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Partial melting and melt percolation in the mantle: The message from Fe isotopes

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Abstract

High precision Fe isotope measurements have been performed on various mantle peridotites (fertile lherzolites, harzburgites, metasomatised Fe-enriched peridotites) and volcanic rocks (mainly oceanic basalts) from different localities and tectonic settings. The peridotites yield an average δ^{56}Fe=0.01‰ and are significantly lighter than the basalts (average δ^{56}Fe=0.11‰). Furthermore, the peridotites display a negative correlation of δ^{56}Fe with Mg# indicating a link between δ^{56}Fe and degrees of melt extraction. Taken together, these findings imply that Fe isotopes fractionate during partial melting, with heavy isotopes preferentially entering the melt.

The slope of depletion trends (δ^{56}Fe versus Mg#) of the peridotites was used to model Fe isotope fractionation during partial melting, resulting in $\alpha_{\text{mantle-melt}} \approx 1.0001$–$1.0003$ or $\ln\alpha_{\text{mantle-melt}} \approx 0.1$–$0.3$‰. In contrast to most other peridotites investigated in this study, spinel lherzolites and harzburgites from three localities (Horoman, Kamchatka and Lherz) are virtually unaffected by metasomatism. These three sites display a particularly good correlation and define an isotope fractionation factor of $\ln\alpha_{\text{mantle-melt}} \approx 0.3$‰. This modelled value implies Fe isotope fractionation between residual mantle and mantle-derived melts corresponding to $\Delta^{56}\text{Fe}_{\text{mantle–basalt}} \approx 0.2$–$0.3$‰, i.e. significantly higher than the observed difference between averages for all the peridotites and the basalts in this study (corresponding to $\Delta^{56}\text{Fe}_{\text{mantle–basalt}} \approx 0.1$‰). Either disequilibrium melting increased the modelled $\alpha_{\text{mantle-melt}}$ for these particular sites or the difference between average peridotite and basalt may be reduced by partial re-equilibration between the isotopically heavy basalts and the isotopically light depleted lithospheric mantle during melt ascent. The slope of the weaker δ^{56}Fe–Mg# trend defined by the combined set of all mantle peridotites from this study is more consistent with the generally observed difference between peridotites and basalts; this slope was used here to estimate the Fe isotope composition of the fertile upper mantle (at Mg#=0.894, $\delta^{56}\text{Fe} \approx 0.02 \pm 0.03$‰).

Besides partial melting, the Fe isotope composition of mantle peridotites can also be significantly modified by metasomatic events, e.g. melt percolation. At two localities (Tok, Siberia and Tariat, Mongolia) δ^{56}Fe correlates with iron contents of the peridotites, which was increased from about 8% to up to 14.5% FeO by post-melting melt percolation. This process produced a range of Fe isotope compositions in the percolation columns, from extremely light (δ^{56}Fe=−0.42‰) to heavy (δ^{56}Fe=+0.17‰). We propose reaction with isotopically heavy melts and diffusion (enrichment of light Fe isotopes) as the most likely processes that produced the large isotope variations at these sites. Thus, Fe isotopes might be used as a sensitive tracer to identify such metasomatic processes in the mantle.

Keywords: Fe isotopes; mantle; partial melting; diffusion; melt percolation; heavy stable isotopes; high temperature isotope fractionation

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1. Introduction

Over its 4.5 billion years of history, the mantle has been modified by partial melting, crustal recycling and metasomatism. These events converted the original "primitive" mantle into heterogeneous mantle lithosphere with a complex pattern of depletion and refertilisation signatures. A major goal of mantle geochemistry is to characterize the processes responsible for the evolution of distinct mantle reservoirs and thus to improve our knowledge of mantle dynamics. Isotopic proxies (such as Sr, Nd, Hf, Pb or O) are frequently used to identify components of crustal recycling and to get information on time scales of mixing in the mantle (e.g. Hofmann et al., 2004 and references therein). In addition to that, stable isotopes, such as Fe and Li, may contribute to a better understanding of melting and transport processes and the role of oxygen fugacity and fluids during mantle metasomatism (Seitz et al., 2004, Williams et al., 2004, 2005; Elliott et al., 2006).

Iron is a major element in most common mantle minerals: olivine, orthopyroxene (opx), clinopyroxene (cpx), spinel, garnet, amphibole and mica. Recent studies revealed that Fe isotopes display a range of values in mantle rocks and their minerals (Zhu et al., 2001, 2002; Beard and Johnson, 2004; Weyer et al., 2004; Williams et al., 2004, 2005; Weyer et al., 2005; Schoenberg and von Blanckenburg, 2006). These studies reported variable Fe isotope fractionation between coexisting minerals of various mantle rocks, indicating isotopic disequilibrium and open system processes. Polyakov and Mineev (2000) used Mössbauer spectroscopy to determine β-factors (reduced isotopic partitioning function ratios) at $T=300$ K on the order of $10^3 \ln\beta \approx 4–8$ for Fe^{2+} bearing minerals which are dominant in most common mantle rocks, and larger β-factors ($10^3 \ln\beta \approx 10–20$) for Fe^{3+} bearing minerals. Applying a relation of $\ln\beta \sim 1/T^2$, isotope fractionation factors α in the order of $\ln\alpha_{A\text{-}B} \approx \Delta_{A\text{-}B} \approx 0–0.4‰$ should be expected at relevant mantle temperatures (1100 K–1700 K) between mantle minerals (or bulk solid mantle) and a partial melt. Much of the reported isotope variations within the mantle fall into this range. However, kinetic isotope fractionation during open system processes does not necessarily follow a $1/T^2$ relationship (Schauble, 2004) and chromatographic processes might further increase isotope fractionation in the mantle.

Weyer et al. (2005) found small but systematic differences in Fe isotopic compositions between averages for peridotites and basalts, with the mantle rocks being slightly isotopically lighter. They concluded that Fe isotopes fractionate during partial melting. This interpretation agrees with findings of Williams et al. (2004, 2005), who observed that Fe isotope compositions of minerals in variably depleted mantle rocks correlate with degrees of melt extraction. However, the magnitude of Fe isotope variations observed in these studies is difficult to explain by partial melting alone. This would imply a much stronger fractionation of Fe isotopes between mantle residues and melts than that observed by Weyer et al. (2005), which is unlikely from theoretical considerations. Williams et al. (2004, 2005) interpreted the high magnitude of Fe isotope variation in the mantle as a combined effect of metasomatic enrichment and partial melting.

The principal objective of this study is to provide better quantitative constraints on Fe isotope fractionation during mantle processes, such as partial melting and metasomatism, based on analyses of appropriate mantle rocks from various tectonic settings. We further aim to test Fe isotopes as a potential tracer to characterize mantle processes. We also provide new Fe isotope data on mantle-derived volcanic rocks (mainly MORB and OIB) from different localities to better characterize Fe isotope fractionation between the residual mantle and its primary melting products.

2. Sample selection

Mantle rocks from several localities were investigated in this study. They were chosen to represent (1) residues of different degrees of melt extraction from fertile mantle, and (2) products of post-melting metasomatic enrichment. These peridotites include xenoliths in late Cenozoic alkali basalts from Tok on the SE Siberian craton (Ionov et al., 2005a,b, 2006a,b) and from off-craton sites in Mongolia (Press et al., 1986; Ionov et al., 1994, 1998), xenoliths from the active Avacha andesitic volcano in Kamchatka representing a subduction zone setting as well as orogenic peridotites from Horoman (Takazawa et al., 2000), Lherz (Ionov et al., 2005b, 2006b) and (one sample each) from Beni Bouchera (Woodland et al., 1992; Williams et al., 2005) and Balmuccia (Weyer et al., 2003). All mantle-derived volcanic rocks analysed in this study are from ocean island or mid-ocean-ridge settings.

Most of the orogenic peridotites as well as xenoliths from Kamchatka in this study are residual peridotites with no or only moderate metasomatism; their modal and major element compositions are mainly controlled by different degrees of melt extraction. The samples from the Horoman Peridotite complex (Hokkaido, Japan) include two spinel harzburgites, two spinel lherzolites and two plagioclase lherzolites. Using major and trace element compositions Takazawa et al. (2000) interpreted these rocks as residues of polybaric melting that began in the garnet stability field. The samples from the Lherz massif (Woodland et al., 1996) include two lherzolites and two