

SUPERIMPOSED METASOMATIC PROCESSES IN THE LITHOSPHERIC MANTLE BENEATH THE EAST AFRICAN RIFT: A SINGLE MELT SOURCE?

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Studies of mantle xenoliths have pointed to the importance of melt and fluid migration as a major control upon geochemistry of the mantle lithosphere, with the most obvious effects being crystallization of secondary minerals (patent metasomatism) and chemical enrichment of incompatible trace elements (cryptic metasomatism). In addition, melt-rock reactions marked by significant modal variations of the predominant rock-forming minerals (olivine and pyroxenes) are observed in high-temperature orogenic peridotites (Kelemen, 1990). The latter have been ascribed to infiltration of asthenospheric magmas in the lower lithosphere, which may occur pervasively (Van der Wal and Bodinier, 1995) or through porous-flow channels (Takazawa et al., 1992). Interaction with basaltic magmas "en route" to the surface was also invoked for the "Fe-Ti metasomatism" observed in wall-rocks of vein-conduits, both in xenoliths and in orogenic peridotites (Menzies et al., 1987; Bodinier et al., 1990). However, the more pervasive forms of metasomatism observed in xenoliths are generally ascribed to volatile- and potassium-rich siliceous fluids, or to carbonate melts (e.g., Menzies et al., 1987; Rudnick et al., 1993). The importance of these fluids as potential metasomatizing agents is confirmed by their existence as micro-inclusions trapped in diamond and silicates (Navon et al., 1988; Schiano and Clocchiatti, 1994). Because of their low viscosity and solidification temperature, they can percolate through very small porosities and infiltrate large volumes of lithospheric peridotites at relatively low temperature. However, the origin of these metasomatic fluids is still debated. For some authors, they are "pristine" melts formed by very low melting degrees of the convective mantle (Zindler and Jagoutz, 1988; McKenzie, 1989). For others they represent differentiated liquids resulting from the crystallisation of basaltic or kimberlitic magmas at depth (Navon et al., 1988; Akagi and Masuda, 1988). In this study of spinel peridotite xenoliths from the Sidamo region (Southern Ethiopia), we present evidence for superimposed metasomatic processes in the lithospheric mantle beneath the East African Rift. Our data lend support to the hypothesis that small fractions of volatile-rich fluids and carbonate melts may derive from basaltic magmas reacting with lithospheric peridotites.

The studied xenoliths range in composition from fertile, cpx-rich, lherzolites to refractory harzburgites with highly variable cpx/opx ratios. They are virtually exempt from patent metasomatism, except for minor amounts of apatite in some samples. The textures vary from porphyroclastic in the apatite-bearing peridotites to coarse-grain recrystallized in the cpx-rich, apatite-free, peridotites. Between these two end-members, the peridotites show a textural evolution marked by increasing degree of recrystallization. The 40 samples selected for the geochemical study were analyzed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) for Rare Earth Elements (REE) and several incompatible trace elements (Rb, Cs, Sr, Ba, Sc, Y, Ti, Zr, Hf, Nb, Ta, Th and U). In addition, the predominant rock-forming minerals were separated from representative samples and analyzed by ICP-MS after acid leaching. The acid-leachates obtained during this procedure were also analyzed. As preliminary results pointed to the importance of spinel-related micro-phases, a complex leaching procedure involving different acids was applied to three separates of this mineral. Furthermore, spinel surfaces were investigated by Scanning Electron Microscopy (SEM) and Electron Probe Micro-Analysis (EPMA) to determine the composition of the attached micro-phases.

None of the studied samples has a trace-element depleted composition comparable to the Depleted MORB-Mantle (DMM), which is generally considered to represent the protolith of the lithospheric mantle (e.g., Jochum et al., 1989). The recrystallized lherzolites are characterized by light-REE (LREE) depleted compositions (N-MORB-type), but they are enriched in highly incompatible trace elements (Rb, Ba, Th, U, Nb, Ta) compared to DMM. All the other samples are

LREE-enriched. A striking feature of trace-element distribution in peridotites is the existence of an overall correlation with textures, the most enriched compositions being observed in the less recrystallized rock-types (porphyroclastic) while the less enriched compositions are typical of the secondary granular facies. This precludes interpretation of the LREE-depleted granular lherzolites as a preserved protolith that would have been enriched only in the most incompatible elements. In addition, the recrystallized peridotites are characterized by remarkably homogeneous mineral compositions for all elements, in spite of a wide range of modal compositions (lherzolites to olivine-rich harzburgites). This indicates that they have suffered extensive reequilibration in open system (metasomatism). In contrast, the enriched porphyroclastic peridotites display variable mineral compositions as a function of peridotite fertility. This is especially true for moderately incompatible elements such as heavy REE (HREE) and Ti, and compatible elements such as Ni. This feature is indicative of chromatographic effects associated with porous flow, leading to incomplete reequilibration of heterogeneous peridotites with an enriched metasomatizing agent (Navon and Stolper, 1987).

The distinct characteristics of the two types of metasomatism have been reproduced with a numerical model of percolation. While the recrystallized peridotites have been metasomatized by a moderately enriched melt at high melt/rock ratio, the porphyroclastic samples are explained by interaction with a strongly enriched metasomatic agent at lower melt/rock ratio. Notwithstanding the possibility that the different melt/rock ratios could result from distinct durations of the percolation processes, we believe that this parameter more likely reflects distinct porosities of the percolation systems. Indeed, a higher porosity would nicely account for the extensive recrystallization of the granular facies, compared to the porphyroclastic peridotites (Van der Wal and Bodinier). Porosity variation is also consistent with the contrasted nature of the inferred metasomatic agents. A basaltic melt is suggested for the recrystallized peridotites, that are depleted or only slightly enriched in Large Ion Lithophile elements (LILE: Ba, Th, U, Sr and LREE) and lack significant anomalies of High-Field Strength Elements (HFSE: Nb, Ta, Zr, Hf and Ti). In contrast, a carbonate melt is inferred for the porphyroclastic peridotites because of their elevated LILE concentrations coupled with strong HFSE negative anomalies. In agreement with textural evidence, the evolution from heterogeneous mineral compositions in the porphyroclastic peridotites to homogeneous compositions in the recrystallized peridotites indicates that the basaltic metasomatism occurred in a later stage than the carbonate-melt metasomatism. As the carbonate-melt metasomatism is thought to represent a relatively late event in Eastern Africa (Rudnick et al., 1993), both metasomatic processes are probably recent, and related to magmatic activity in the East African Rift.

Detailed study of trace-element bearing micro-components has revealed the existence of a third type of metasomatism in all types of peridotites. This process is attested by thin (< 10 μm thick) reactional layers on spinel surfaces, dominantly composed of phlogopite and Nb-Cr-Fe-rutile. These spinel rims are reminiscent of titanates-bearing metasomatic assemblages in kimberlite-borne xenoliths (Haggerty, 1991) and are considered to represent a cryptic form of the "K-metasomatism" (Menzies et al., 1987). They are probably related to infiltration of volatile- and potassium-rich siliceous melts comparable to the silicate-hosted inclusions described by Schiano and Clocchiatti (1994). Indeed, the acidic and volatile-rich composition of these melts is consistent with rutile precipitation (Ryerson and Watson, 1987; Foley and Wheller, 1990). Hence, cryptic K-metasomatism is probably as widespread in the lithospheric mantle as the silicate-hosted inclusions. This is of enormous importance for the fractionation of some highly incompatible elements (especially Nb and Ta) during mantle processes. Our data indicate that the distribution of Nb, Ta, Cs, Rb, Ba - and to a lesser degree Zr, Hf and Ti - in the studied peridotites is largely controlled by small volumes of phlogopite and rutile associated with spinel. For instance, very small amounts of rutile (0.0005 to 0.015%) account for 65 to 90% of the whole-rock budget for Nb and Ta. However, as it is balanced by negative anomalies in clinopyroxene, Nb and Ta concentration in rutile is not associated with significant positive anomalies of these elements in whole-rocks. As it is very unlikely that phlogopite rims around spinel can be preserved in rocks

affected by subsequent recrystallization and reequilibration with basaltic melts, the K-metasomatism is clearly the latest fluid infiltration event suffered by the studied xenoliths. This leads to suggest that the small fractions of fluids responsible for this metasomatism are not pristine melts from the convective mantle. More likely, they represent differentiation products from basaltic melts, such as those responsible for the basaltic metasomatism. In turn, phlogopite and rutile precipitation from these fluids may be responsible for the evolution of carbonate-rich liquids (Watson et al., 1990). In this scheme, rutile precipitation would nicely account for the strong HFSE negative anomalies typical of carbonate-melt metasomatism.

In conclusion, our results suggest that the lower lithosphere beneath the East African Rift has been chemically modified by metasomatic processes that are all related to infiltration of asthenospheric basaltic melts. Differentiated metasomatic fluids (volatile- and potassium-rich siliceous melts as well as carbonate melts) are thought to evolve from infiltrated basalts through successive stages of melt-rock reactions at decreasing melt volume and temperature. In the lower part of the lithosphere, reactions involving basaltic melts would occur in a high-porosity (> 1%) porous-flow domain probably comparable to the one observed in the Ronda peridotite (Van der Wal and Bodinier, 1995). As in Ronda, melt-rock reactions are associated with extensive recrystallization. Because of the thermal structure of the lithosphere, mineral precipitation (cpx \pm olivine) would increase near the basaltic percolation front, leading to the evolution of residual liquids enriched in incompatible elements and volatiles, and probably also in silica. Because of their low viscosity and crystallisation temperature (down to 1050-1100°C - Olafsson and Eggler, 1983), these liquids can migrate ahead of the basaltic percolation front, in low porosity (< 1%) peridotites. Metasomatic crystallization of phlogopite and rutile after spinel would result in fluid differentiation towards carbonate-rich compositions. The movement of very small volumes of carbonate melt may be responsible for metasomatic enrichment of lithospheric regions up to the 950° isotherm (Wallace and Green, 1988). This process would produce distinct metasomatic fronts leading to chemical stratification of the lower lithosphere. However, channelling effects, as well as subsequent thermal evolution of the lithosphere upon rifting, may significantly disturb the spatial arrangement of the metasomatic fronts. The inferred chemical structure of the lower lithosphere also bears implications for the processes of contamination of asthenospheric melts by the lithospheric mantle. In particular, interaction with rutile-bearing peridotites - or/and with HFSE-depleted peridotites affected by carbonate-melt metasomatism - may account for the genesis of continental flood basalts characterized by negative anomalies of Nb and Ta.

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