

MECHANISMS OF MANTLE METASOMATISM: RE-EXAMINATION AND MODELLING OF WALL-ROCK REACTIONS IN THE LHERZ PERIDOTITE, BASED ON SIMS, ICP-MS AND ND-SR ISOTOPIC DATA

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ABSTRACT

In the Lherz orogenic peridotite, Bodinier et al. (1990) studied a 65 cm section of harzburgite wall-rock perpendicular to an amphibole pyroxenite dike. Their results revealed significant mineralogical and chemical zonation of the wall-rock. At less than ~ 20 cm from the dike/wall-rock boundary, the peridotite is modally metasomatized and displays patterns of decreasing concentrations of Fe, Ti, Mn, Al, Ca, Na and HREE, and increasing concentrations of Mg and Ni away from the dike. In this zone, the chondrite-normalized REE patterns are convex-upward in shape and relatively unfractionated ($La_N/Yb_N \sim 1$). At > 20 cm from the dike, the peridotites display the typical features of cryptic metasomatism, i.e., selective LREE enrichment in otherwise anhydrous mineralogy except for the presence of very small amounts of apatite (<< 1 %) (Woodland et al., 1996). The normalized REE patterns vary from U-shaped at 15-25 cm ($La_N/Yb_N \sim 1.7-2.6$) to strongly LREE-enriched at 25-65 cm ($La_N/Yb_N \sim 3-16$). This variation encompasses almost the whole range of LREE/HREE ratios in metasomatized mantle xenoliths from alkali basalts. Bodinier et al. (1990) explained wall rock zonation as a single-stage process involving progressive chemical evolution of melts infiltrated from the vein into the harzburgite wall-rock. In this model, which is supported by a 1-D numerical simulation of diffusion and advection-controlled metasomatism, the compatible and moderately incompatible elements are buffered by the wall rock peridotite proximal to the vein (< 20 cm) whereas distal to the vein the most incompatible elements remain controlled by the infiltrated melt. This mechanism results in a chromatographic fractionation of REE and accounts for the high LREE/HREE ratios observed distal from the vein (see, also, Zanetti et al., 1996).

However, Nielson and Wilshire (1993) criticised this interpretation. In particular, they questioned the ability of mantle melts to percolate through lithospheric peridotites over distances greater than a few centimeters. This negated the very existence of chromatographic fronts in the upper mantle (Navon and Stolper, 1987). They suggested an interpretation for the Lherz wall-rock that involved multi-stage metasomatism with a requirement for vein conduits not seen in the peridotite block. At first sight, this interpretation is supported by Nd-Sr isotopes (Downes et al., 1991) in three samples of the wall-rock block. These ratios indicate that the isotopic signature of the dike does not extend over more than 20 cm into the wall rock. Yet, the strong LREE enrich-

ment typical of the host peridotite at > 25 cm from the dike has never been observed in peridotites unrelated to amphibole-pyroxenite dikes, neither in Lherz nor in other Pyrenean peridotites (Bodinier et al., 1988; Downes et al., 1991; Fabriès et al., 1998; Burnham et al., 1998). On the other hand, a similar composition has been found in harzburgites from the small Montaut massif (western Pyrenees), which contain abundant and massive (meters thick) amphibole-feldspar segregates.

To re-examine the possible links between cryptic and vein-related, Fe-Ti metasomatism and to further constrain the mechanisms of mantle metasomatism, we cored new samples in the peridotite block at Lherz. Woodland et al. (1996) reported petrographic observations and f_{O_2} measurements for these samples. For the present study, SIMS analyses were performed at Woods Hole, and Sr-Nd isotope data at Royal Holloway, Egham. In addition, some samples previously analyzed by AAS and INAA (Bodinier et al., 1990) were re-analyzed by ICP-MS, at Montpellier. Furthermore, the plate model proposed by Vernières et al. (1997) for the simulation of trace-element mobilization during melt-rock interactions has been adapted for radiogenic isotopes and applied to the data obtained for this study.

In agreement with the previous bulk-rock INAA data, the SIMS analyses show a progressive increase in the LREE/HREE ratio in cpx away from the dike, with a maximum at 30 - 60 cm distance where La_N/Yb_N values are in the range 14 - 18. This variation is merely a reflection of a significant increase in the concentration of the LREE in cpx. From values in the range 10 - 30 at < 20 cm from the dike, the chondrite-normalized La, Ce and Nd contents increase up to values in the range 40 - 110 at > 30 cm in the wall-rock. Conversely, Zr and Ti in cpx (as well as HREE, to a lesser degree) decrease markedly and reach a minimum at 30 - 60 cm, where Zr_N is in the range 3 - 5, compared with 20 - 50 at < 20 cm from the dike. These variations result in contrasted chondrite-normalized trace-element patterns for cpx. In the modal zone (< 20 cm from the dike) the cpx patterns are poorly fractionated, slightly convex and smooth in shape, except for a subtle positive anomaly of Zr ($Zr_N/Sm_N = 1.3 - 2.3$). In contrast, cpx from the cryptic zone (> 30 cm) has strongly fractionated (LREE-enriched) trace-element patterns with negative anomalies of Zr and Ti. At 30 - 60 cm from the dike, the Zr_N/Sm_N and Ti_N/Dy_N ratios in cpx are systematically lower than 0.1. The bulk-rock ICP-MS

analyses confirm the strong fractionation of trace elements in the wall rock as a function of distance from the dike. Similar to the LREE, Th and U are strongly enriched in the cryptic zone while the HFSEs (Nb, Ta, Zr and Hf) are depleted. The LILE-enriched, HFSE-depleted trace-element patterns observed at > 30 cm from the dike are identical to the patterns found in mantle xenoliths and ascribed to carbonate-melt metasomatism (e.g., Ionov et al., 1993). To our knowledge, this signature has never been reported from peridotite massifs. The resemblance to carbonate-melt metasomatism is enhanced by the presence of apatite (Woodland et al., 1996).

The contrasted geochemical signatures of the modal and cryptic zones is also emphasized by the Nd-Sr isotopes. Close to the dike/wall-rock contact (< 10 cm), the wall rock has an isotopic signature ($\epsilon_{Nd} = 6$ to 7 ; $\epsilon_{Sr} = -20$ to -25) comparable to that of the dike itself and other amphibole pyroxenites in Lherz (Downes et al., 1991; Mukasa et al., 1991; McPherson et al., 1996). Farther into the wall-rock, the isotopic composition evolves towards more enriched values, reaching $\epsilon_{Nd} = -5$ and $\epsilon_{Sr} = +10$ at > 20 cm. The enriched isotopic signature of the cryptic zone is consistent with its refractory, harzburgitic composition. Indeed, in Lherz and other eastern Pyrenean lherzolite body, the peridotites unrelated to dikes and pyroxenite layers show a negative correlation between Nd-Sr isotopic enrichment and "fertility" (Downes et al., 1991). The samples collected at > 20 cm from the dike plot on this correlation and are therefore considered to represent the isotopic signature of the wall-rock protolith prior to dike emplacement. Conversely, the samples collected at < 20 cm from the dike plot away from the correlation and were clearly contaminated during dike emplacement.

Trace-element variations, comparable to those observed in the Lherz wall-rock, have been reported from several suites of mantle xenoliths (e.g., Hauri et al., 1993; Bedini et al. 1997, Baker et al. 1998). Bedini et al. (1997) observed similar variations in xenoliths from the East African Rift, that correlate with textural/mineralogical features and equilibrium temperatures. In mantle xenoliths, flat trace-element patterns are observed in relatively high-T, apatite-free samples whereas the LILE-enriched, HFSE-depleted signature is typical of lower-T, apatite-bearing samples. Bedini et al. (1997) ascribed this variation to a km-scale, single-stage process involving gradual solidification of melt infiltrated into the lithospheric mantle through successive melt-rock reactions down a conductive, thermal gradient. This process would be associated with strong chemical evolution of the melt, from an originally basaltic composition to progressively volatile-enriched compositions, culminating in low-T, small volume carbonate melts. This model is supported by trace-element modelling (Vernières et al., 1997) showing that the ultra-enriched LREE and Th-U compositions can be explained by the coupled effects of melt movement and reactions at decreasing melt mass. In contrast, HREE and compatible elements are buffered by the peridotite minerals (olivine, opx, cpx), while the HFSE and Rb-Ba are buffered by very small amounts of Ti-oxides and phlogopite, respectively.

The same model can be applied to the Lherz wall rock to account for the observed trace element variation with a single-stage process. The only significant difference with the model of Bedini et al. (1997) is that the distance of percolation would be much shorter. However since the host peridotites were at a temperature of about 900 - 1000°C during

dike emplacement (Fabriès et al., 1991), the wall rock experienced a similar temperature gradient to that envisioned by Bedini et al. (i.e., a few hundred degrees) provided the dike was active. The fact that the isotopic signature of the dike is restricted to the modal zone is not inconsistent with this model. With the use of numerical modelling, we have demonstrated that Nd-Sr isotopic contamination, by infiltrated silicate melt, does not extend beyond the chromatographic fronts of these elements. In contrast, the ultra-enrichment of LILE occurs distal to the vein within the wall-rock, between the chromatographic fronts and the infiltration front. This resolves the paradox of the spatial decoupling between isotopic contamination and LILE enrichment.

In detail, the fact that several elements with distinct incompatibility degree have their chromatographic fronts coinciding with the transition between the modal and cryptic zones (20 - 30 cm) suggests that this transition corresponds to a significant drop in the melt/rock ratio and was bounded by a thermally-controlled, permeability barrier along which infiltrated silicate melts were refracted. Yet, the boundary was traversed by low-T small melt fractions, probably carbonatitic in composition. In that sense, the modal zone may be considered as a small-scale analogue of the thermal boundary layer, at base of lithospheric mantle infiltrated by plume-derived melts (Bedini et al., 1997; Baker et al. 1998; Xu et al., 1998).

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