

Evidence for young carbonatitic metasomatism in the continental mantle root beneath the Middle Atlas, Morocco

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Introduction

Intra-plate volcanism occurred c. 2 Ma in the Middle Atlas, Morocco and sampled the continental mantle root in the form of variably depleted peridotite xenoliths (olivine modal abundance 54-90%). We present preliminary major element and Os isotope data for whole rock peridotites (n = 11) collected from a single Maar. In addition, constituent clinopyroxenes have been analyzed for trace element and Pb, Sr, Nd and Hf isotope systematics.

Whole-rock major and minor element data

Major element systematics of these spinel-facies off-craton peridotites are variable and range from values more enriched than primitive mantle to depleted compositions ($\text{Al}_2\text{O}_3 = 4.9 - 1.87 \text{ wt\%}$, $\text{SiO}_2 = 41.6 - 44.0 \text{ wt\%}$).

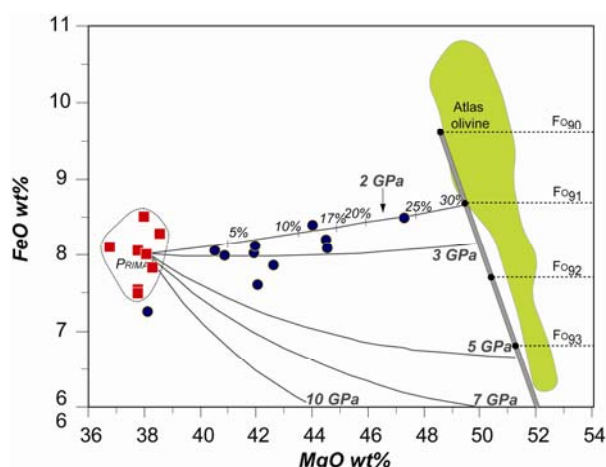


Fig. 1 Whole-rock FeO vs MgO of Middle Atlas peridotites. Polybaric melting trends for various pressures shown in GPa (Herzberg, 2004). Also shown is the range of olivine compositions in Middle Atlas xenoliths.

Generally, major elements such as FeO and MgO plot along ~ 2 GPa melt residue trends indicating up to 25% melt extraction, although some scatter does occur (Fig. 1). Some of this scatter could be explained by moderate addition of pyroxene. Considering such a spinel-facies melting scenario, Sc and V abundances confirm the range of melt extraction and indicate $f\text{O}_2$ conditions (~NNO-1 to -2, Fig. 2) similar to those anticipated for abyssal peridotites (Canil, 2002 & 2004), thus suggesting depletion in a setting akin to present-day mid-ocean ridges.

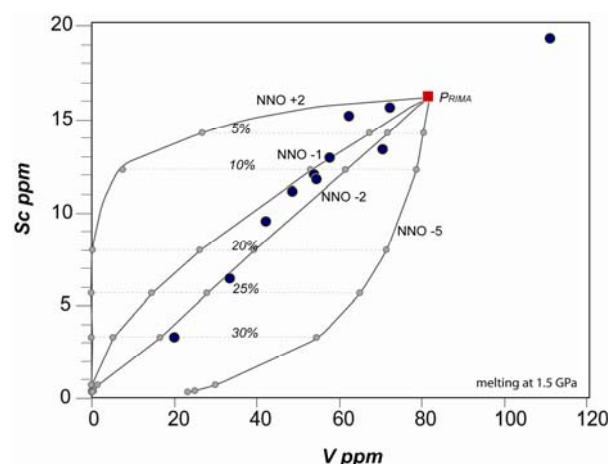


Fig. 2 Whole-rock Sc vs V. Melting trends calculated at 1.5 GPa for various $f\text{O}_2$ (NNO+2 – NNO-5) after Canil (2002 & 2004).

Os isotope systematics

Whole-rock Os abundances and isotope ratios range from 0.8 to 6.0 ppb and $\gamma_{\text{Os}} = -6.3$ to +1.8. Os isotope systematics correlate broadly with indicators of depletion such as Al_2O_3 (Fig. 4). The timing of lithosphere formation in the Atlas region is poorly

constrained and the Re-Os isotope systematics of these peridotites potentially provide evidence for a Paleoproterozoic stabilization of a variably depleted continental mantle root beneath the Middle Atlas. However, abyssal peridotites exhibit a similar range of Os isotopes (Harvey et al., 2006) and have decoupled Os isotope- Al_2O_3 systematics. Hence, more recent or repeated separation of the Middle Atlas lithospheric mantle from the convecting mantle cannot be excluded and further study into the evolution of Middle Atlas continental crust and the associated mantle roots is required.

One Middle Atlas peridotite is distinct from the bulk of these mantle xenoliths. It has major and minor element systematics that are more enriched than primitive mantle (Fig. 1 & 2) and falls off the trend formed by Os isotopes and Al_2O_3 . This sample contains ~23% clinopyroxene and its trace element abundances are the highest recorded in these peridotites.

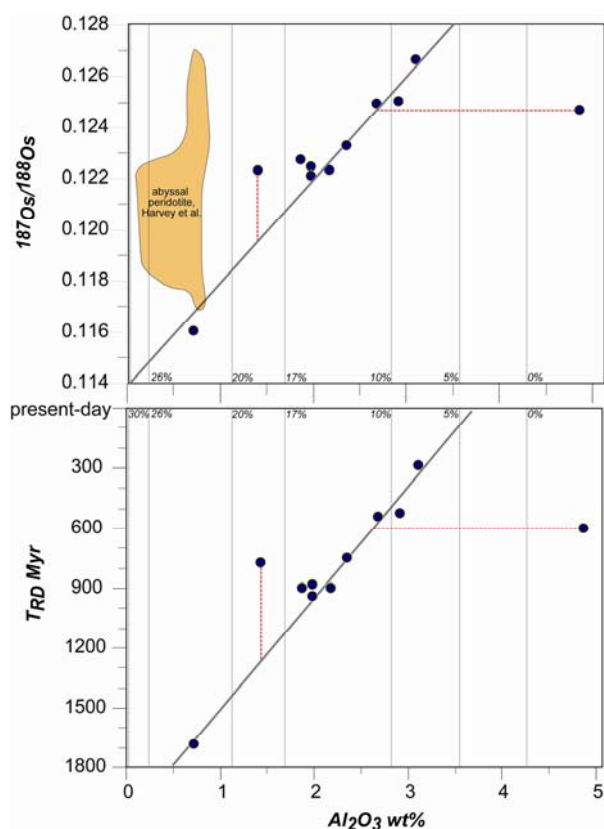


Fig. 3 Whole-rock $^{187}\text{Os}/^{188}\text{Os}$ and T_{RD} model ages (Myr) vs Al_2O_3 . Vertical lines indicate degree of depletion derived from Al_2O_3 at 2 GPa (0 – 30%, Herzberg, 2004).

Mineral trace element data

Handpicked and thoroughly leached clinopyroxenes separated from the Middle Atlas peridotites are marked by high abundances of incompatible trace elements although some variation in absolute concentration does occur. HFSE abundances appear comparatively low (Fig. 4). Overall, these lithophile trace element systematics are not suggestive of the significant melt depletion indicated by the major element systematics of the corresponding whole rocks. The incompatible trace elements in these xenoliths thus preserve

predominantly a record of metasomatic enrichment. For example, Lu/Hf ratios of the Middle Atlas clinopyroxenes vary between 0.14 and 0.37, which is consistent with clinopyroxene experiencing only 0 to 5% spinel-facies melting (Wittig et al., 2007). Notably, the least incompatible and relatively immobile REE, Lu, appears to preserve a record of shallow melting to the extent of ~20%. This suggests that Hf abundances (and elements more incompatible/mobile than Lu) are substantially enriched despite the negative Nb-Ta and Zr-Hf anomalies exhibited by these clinopyroxenes. Moreover, the very high abundances of Th exclude hydrous fluid infiltration as a mechanism for generating the most recent enrichment recorded by these clinopyroxenes. In addition, ratios of elements with similar incompatibility during silicate melting and metasomatism (e.g. La/Ce, Th/U, U/Nb, Nd/Pb) are fractionated variably (e.g. Nd/Pb = 14 – 211). These trace element systematics suggest that the metasomatic agent causing the enrichment of the Middle Atlas continental mantle clinopyroxenes had considerably more variable trace element systematics than putative mafic silicate melts, and that the metasomatic agent may have been carbonatitic liquids.

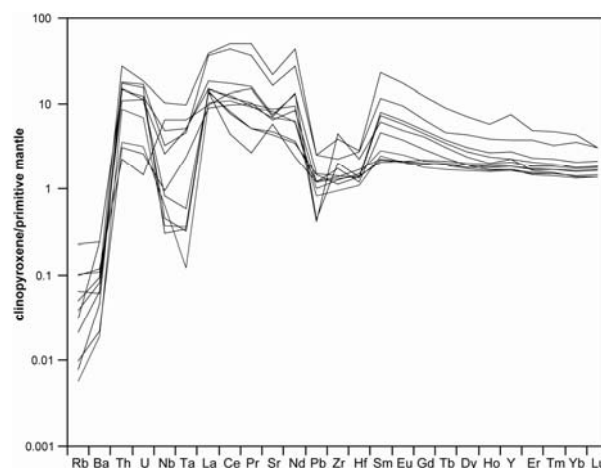


Fig.4 Primitive-mantle normalized trace element abundances of Middle Atlas clinopyroxene. Primitive mantle after Sun and McDonough.

Clinopyroxene Sr-Hf-Nd isotope data

Sr-Nd-Hf isotope systematics of these clinopyroxenes are relatively homogeneous and within the range previously reported from world-wide off-craton mantle clinopyroxene. The Middle Atlas xenoliths have somewhat unradiogenic Nd isotopes compared with most off-craton peridotites (Fig. 5). Sr and Nd isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70317 - 0.70340$; $\epsilon_{\text{Nd}} = +3.4 - +7.4$) are well correlated and particularly Nd isotopes are more radiogenic than the host intra-plate volcanic ($\epsilon_{\text{Nd}} < 4$, Duggen et al., unpublished data). Clinopyroxene Nd isotopes and Nd, Sm and Eu abundances indicate yield a tight mixing array ($R^2 = 0.98$) whereas Sr and Hf isotopes and abundances do not show such mixing relationships. Sr concentrations are highly variable (Fig. 5) both between samples and within single samples (Malarkey et al., this volume).

Hf and Nd isotopes ($\epsilon_{\text{Hf}} = +10.2 - +18.6$) do not correlate along the OIB correlation line but form a nearly perpendicular array. Here, the sample with least radiogenic Nd has the most radiogenic Hf. The clinopyroxene lithophile isotope systematics – including the supposedly more robust Hf isotope system – do not appear to preserve a Paleoproterozoic depletion event that could be deduced from Os whole-rock isotope systematics. These Sr-Nd-Hf isotope systematics and particularly the decoupling of Hf from Nd and Sr isotopes also advocate carbonatitic fluids to have played an important role during the metasomatic evolution of this portion of continental lithospheric mantle.

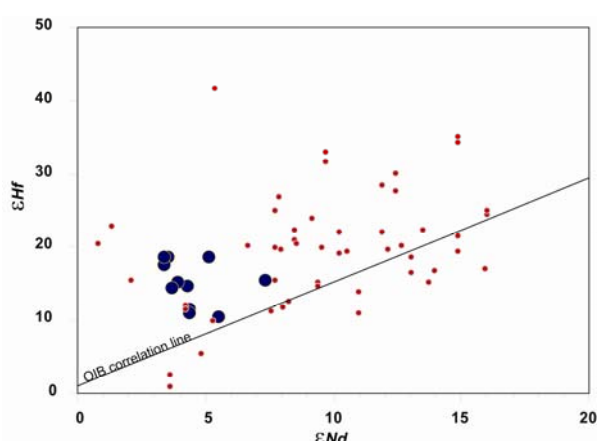


Fig. 5 Middle Atlas clinopyroxene ϵ_{Hf} vs ϵ_{Nd} in comparison to other off-craton clinopyroxenes (Wittig et al. 2007, Shaw et al., 2007). OIB correlation line after Johnson and Beard, 1993.

Clinopyroxene U-Th-Pb isotope data

Pb isotope systematics in clinopyroxenes are similarly homogeneous ($^{206}\text{Pb}/^{204}\text{Pb}$ 19.93 – 20.25) to Sr-Nd and Hf isotopes. No correlation of Pb isotopes with these other isotope systematics is evident. In comparison to other mantle clinopyroxene suites the samples from the Middle Atlas appear unusually homogeneous and the intra-plate volcanic rocks ($^{206}\text{Pb}/^{204}\text{Pb} < 19.72$) are considerably less radiogenic.

The parent isotope ratios $^{238}\text{U}/^{204}\text{Pb}$ and $^{232}\text{Th}/^{204}\text{Pb}$ of these clinopyroxenes are variable and extend to extremely high values (24 – 81, 136 – 399, respectively). Neither the U-Th-Pb nor Rb-Sr, Sm-Nd or Lu-Hf parent-daughter isotope ratios correlate with each other. This, and the extreme nature of $^{238}\text{U}/^{204}\text{Pb}$ and $^{232}\text{Th}/^{204}\text{Pb}$, coupled with their comparatively short half-lives require the latest metasomatism to have occurred very recently; probably within the past 20 Myrs. Importantly, back-modelling of the U-Th-Pb isotope systematics shows that the clinopyroxenes do not result from interaction with the host volcanic rocks. The percolating liquids causing the enrichment recorded by the clinopyroxene are required to be isotopically more extreme than the host lavas and also different from the exposed carbonatites (e.g. Tamazert) occurring in the Middle Atlas region.

Summary

The variably depleted spinel-facies continental mantle root beneath the Middle Atlas hosts lherzolites and harzburgites with major and minor element and Os isotope systematics that appear to record melt extraction of up to 25% in a shallow setting (≤ 2 GPa), possibly at a mid-ocean ridge. Constituent clinopyroxenes have enriched trace element systematics, with low HFSE and variable Sr abundances that are best reconciled if the most recent enrichment is assumed to result from carbonatitic liquids. Sr-Nd-Hf-Pb isotopes are relatively homogeneous and only Sr-Nd isotopes are well correlated. Generally, these lithophile isotope systematics are within the range of other off-craton mantle clinopyroxenes, and similar to the convecting mantle. However, $^{238}\text{U}/^{204}\text{Pb}$ and $^{232}\text{Th}/^{204}\text{Pb}$ are unusually high and considering the homogeneous Pb isotope record for these clinopyroxenes pervasive metasomatic enrichment must have occurred very recently.

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