Earth and Planetary Science Letters 418 (2015) 91–102

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Tracking the source of the enriched martian meteorites in olivine-hosted melt inclusions of two depleted shergottites, Yamato 980459 and Tissint

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ARTICLE INFO

Article history:
Received 11 October 2014
Received in revised form 19 February 2015
Accepted 20 February 2015
Available online 13 March 2015
Editor: T. Mather

Keywords:
martian mantle melting
mantle depletion
olivine-phyric shergottites
olivine-hosted melt inclusions
Rare Earth Elements
crustal recycling

ABSTRACT

The apparent lack of plate tectonics on all terrestrial planets other than Earth has been used to support the notion that for most planets, once a primitive crust forms, the crust and mantle evolve geochemically-independent through time. This view has had a particularly large impact on models for the evolution of Mars and its silicate interior. Recent data indicating a greater potential that there may have been exchange between the martian crust and mantle has led to a search for additional geochemical evidence to support the alternative hypothesis, that some mechanism of crustal recycling may have operated early in the history of Mars.

In order to study the most juvenile melts available to investigate martian mantle source(s) and melting processes, the trace element compositions of olivine-hosted melt inclusions for two incompatible-element-depleted olivine-phyric shergottites, Yamato 980459 (Y98) and Tissint, and the interstitial glass of Y98, have been measured by Secondary Ionization Mass Spectrometry (SIMS). Chondrite-normalized Rare Earth Element (REE) patterns for both Y98 and Tissint melt inclusions, and the Y98 interstitial glass, are characteristically light-REE depleted and parallel those of their host rock. For Y98, a clear flattening and upward inflection of La and Ce, relative to predictions based on middle and heavier REE, provides evidence for involvement of an enriched component early in their magmatic history; either inherited from a metasomatized mantle or crustal source, early on and prior to extensive host crystallization.

Comparing these melt inclusion and interstitial glass analyses to existing melt inclusion and whole-rock data sets for the shergottite meteorite suite, defines mixing relationships between depleted and enriched end members, analogous to mixing relationships between whole rock Sr and Nd isotopic measurements. When considered in light of their petrologic context, the origin of these trace element enriched and isotopically evolved signatures represents either (1) crustal assimilation during the final few km of melt ascent towards the martian surface, or (2) assimilation soon after melt segregation, through melt–rock interaction with a portion of the martian crust recycled back into the mantle.

1. Introduction

Meteorites from Mars provide a unique opportunity to explore the formation and evolution of another planet in the inner-solar system and allow for comparative studies with Earth to help better understand the differentiation and thermal evolution of planetary interiors. The shergottite meteorites are a suite of martian basaltic to lherzolitic igneous rocks that have provided important constraints on the accretion, evolution, structure, and bulk composition of Mars (e.g. McSween and Treiman, 1998). They represent a period of relatively young mantle melting and surface volcanism, ∼ 550–150 Ma (e.g. Nyquist et al., 2001); although crystallization ages of 4.1–4.3 Ga have been proposed (e.g. Bouvier et al., 2008, 2009).

The isotopic and elemental geochemistry of the shergottites span a wide compositional spectrum (Fig. 1); from trace element

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http://dx.doi.org/10.1016/j.epsl.2015.02.033
0012-821X/

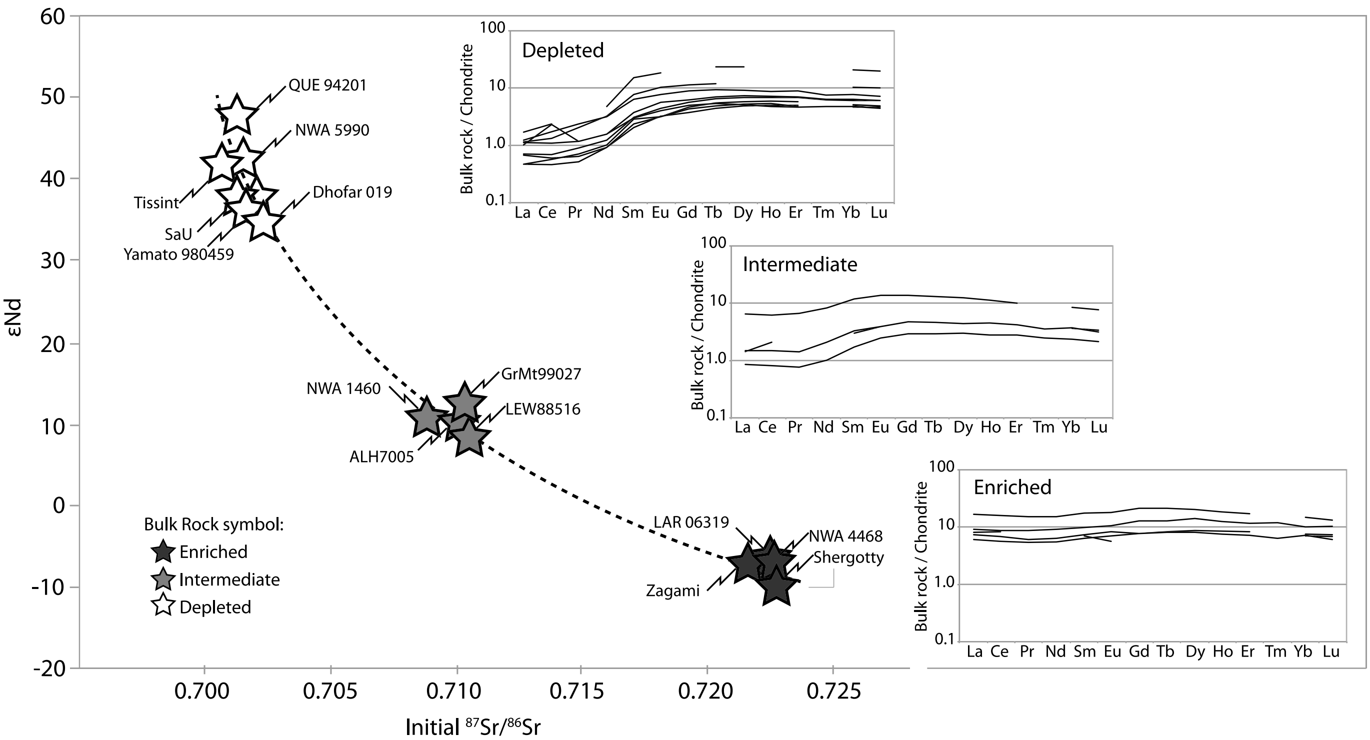

Fig. 1. ε^{143}Nd vs. initial $^{87}Sr/^{86}Sr$ for the shergottite meteorites (after Symes et al., 2008, and references therein). Inserted are whole rock REE patterns that define the three groups; (1) depleted, (2) intermediate, and (3) enriched shergottites. Other isotopic and trace-element data sources are listed in Appendix 6 of the supplementary materials.

depleted and isotopically primitive, to enriched and isotopically evolved. The depleted shergottites are considered partial melts from an initially olivine–pyroxene–garnet cumulate portion of the martian mantle that had undergone extensive melting (e.g. Borg et al., 1997; Borg and Draper, 2003; Shih et al., 2005; Debaille et al., 2008). This history of melting led to significant depletions in elements incompatible, particularly the LREE and radiogenic heat producing elements K, Th, and U (e.g. Borg and Draper, 2003). These trace element depletions are correlated with primitive radiogenic isotope ratios that yield 4.0–4.5 Ga whole-rock model isochron ages, indicative of early mantle depletion during, or immediately following, magma ocean crystallization (e.g. Shih et al., 1982, 2005; Blichert-Toft et al., 1999; Borg et al., 1997; Brandon et al., 2012; Debaille et al., 2008; Bouvier et al., 2005).

The intermediate and enriched shergottites are also considered melts from the depleted mantle, but have experienced variable degrees of contamination from an isotopically evolved and trace element enriched ancient geochemical reservoir (e.g. Borg et al., 1997; Borg and Draper, 2003). This evolved and enriched reservoir is considered to represent either (1) ancient oxidized martian crust, assimilated during emplacement and crystallization of a depleted mantle melt (e.g. Jones, 1989; Usui et al., 2012), or (2) an incompatible-trace-element-rich component, analogous to lunar KREEP, that represents a trapped residual melt formed during fractional crystallization of the martian magma ocean (e.g. Borg et al., 1997; Borg and Draper, 2003; Brandon et al., 2012; Debaille et al., 2008; Symes et al., 2008; Basu Sarbadhikari et al., 2011). Distinguishing between either model and constraining the location of the enriched reservoir relative to the depleted shergottite mantle source, however, remains debated, but has important implications for the geodynamic evolution of the martian mantle, generation of an early martian crust, and the possibly of Earth-like crustal recycling early in the history of Mars.

Here we address the origin(s) of trace element enriched (and isotopically evolved) signatures for the depleted shergottite meteorites using the trace element compositions of olivine-hosted melt inclusions in two depleted olivine-phyric shergottite meteorites, Y980459 (Y98) and Tissint, and the interstitial glass of Y98. The data presented suggests both Y98 and Tissint melt inclusions record the progressive collection of melt components from a residual olivine, orthopyroxene, and garnet mantle source. It is also shown that the origin of an enriched component in Y98 occurs early in its magmatic history, either inherited from its source or incorporated at a time prior to the onset of host crystallization. This early incorporation of enriched trace element signatures is discussed in the context of recent models to represent assimilation of an ancient portion of martian crust, recycled into the upper mantle during an early stage in the history of Mars.

2. Samples

Yamato 980459 (Y98) and Tissint are olivine-phyric shergottite meteorites, displaying a porphyritic texture with olivine megacrysts set among a fine-grained groundmass. They are ∼18 wt% MgO, with <1% total alkalis (i.e. $Na_2O + K_2O$), similar to high-temperature picritic or basaltic komatiitic melts (e.g. Le Bas, 2000), and closely represent true liquids (e.g. Usui et al., 2008; Aoudjehane et al., 2012).

Y98 and Tissint are ideal candidates to probe their primitive mantle source. They are two of the most magnesian shergottites (Y98 Mg#$_{66}$: Shirai and Ebihara, 2004; and Tissint Mg#$_{60}$: Aoudjehane et al., 2012), and have particularly primitive ε^{143}Nd values; +37 at 475 Ma (Fig. 1: Shih et al., 2005) and +44 at 472 Ma (Fig. 1: Shih et al., 2014), for Y98 and Tissint, respectively. These initial ε^{143}Nd values are 4–9 epsilon units lower than that of QUE 94201 (Fig. 1: ε^{143}Nd = 48 at 327 Ma), the best-characterized and most isotopically primitive depleted shergottite (Borg et al., 1997).

Y98 is an Antarctic find and the most mineralogically primitive olivine-phyric shergottite (e.g. Greshake et al., 2004; Usui et al., 2008). The sample studied herein, Y-980459 (51-2), is described in Usui et al. (2008) and contains 12 vol% olivine (6.2 vol% for olivine