migration of a fluid from the veinlets into the surrounding lherzolites. The host alkali basalts were derived from a heterogeneous, incompatible element-enriched upper-mantle source probably similar in composition and nature to the composite xenoliths, but were formed in a garnet stability field.

KEYWORDS: geochemistry, ultramafic xenoliths, basalts, Tallante, Spain.

SEVERAL mechanisms have been suggested to explain the high contents of incompatible elements in alkali basalts. They include a low degree ($< 3\%$) of partial melting of chondritic upper mantle (Gast, 1968; Kay and Gast, 1973), melting of a source previously enriched by a metasomatic event (Lloyd and Bailey, 1975; Frey *et al.*, 1978; Wass and Rogers, 1980; Wilshire *et al.*, 1980) and an enrichment of magma by zone refining during its ascent (Harris, 1957; Alibert *et al.*, 1983).

However, there is still not enough critical information on the processes that lead to the generation of alkali basaltic magmas. The purpose of this paper is to present data on the major and trace

element abundances in several ultramafic xenoliths and their host alkali basalts from Tallante, southern Spain. The data are used to place constraints on the petrogenesis of the basaltic and ultramafic rocks and to characterize the source of the alkali basalts and the nature of the metasomatic processes in the upper mantle.

Geological setting

Several small volcanic centres which crop out in the vicinity of the village of Tallante (20 km W. of Cartagne in southern Spain) were dated at 2.6 Ma (Boivin, 1982). In this region, the volcanic activity is associated with Plio-Quaternary rifting which produced a series of small horsts and basins. The volcanic outcrops are mainly composed of basaltic lava flows and a phreato-magmatic diatreme of stratified breccias and basaltic tuffs containing, in addition to high-grade metasedimentary xenoliths, numerous ultramafic nodules the size of which vary from 1 to 15 cm in diameter (Boivin, 1982; Vielzeuf, 1983).

Petrography and mineralogy

The host rocks are typical alkali olivine basalts and basanites. Their olivine and clinopyroxene phenocrysts suggest crystallization temperatures of 1120 °C (geothermometers: Roeder and Emslie, 1970; Leeman and Scheidegger, 1977) and a pressure of 7 kbar (geobarometer: Presnall *et al.*, 1978). The basaltic rocks contain peridotitic xenoliths whose minerals are typical of those in spinel lherzolites world wide. Their equilibrium temperatures (geothermometers: Obata, 1976; Wells, 1977;

Fabries, 1979) are in the range of 820 to 1015 °C, but mostly around 850 °C. These values are too low to represent mantle conditions and probably represent subsolidus re-equilibration.

Peridotite xenoliths are frequently intruded by veinlets of 'basic' rocks (pyroxenite and gabbroic anorthosite) usually 0.2 to 3 cm thick which are sometimes distributed as swarms. The contact between the two rocks are sharp. The pyroxenite veinlets consist mainly of clinopyroxene (usually diopside) and subordinate amounts of olivine, amphibole, and opaque minerals (hematite). Amphibole (Ti-rich kaersutite or pargasite) forms interstitial and poikilitic crystals. It seems that clinopyroxene and olivine are cumulate phases, whereas amphibole is an intercumulus phase (Boivin, 1982). The mineral composition of clinopyroxenite changes slightly close to the contact with the host peridotite. In particular, the Fo content of olivine increases from 79 to 89. Also in the peridotite the mineral compositions vary with the distance from the contact with the clinopyroxenite veinlets. As already shown elsewhere (Irving, 1980) spinel displays systematic variations

in its major element compositions: Fe and Cr decrease while Al increases with distance from the 'basic' veinlets. Relatively rare veinlets of gabbroic anorthosite, composed of plagioclase (85%) and orthopyroxene (15%), are separated from the surrounding peridotite by a thin (1-2 mm) band of phlogopite and rare relics of olivine and spinel. Plagioclase crystals are homogeneous but range in composition from An 92 to An 75 while orthopyroxene corresponds to En 85 Fs 10 Wo 5 with 3-5% Al₂O₃.

Analytical notes

Whole-rock major and trace element data were obtained for three alkali basalts, one spinel lherzolite xenolith and five composite xenoliths. The composite xenoliths were each cut into several slices (3 to 5 mm thick) in order to analyse clinopyroxenite, peridotite, and their contacts separately (Table I). The samples of veinlets recovered for the chemical analyses were 1-2 cm³ in volume and were modally representative of the whole veinlet. The representative character of the

Table I. Major and trace element data for xenoliths and their host basalts from Tallante, southern Spain

	1				2				3											
	6348	6349	6350	6351	Tal-1			Tal-9			Tal-12				Tal-2					
					A	C	D	A	B	C	D	A	B	C	D	A	B	C	D	
SiO ₂	47.06	47.27	47.29	44.70	43.90	44.50	43.52	46.30	45.30	43.72	42.13	44.50	43.11	44.11	42.13	51.43	50.84	44.31	43.31	
Al ₂ O ₃	15.42	14.52	14.68	2.00	6.70	2.00	1.66	6.30	6.53	2.15	1.45	10.90	11.94	3.25	2.45	5.63	5.20	1.76	2.30	
Fe ₂ O ₃	9.18	10.44	10.50	8.75	12.93	9.34	11.25	10.00	9.94	9.52	12.03	9.23	9.75	9.26	13.00	7.57	15.02	10.06	12.93	
MnO	0.16	0.16	0.16	0.12	0.16	0.13	0.15	0.13	0.13	0.13	0.16	0.11	0.11	0.14	0.18	0.12	0.28	0.13	0.16	
MgO	6.82	8.13	7.51	43.49	21.30	42.52	40.30	19.55	20.00	41.95	40.00	12.90	13.46	38.56	37.72	30.43	27.17	40.40	38.25	
CaO	8.77	9.00	9.15	1.51	11.97	1.96	2.50	15.43	14.72	1.83	2.67	15.93	14.98	3.14	3.77	3.34	0.94	2.29	3.05	
Na ₂ O	3.20	3.16	4.05	0.07	1.24	0.08	0.14	0.80	0.85	0.09	0.20	1.76	1.94	0.36	0.28	0.22	0.24	0.10	0.08	
K ₂ O	2.63	2.17	1.13	0.01	0.41	0.01	0.01	0.18	0.23	0.01	0.06	0.73	0.88	0.03	0.12	0.04	0.11	0.01	0.01	
TiO ₂	2.27	2.65	2.55	0.10	2.00	0.10	0.15	1.57	1.87	0.20	0.25	3.94	3.97	0.17	0.28	0.20	0.32	0.11	0.15	
P ₂ O ₅	0.72	0.77	0.78	0.04	0.23	0.04	0.04	0.12	0.09	0.05	0.04	0.12	0.13	0.05	0.04	0.27	0.17	0.04	0.03	
H ₂ O ⁺	3.13	1.50	1.71																	
H ₂ O ⁻	0.71	0.43	0.48																	
Σ	100.07	100.20	99.99	100.79	100.84	100.68	99.72	100.38	99.66	99.65	98.99	100.12	100.27	99.07	99.97	99.25	100.29	99.21	100.27	
[Mg]	.62	.64	.61	.92	.79	.91	.89	.82	.82	.91	.88	.76	.76	.90	.87	.90	.81	.90	.87	
Li (ppm)	9.	7.	9.																	
Rb	79.	58.	24.																	
Sr	860.	830.	826.																	
Ba	900.	745.	755.																	
Sc	16.	17.	17.	10.	32.	12.	12.	43.	42.	11.		48.	44.	16.	13.	14.	24.	12.	13.	
V	194.	205.	208.	44.	261.	55.	55.	277.	287.	53.	58.	430.	454.	79.	76.	60.	137.	54.	60.	
Cr	235.	250.	260.	2540.	1000.	1995.	2235.	1250.	1175.	2825.	1965.	460.	500.	3650.	3060.	3220.	2500.	2370.	3400.	
Co	33.	41.	41.	109.	90.	108.	115.	73.	75.	108.	125.	54.	64.	104.	115.	66.	68.	106.	107.	
Ni	136.	162.	170.	2260.	600.	2155.	2035.	485.	565.	2155.	1875.	345.	450.	2080.	1825.	1200.	755.	2190.	2380.	
Cu	41.	38.	40.	11.	43.	10.	15.	65.	67.	7.	16.	43.	60.	16.	13.	16.	6.	10.	11.	
Zn	90.	100.	102.	139.	83.	70.	74.	56.	54.	76.	75.	50.	48.	82.	102.	67.	155.	68.	110.	
La	64.2	51.0	50.3	0.135	13.0	0.40	1.20	8.50	7.90	0.62	1.60	14.1	13.0	1.30	2.80	16.2	14.7	0.50	2.00	
Ce	119.	101.	99.2	0.39	31.6	0.63	1.90	22.7	21.6	1.26	3.70	34.6	32.6	2.40	5.60	27.80	26.7	1.00	5.10	
Nd	46.7	44.7	44.1	n.d.	18.2	n.d.	n.d.	16.3	n.d.	n.d.	n.d.	25.2	n.d.	n.d.	n.d.	9.0	10.1	n.d.	n.d.	
Sm	8.70	8.60	8.50	0.066	4.70	0.092	0.193	4.30	4.30	0.20	0.50	6.50	6.42	0.37	0.81	1.79	1.55	0.16	0.62	
Eu	2.50	2.57	2.58	0.037	1.43	0.030	0.063	1.31	1.36	0.073	0.14	2.01	2.04	0.12	0.25	0.56	0.24	0.05	0.14	
Tb	1.20	1.10	1.05	0.01	0.58	n.d.	0.38	0.51	0.50	0.045	0.07	0.81	0.82	0.10	0.13	0.27	0.32	0.04	0.10	
Yb	1.79	1.75	1.77	0.116	0.90	0.214	0.24	0.87	0.80	0.20	0.20	1.31	1.26	0.43	0.35	0.61	1.22	0.18	0.38	
Lu	0.28	0.25	0.25	0.022	0.138	0.046	0.054	0.122	0.13	0.032	0.035	0.20	0.18	0.078	0.06	0.09	0.19	0.03	0.06	
HF	6.0	5.3	5.4	0.10	1.8	0.10	0.20	1.7	1.6	0.10	n.d.	3.3	3.1	0.20	0.30	1.30	6.8	0.10	0.20	
Th	27.8	17.1	16.7	0.20	5.8	0.20	0.50	2.7	2.0	0.50	n.d.	3.5	3.5	0.40	0.30	1.10	6.7	0.30	0.50	

1 - alkali basalts, 2 - xenoliths of spinel lherzolite without "basic" veinlets, 3 - spinel lherzolite xenoliths with "basic" veinlets; A - core of veinlet; B - veinlet from contact with peridotite; C - lherzolite 3 cm from veinlet; D - lherzolite from contact with veinlet; Tal-1, Tal-9 and Tal-12: xenoliths with clinopyroxene veinlets, Tal-2: xenolith with gabbroic anorthosite veinlet. The composite xenoliths contain variable proportions of veinlets: Tal-1 = 50%, Tal-9 = 60%, Tal-12 = 30%, and Tal-2 = 15%. n.d. - not detected; [Mg] = (Mg/Mg+Fe²⁺) atom ratio; Fe²⁺/Fe⁴⁺ standardized to 0.15, except for basalts which were standardized to 0.30.

samples was also tested by comparing the analyses of samples from different parts of the same veinlets.

The major elements were analysed by wet methods and Li, Rb, Sr, Ba, V, Cr, Co, Ni, Cu, and Zn by atomic absorption spectroscopy. Rare-earth elements (*REE*) in basalts, together with Sc, Th, and Hf, were determined by instrumental neutron activation, whereas in ultramafic rocks they were analysed by a radiochemical neutron activation technique described by Savoyant *et al.* (1984). The precision and accuracy of the trace element determinations have been reported by Dostal *et al.* (1983) and Savoyant *et al.* (1984). The precision is generally better than 10%. Mineral analyses were carried out on a microprobe in Clermont-Ferrand.

Results

Basalts. The three analysed samples are compositionally similar for all elements except K, Rb, and Th which vary over a large range. Since the variations are restricted to the three incompatible elements which are strongly enriched in the crust it may suggest that these samples have been variably affected by crustal contamination. The basalts are SiO₂-undersaturated with contents of normative nepheline between 3 and 5%. Their [Mg] ratio (Mg/(Mg + Fe²⁺)) with Fe³⁺/Fe²⁺ = 0.15 is 0.61–0.64 and Ni content (< 200 ppm) suggest that they underwent some fractionation. The rocks have chondrite-normalized *REE* patterns (fig. 1) highly enriched in light *REE* (*LREE*), characteristic of silica-undersaturated basalts (Kay and Gast, 1973). Their Ti/V ratio (70–77) is also typical of alkali basalts and could indicate partial melting of a source containing amphibole (Wass, 1980).

Spinel peridotites. Their composition is variable particularly in the composite xenoliths. Samples taken far from the contact with the 'basic' veinlets (> 3 cm distance) have [Mg] ratios between 0.90 and 0.92; their major element composition is similar to the average of the spinel lherzolite of Maaloe and Aoki (1977), xenoliths of the Salt Lake Crater (Reid and Woods, 1978) and also to the peridotite inclusion without veinlets. At the contact with the veinlets, the lherzolites display a decrease of the [Mg] ratio (0.91–0.87) resulting from an enrichment of Fe and a depletion of Mg while Ca increases. Ti, Na, and K either remain constant or slightly increase. Ni and Co generally behave like Mg and Fe: Ni tends to decrease towards the contact with the veinlets while Co increases. All other transition elements show no obvious evolutionary trend.

Several types of *REE* patterns of the spinel lherzolites (fig. 2) can be distinguished.

(a) Sample 6351 from the xenolith devoid of

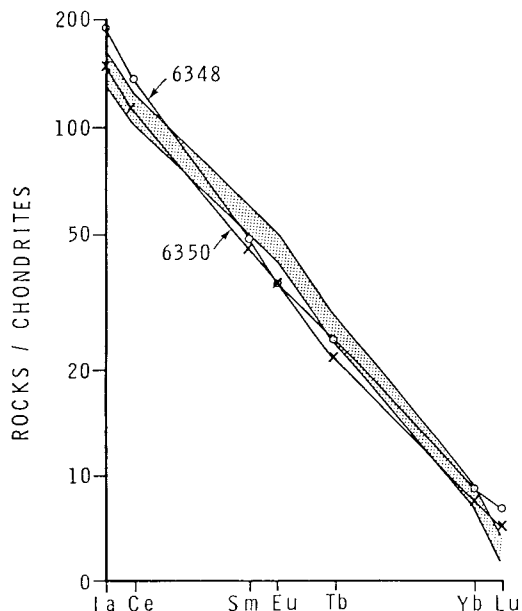


FIG. 1. Chondrite-normalized *REE* contents of alkali basalts from Tallante. The range of *REE* contents in alkali basalts from Western Victoria, SE Australia (Frey *et al.*, 1978) is shown for comparison (shaded area).

intrusive 'basic' veinlets, has the lowest *REE* content and its pattern is marked by a *LREE* depletion.

(b) Samples 6354 and 6355 have U-shaped patterns (fig. 2) characterized by an enrichment of *LREE* and heavy *REE* (*HREE*). These patterns are similar to those of spinel lherzolite type 1B described by Stosch and Seck (1980). The samples in contact with the veinlets (e.g. 6354) display an enrichment of all *REE* without any obvious change in the shape of the pattern.

(c) Samples 6366 and 6367 display a *LREE* enrichment without significant fractionation of *HREE* (fig. 2). These patterns are similar to those of spinel peridotite type 1A of Stosch and Seck (1980). The samples at the contact (e.g. 6366) have larger *LREE* enrichment. In addition to *LREE*, the samples have higher Th and Hf contents. The variations of some incompatible elements are related to the major elements. For example, the *LREE* are strongly correlated with Ca.

'Basic' veinlets. The pyroxenite veinlets have both major and transition element compositions intermediate between basalts and peridotites. Their [Mg] values range between 0.76 and 0.82 and are accompanied by a regular variation of several major and trace elements because of the different mineralogical composition. With decrease of [Mg], the elements Al, K, Na, and Ti increase, whereas Cr

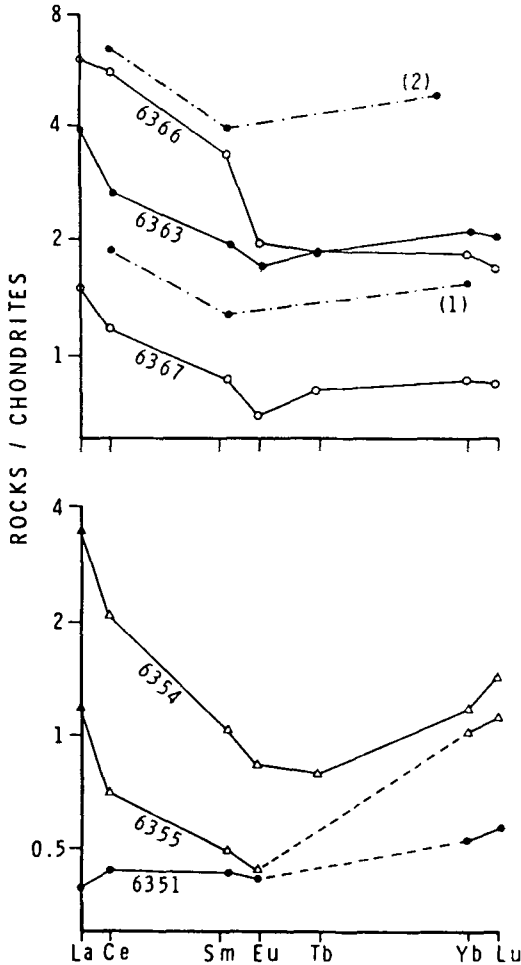


FIG. 2. Chondrite-normalized REE contents of spinel peridotites. Xenolith Tal-1: 6354—contact with clinopyroxene veinlets; 6355—from distance > 3 cm from veinlets; Tal-2: 6366—contact with gabbroic anorthosite veinlet, 6367—from distance > 3 cm from veinlet; Tal-12: 6363—from distance > 3 cm from veinlet. For comparison, the REE abundances in the metasomatized upper mantle peridotite calculated according to equation 7 of Mysen (1979) are shown (dash-dotted lines). The solid-vapour partition coefficients for 20 kbar and 1100 °C of Mysen (1979) were used in the calculation. It was assumed that the upper mantle had REE abundances corresponding to peridotite 6351 and that the source rock had 10 times chondritic abundances. The proportion of the chondritic abundances assumed to be converted into a fluid phase was 0.01, while the proportion of fluid in the rocks was taken to be 0.0025 (line 1) and 0.01 (line 2).

and Ni decrease. Some other elements such as Ca, Sc, and V initially decrease with decreasing [Mg] but then increase to reflect variable proportions of

clinopyroxene. These rocks have REE patterns with flat LREE and fractionated HREE (fig. 3), similar to the patterns reported for pyroxenite inclusions from elsewhere (Frey and Prinz, 1978; Frey, 1980; Ehrenberg, 1982; Miller and Richter, 1982). The studied samples have high La/Yb (10–15) and are relatively enriched in LREE and other incompatible elements suggesting that their cumulate character is obliterated by the presence of a trapped magmatic liquid as an intercumulus phase. The veinlets have transition element contents similar to basalts and are characterized by an enrichment of Ti and a relative depletion of both Cr and Ni compared to the peridotites.

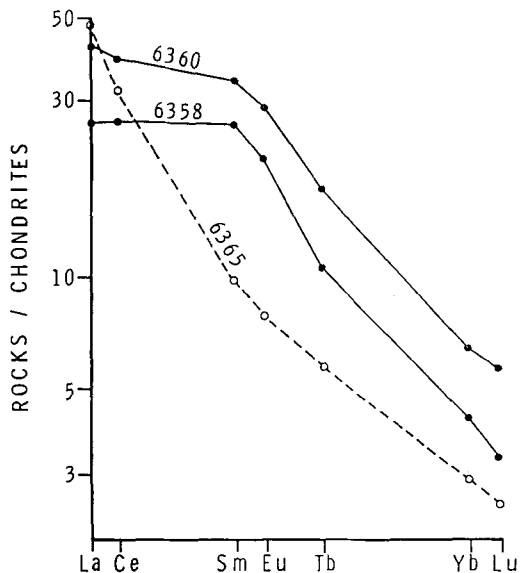


FIG. 3. Chondrite-normalized REE contents of pyroxenite (6358 and 6360) and gabbroic anorthosite (6365) veinlets.

The gabbroic anorthosite veinlet (sample 6365) has a rather different chemical composition. In addition to its high [Mg] value (0.90), similar to that of peridotites, the gabbroic anorthosite sample is enriched in Cr and Ni and depleted in Ti, Na, K, and V. In this respect it resembles the equivalent rock type (PM 65 B) analyzed by Frey and Prinz (1978) but differs from it by a higher P and REE content. The REE pattern is very similar to the analysed basalts with fractionated HREE and La/Yb *c.* 26. The sample (6364) containing phlogopite, which was collected adjacent to the peridotite, has a chemical composition similar to sample 6365 except for its negative Eu anomaly and higher Fe, V, and Ti contents.

Discussion

The presented geochemical data are used to discuss the following petrogenetic problems: (a) origin of 'basic' veinlets; (b) causes of enrichment of large-ion-lithophile elements (*LILE*) in peridotites; and (c) composition of source rocks for basalts.

'Basic' veinlets. It has been suggested that many pyroxene-rich xenoliths and pyroxenite veinlets in peridotite inclusions are cumulates derived from magma with a composition similar to their host basalts (e.g. Irving, 1974; Frey and Prinz, 1978; Irving, 1980). Pyroxenites which occur in the Tallante volcanic centre as veinlets cross-cutting the peridotite nodules show some textural and chemical features consistent with such an origin. The cumulate model is quantitatively evaluated in fig. 4, where the pyroxenite bulk rock *REE* abundances are divided by the *REE* content of the host basalt. The crystal segregation model requires that the *REE* abundance ratios of pyroxenite to the host basalts are similar to the bulk solid/liquid partition coefficients provided that trapped liquids did not significantly affect the trace element abundances in the pyroxenites. In fig. 4, the bulk partition coefficients for *REE* from Sm to Lu are in

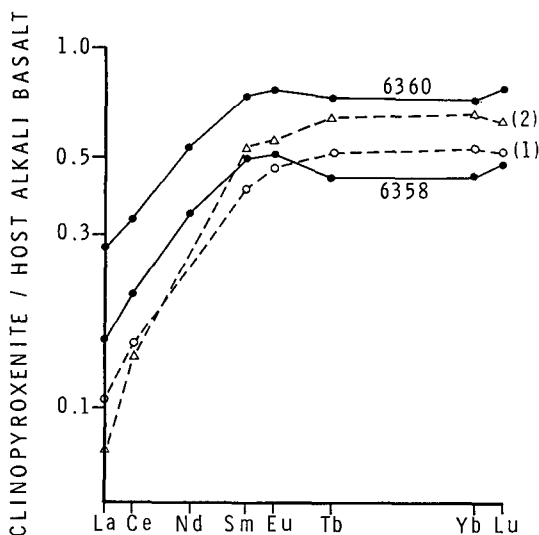


FIG. 4. *REE* abundance ratios of two clinopyroxenites relative to alkali basalt 6349 (solid lines). The dashed lines are the estimated bulk partition coefficients for clinopyroxenite 6360 which has the following modal composition: clinopyroxene 0.49, amphibole 0.46, olivine 0.01 and plagioclase 0.04. The partition coefficients used for the calculation of line 1 are from Irving and Price (1981). Line 2 shows the calculations using the partition coefficients for clinopyroxene of Onuma *et al.* (1968).

agreement with the calculated pyroxenite/basalt ratios. This agreement may also be extended to several transition elements. For example, the clinopyroxenite/basalt ratio for Sc is between 2 and 2.5 which corresponds to the published values for partition coefficients of clinopyroxene (e.g. Frey *et al.*, 1978). However, there is a discrepancy of *LREE* and other highly incompatible element values between the two sets of data. The bulk partition coefficients have lower values indicating, as previously suggested, the presence of a small amount of trapped liquid within the clinopyroxenite. These rocks are relatively enriched in *LREE*, K, and Th, and contain poikilitic amphibole which may represent the crystallization product of the trapped pore liquid. Although the pyroxenite veinlets may be interpreted as upper-mantle cumulates or crystal segregates formed from basaltic melt similar in composition to the host basalts, they are not cognate with the host rocks. The deformation, clinopyroxene exsolution and other textural features (Boivin, 1982) suggest that the pyroxenites of the veinlets were derived from magmas generated earlier.

Because of the *REE* partition coefficients, the veinlets of gabbroic anorthositic cannot be considered as cumulates in equilibrium with an alkali basalt liquid. They have a distinctly fractionated *REE* pattern with a high La/Yb ratio (*c.* 27) which differs from the calculated pattern for plagioclase and orthopyroxene (\pm apatite) separated from a basaltic liquid similar to the host lavas of the xenoliths. The high contents of *LREE* and P in the veinlets also cannot be explained by the presence of a trapped liquid, since K and Na abundances are low (Table I). In fact, their abundances of trace elements are very similar to amphibole-apatite-rich xenoliths from a basanitic dyke studied by Wass and Rogers (1980) who suggest that the enrichment of *LREE* is the result of a mantle metasomatism.

LILE enrichment in peridotite xenoliths. Peridotite xenoliths display a wide range of composition evolving between two extremes. One extreme is represented by sample 6351 (xenolith without veinlets) which has a typical spinel lherzolite composition characterized by high [Mg] values, depletion of Ti, Ca, Al, and half of chondritic *REE* abundances. The other extreme, sample 6363 (composite xenolith), has the major element composition of pyrolite (Ringwood, 1975). This similarity also extends to some trace elements, for example the contents of Yb (0.43 ppm) and Sc (16 ppm), which are close to the pyrolitic estimate of Jagoutz *et al.* (1979).

The compositional changes include systematic variations, such as a positive correlation of Na₂O

and K_2O which is typical of upper-mantle residue after the extraction of basaltic magma (Green and Ringwood, 1967). Further evidence relating various peridotite xenoliths by a crystal-liquid equilibria process is provided by the correlation among Sc, V, Cr, and HREE. According to Frey and Green (1974) such a correlation may be attributed to fractionation of clinopyroxene. However, this mechanism alone cannot explain all the observed characteristics (e.g. high contents of REE, U-shaped REE patterns). Similar REE patterns and concentrations in peridotite xenoliths have been attributed to metasomatic activity (Stosch and Seck, 1980). In addition, the data in Table I show that REE progressively increase in the peridotite xenoliths toward the contact with the pyroxenite veinlets, suggesting contamination of peridotite during the emplacement of these veinlets. Frey and Green (1974) have suggested that such contamination results from the introduction of small amounts of basaltic liquid into the xenoliths. However, this explanation is not corroborated by the thin section observations which indicate that peridotites are devoid of basaltic liquid. It is also inconsistent with the calculation of simple mixing of basaltic liquid and peridotite xenoliths, involving REE and K. Furthermore the fission tracks show that the bulk of the U (and probably also REE) is present in the mineral phases where it is uniformly distributed.

Several authors (Mysen, 1979; Wendlandt and Harrison, 1979) have proposed that mantle metasomatism by a H_2O and/or CO_2 -rich vapour which has relatively high REE concentrations can produce the REE enrichment in peridotite nodules. A model calculation of such a process (fig. 2) reproduces both the enrichment of REE and their U-shaped pattern observed in the lherzolites and suggests that all composite xenoliths are variably contaminated by volatile-rich fluids which accompanied the emplacement of the pyroxenite veinlets.

Source composition for basalts from Tallante. The composition of the upper-mantle source was calculated using the most primitive analysed basalt (sample 6349). Assuming that primary melts from the upper-mantle peridotite have [Mg] around 0.7, the composition of basalt 6349 with [Mg] of 0.64 was corrected for the effects of low-pressure fractionation to obtain a possible primary magma. Compositional changes were assumed to be caused by fractional crystallization of olivine. To estimate the degree of partial melting required to generate such a primary melt it was assumed that the content of Yb in the parental source was 0.22 ppm which is the average content in the peridotite samples taken at a distance of at least 3 cm from the veinlet. This value is also close to that of chondrites. The composition of the residue was taken as the modal

Table II. Comparison of abundances of transition elements in peridotite xenoliths and calculated source of host alkali basalts

	$x(\pm s)$	C^1	C^A
V (ppm)	59 (11)	184	49
Ni	2104 (166)	356	2310
Co	111 (6)	60	124
Zn	84 (26)	100	91
Sc	12 (2)	16	13

$x(\pm s)$ - mean and 1 standard deviation for 9 analysed samples of peridotite xenoliths (Table I), C^1 - hypothetical primitive upper mantle liquid derived by addition of 10% of olivine to the basalt 6349; the partition coefficients were compiled from Hart and Davis (1978), Glassley and Piper (1978), Lindstrom and Weill (1978), Dupuy et al. (1980), Stosch (1981) and our unpublished data. C^A - calculated compositions of the upper mantle source for C^1 derived by 8.5% of melting.

proportion of peridotite Tal-1 (olivine 0.75, orthopyroxene 0.17, clinopyroxene 0.07 and spinel 0.01). The calculations resulted in a degree of partial melting of 10.5%. The extent of partial melting for basalts was also calculated from the P_2O_5 contents assuming a pyrolite source and complete partitioning of this element into the melt (cf. Frey et al., 1978). The value obtained was 8.5%. Both these figures were then used to calculate the composition of REE and some transition elements in the upper-mantle source for basalt 6349. The calculated abundances of transition elements in the source (Table II) are in agreement with the average abundances in the peridotite xenoliths indicating that the spinel peridotites could represent a source for basalts. The results of similar calculations for REE are shown on fig. 5 where they are normalized

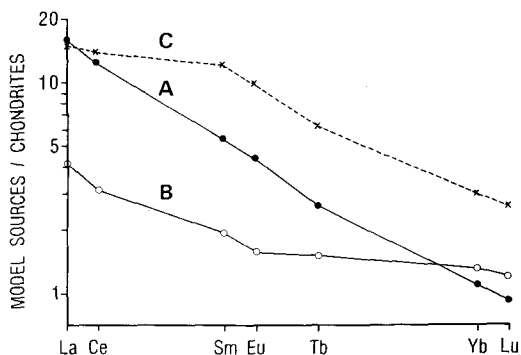


FIG. 5. REE abundances in the calculated mantle sources for alkali basalts from Tallante (line A). The parameters of melting are given in the text; the partition coefficients are from Frey et al. (1978) (Set I). The line B is the average of nine peridotite xenoliths of Tallante (Table I), whereas line C is the mixing of this average with pyroxenite veinlet 6360 in the proportion 7:3.

to chondrites. The upper-mantle source for basalts and the compositional range of peridotite xenoliths have similar heavy *REE* concentrations but for middle and light *REE* the calculated source is much higher. Fig. 5 shows, however, that the discrepancy decreases if spinel peridotites contain pyroxenite veinlets. Composite xenoliths containing about 30% veinlets have a composition closely approximating that of the calculated source. However such a source cannot fully account for the fractionation of *REE*. The highly fractionated *REE* patterns of alkali basalts require the presence of garnet in addition to clinopyroxene (\pm amphibole) in the residue after the melting of the metasomatized veined upper mantle. Thus, the available data suggest that garnet peridotites containing abundant pyroxenite veinlets and compositionally similar to the composite xenoliths are a more likely source for alkali basaltic rocks. In fact, the bulk composition of some composite xenoliths is similar to that of pyrolite (Ringwood, 1975).

Conclusion

The pyroxenite veinlets are similar to cumulate xenoliths found elsewhere (e.g. Frey, 1980, 1983; Irving, 1980). They probably originated within the upper mantle by crystal segregation from a basaltic liquid which had some *REE* and transition element abundances similar to the host basalts. However deformation and other textural features suggest that the pyroxenite veinlets do not have a direct cognate relationship with the host basalts. In fact, their formation preceded that of the basalts. The pyroxenites mainly consist of crystals physically separated from their coexisting equilibrium liquid by a mechanism such as crystal-liquid separation within narrow conduits or a dynamic flow crystallization during migration of basaltic magma through spinel lherzolite (Irving, 1980).

As in some other localities (e.g. Frey and Green, 1974; Frey, 1983), the major and transition element abundances of the spinel lherzolites with $[Mg] > 0.87$ suggest that these rocks are partial melting residue after extraction of basaltic liquid from an upper-mantle peridotite. These xenoliths are lower in Al, Ca, Na, Ti, Sc, and V and higher in Mg and Ni than pyrolite (Ringwood, 1975). On the other hand, the composite xenoliths have bulk major element compositions similar to upper-mantle pyrolite.

Compared to the simple spinel lherzolite xenoliths (without 'basic' veinlets), peridotites from the composite xenoliths have variable but higher contents of Ca, Ti, and *REE*. The abundances of several incompatible elements, particularly *LREE*, increase towards the contact with the pyroxenite veinlets. It seems that these abundances in peridotites were

affected during the emplacement of the pyroxenite veinlets. Such a contamination probably resulted from migration of a fluid enriched in these elements into the surrounding lherzolite where it produced compositional variations. This suggests that the upper mantle has highly heterogeneous contents of several incompatible elements even within a single rock-type and within a distance of a few centimetres.

The calculations show that the source for alkali basalts from Tallante had concentrations of transition elements similar to those of associated peridotite xenoliths but had significantly higher abundances of *LREE*. The enrichment of *LREE* in the source prior to the partial melting event can be explained by the melting of a heterogeneous upper-mantle source consisting of pyroxenite veinlets and peridotite similar to that of the composite xenoliths. However, a veined upper-mantle source cannot account for all geochemical features of alkali basalts. The strongly fractionated *REE* patterns of these rocks require the presence of garnet in the melting residue.

The data on the composite xenoliths suggest a multi-stage evolution of the upper mantle beneath Tallante, characterized by repeated melting events interjected with periods of metasomatism accompanied by the emplacement of the 'basic' veinlets. The lherzolites are upper-mantle residue which was later cross-cut by pyroxenites derived from a basaltic liquid very similar to the host rocks but formed earlier. At some later stage, the veined lherzolites were scavenged by rising alkali basalt magma. The host magma was generated at a greater depth, in the garnet stability field, by the melting of veined upper mantle.

Our results also support the model of Hanson (1977) which assumes that the upper mantle has heterogeneous abundances of trace elements due to the occurrence of abundant pyroxenite veinlets.

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