A HYBRIDIZED MARTIAN MANTLE SOURCE FOR SHERGOTTITES

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Introduction: Shergottites are a suite of Martian meteorites that exhibit a substantial range in mineralogy, trace element and radiogenic isotope compositions that reflect both the magmatic processes that produced the individual igneous rocks (e.g. evolution from a parent magma), but also the composition of the parent magma source materials. Identifying shergottite parental magma source materials is critical for understanding magmatic processes in Mars which have been ongoing for over 4 Ga. Here we show Lu-Hf and Sm-Nd isotopic evidence for a hybridized upper-mantle source of shergottites as well as ALH 84001. In this model, the mantle assemblage formed during planetary differentiation resulting from the crystallization of a deep magma ocean where cumulate phases are in equilibrium with liquid [4]. The cumulates and trapped liquid represent the depleted and enriched end-member compositions, respectively. This hybridized mantle source model does not require very late stage residual liquids after magma ocean crystallization (perhaps similar to lunar KREEP basalt sources) nor assimilated crustal components as an enriched end-member lithology.

Previous work: Borg and Draper [1] proposed a hybridized mantle that formed during crystallization of a Mars magma ocean as the soure of shergottites. Based on the results of their magma ocean crystallization model, cumulates with depleted Sm/Nd and Lu/Hf ratios and very late-stage residual liquids with enriched Sm/Nd and Lu/Hf ratios represent the depleted and enriched mantle end-member compositions, respectively. Here we build upon and refine this model in light of new Lu-Hf and Sm-Nd age and isotopic data of shergottites and ALH 84001 [2,3]. Further model parameters are from new magma ocean crystallization modeling of Debaille et al. [4]. Also included in this discussion are Lu-Hf and Sm-Nd isotopic and age data from [2-11].

Methods: Initial $^{176}Hf/^{177}Hf$ and $^{143}Nd/^{144}Nd$ ratios of shergottites and ALH 84001 are used to calculate the $^{176}Lu/^{177}Hf$ and $^{147}Sm/^{144}Nd$ ratios of the meteorite magma sources under the following assumptions: a planetary differentiation age of 4.51 Ga [10], CHUR parameters of Bouvier et al. [12], and ^{176}Lu decay constant of Scherer et al. [13]. Magma ocean crystallization models and calculated results of Debaille et al. [4] are used to constrain cumulate and liquid compositions that are established during the crystallization process.

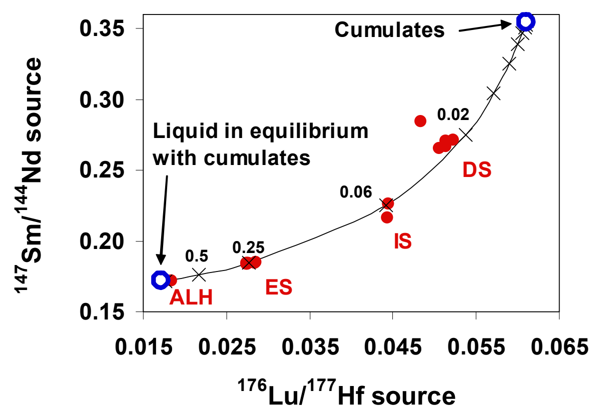

Figure 1. Mixing diagram for shergottites and ALH $^{147}Sm/^{144}Nd$ and $^{176}Lu/^{177}Hf$ source compositions. Red dots are shergottites; DS = depleted shergottites; IS – intermediate shergottites; ES = enriched shergottites; ALH = ALH 84001. The black binary mixing line is based on source compositions of cumulates and liquids in equilibrium with the cumulates in the upper mantle assemblage (UM1) of [4] produced in a 2000 – 1350 km deep MO. Isotope data used for the source calculations of shergottites come from [2-11]. Labeled mixing proportions (black symbols) are based on the fractions of residual trapped liquid.

Results: Shergottites span a range in source $^{176}Lu/^{177}Hf$ and $^{147}Sm/^{144}Nd$ ratios of 0.028 – 0.052 and 0.18 – 0.28, respectively. Source $^{176}Lu/^{177}Hf$ and $^{147}Sm/^{144}Nd$ compositions of ALH 84001 (ALH), calculated for the measured Lu-Hf age of 4.091 Ga [2], are 0.018 and 0.172, respectively. Although ALH is distinct both in age and lithology, it's source compositions are consistent with mixtures of depleted and enriched end-member compositions that describe the Lu-Hf and Sm-Nd mixing array of shergottites (Figure 1). Furthermore, calculated source compositions of ALH indicate that it is derived from a source that has the highest proportion of the enriched component relative to recognized shergottites.

Modeling of a crystallizing 2000 km thick magma ocean by Debaille et al. [4, 10] provides a data set of mantle reservoir Sm-Nd and Lu-Hf compositions we have tested for compatibility with the observed source variation of shergottites. An upper mantle (200 - 750 km) assemblage consisting of olivine, CPX, OPX, and

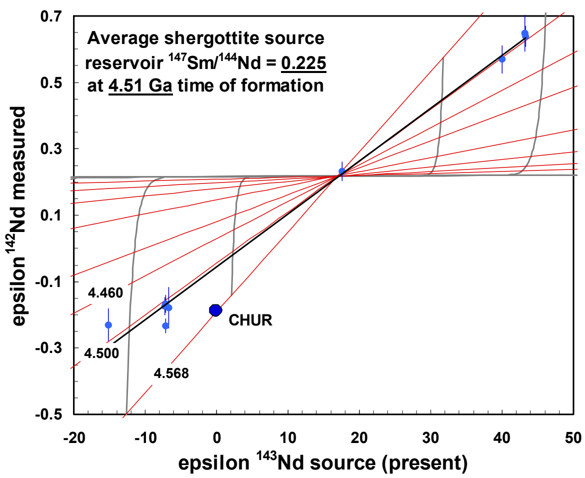

Figure 2. ^{142}Nd – ^{143}Nd evolution diagram of shergottites. Model parameters and data are from Debaille et al. [10]. Error bars are at the 2σ level. The ε^{143}Nd of the source is calculated assuming a two-stage model where the Sm/Nd ratio was chondritic from 4.568 Ga until differentiation of silicate portion of Mars at 4.513 Ga. The age defined by the slope of the York fit line through the measured shergottite data is 4.51 Ga. Ages (in Ga) of representative isochrons (red lines) are shown as numbers overlapping the isochrons.

garnet (with a majorite component) cumulates and trapped residual liquid in equilibrium with the cumulates [4] is consistent with the inferred depth of mantle partial melting (250 – 400 km [14]). Furthermore, mixing of the cumulates and trapped liquid in this upper-mantle assemblage can describe the Lu-Hf and Sm-Nd source characteristics of shergottites and ALH (Figure 1). This upper mantle assemblage formed during magma ocean crystallization of the remaining ~35 – 7% liquid [please see 4]; some of the remaining ~ 7% liquid likely went on to crystallize the shallow upper mantle and (possibly) primordial crust. The calculated ^{147}Sm/^{144}Nd and ^{176}Lu/^{177}Hf ratios of the very late stage residual liquid after ~ 98% magma ocean crystallization are < 0.16 and < 0.017 [4]. Although the ^{176}Lu/^{177}Hf composition of this very late stage liquid is compatible with the model, the ^{147}Sm/^{144}Nd ratio is too low to be a major component of the enriched end-member. In light of both enriched shergottite and ALH source data, Lu-Hf and Sm-Nd compositions of very late stage residual liquids and associated cumulates are no longer consistent with the enriched component of shergottites sources.

Cumulates and trapped liquid in equilibrium with the cumulates that constitute the mantle source of shergottites must have formed at the same time. Because Sm/Nd ratios of the cumulate fractions are very different from that of the liquid and formation of these components occurred while ^{146}Sm was extant, ^{142}Nd/^{144}Nd ratios will be variable in this reservoir. This variation is evident in the measured ^{142}Nd/^{144}Nd ratios of shergottites [10] which are well correlated with the calculated source Sm/Nd ratio. If we we infer that the sources of shergottites are solely derived from the upper mantle assemblage described above, the array of shergottite data on a ^{142}Nd – ^{143}Nd evolution diagram must pass through the origin of the modeled isotope evolution trajectories (center of the bowtie), regardless whether the measured data define a mixing line and/or an 'isochron' (Figure 2). The ^{147}Sm/^{144}Nd ratio of the average upper mantle reservoir (cumulates plus trapped liquid) defined by the intersection of the 'bowtie' origin with the shergottite array is 0.225. The point of intersection between the shergottite array and the center of the 'bowtie' indicates average relative proportions of cumulates to trapped liquid of 0.94:0.06 and suggests that a substantial amount of liquid was trapped in the upper mantle. The shergottites and ALH do not appear to sample highly incompatible element enriched source material reflective of a late stage residual liquid after > 98% magma ocean crystallization. This suggests that this material was removed during impact processing of the proto-crust, was not uniformly distributed, or simply did not have the volume to form a substantial reservoir that influenced shergottite compositions.

Future work: We are analyzing a suite of newly discovered shergottites to better constrain the two-component mixing array in Fig. 1. As it stands now, there are two source regions recognized, one that produced the shergottites plus ALH, and one that produced the nakhlites. Preliminary work on the olivine-phyric shergottite NWA 2990 indicates that this rock has an old age, perhaps older than 600 Ma, and initial isotope systematics that may define a third distinct mantle reservoir.

References: [1] Borg L. and Draper D. (2003) MAPS, 38, 1713-1731. [2] Righter M. et al. (In Review). [3] Lapen T. et al. (2009) 39th LPSC. [4] Debaille V. et al. (2008) EPSL, 269, 186-199. [5] Borg L. et al. (2003) GCA, 67, 3519-3536. [6] Borg L. et al. (2008) LPSC XXXIX. [7] Bouvier A. et al. (2005) EPSL, 240, 221-233. [8] Bouvier A. et al. (2008) EPSL. [9] Blichert-Toft J. et al. (1999) EPSL, 173, 25-39. [10] Debaille V. et al. (2007) Nature, 22, 525-528. [11] Nyquist L. et al. (2001) Space Sci. Rev., 96, 105-164. [12] Bouvier A. et al. (2008) EPSL, 273, 48-57. [13] Scherer E. et al. (2001) Science, 293. [14] Kiefer W. (2003) MAPS, 39, 1815-1832.