THE ROLE OF GARNET IN MARTIAN MANTLE EVOLUTION: FURTHER EVIDENCE FROM SHERGOTTITE RARE EARTH PATTERNS

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REE fractionation and isotopic decoupling effects in SNC meteorites have been attributed in the past to the presence of garnet in their mantle source regions [1,2]. Quantifying the garnet effect is now possible using the parent melt REE compositions determined by [3] for the shergottites, a group of SNC meteorites characterized by complex rare earth element (REE) patterns and 180 Ma isotopic ages [4,5,6,7]. Below, we develop a multi-stage REE evolution model for a shergottite source which underwent fractional fusion at earlier stages with garnet present. Similar processes may account for (1) the decoupling of the Sm-Nd isotopic system from the Rb-Sr and U-Th-Pb isotopic systems in SNC meteorites [8], and (2) non-chondritic abundance ratios for certain refractory lithophile elements (*e.g.*, high Th/La, U/La, and low Al/Ti) in SNC's [1,9]. If this model is generally correct, it then requires a planet large enough to have crystallized substantial garnet in its mantle source regions, consistent with a martian origin for the SNC's [10].

Fractional fusion involving residual garnet in the source at early stages of melt removal has previously been suggested to explain both the strong REE fractionation and low Al abundances in the SNC's [1,2]. Ma *et al.* [11] modeled the ALH77005 shergottite REE pattern using an incremental batch melting model, and inferred from this that garnet played a key role in the LREE depletion of shergottites. However, this model was based on a whole rock isochron age of ~1.3 Ga for the shergottites, an assumption which requires a long-term LREE-rich source (and presumably one that was LREE-enriched at the time of melting), with ϵ_{Nd} of -13 [2,12]. The shergottite whole rock "isochron" has since been demonstrated to be an artifact of mixing processes [5], and therefore probably has no age significance. A 180 Ma igneous crystallization age is now well established from U-Pb, Rb-Sr and Sm-Nd internal isochrons for most of the shergottites [4,5,6], and we have accordingly developed a REE model which quantifies the effects of dynamic melt removal from a garnet-bearing, long-term LREE-depleted (ϵ_{Nd} = +20) peridotite source at 180 Ma.

The new model makes use of the parent magma shergottite REE patterns determined by [3], which provide the best means for calculating a hypothetical shergottite source REE pattern. We previously developed an assimilation/mixing model based on these data and Nd isotopes (Fig. 1) in order to quantify a possible AFC relationship between the shergottites, demonstrating that they could be linked to a "common" depleted mantle source at 180 Ma [3,5,7,13,14]. The REE patterns of the Antarctic shergottites are the most LREE-depleted and show the least evidence for crustal assimilation [2,5]; therefore, the parent magma REE pattern determined for one of the Antarctic shergottites (LEW88516) by [3] was chosen for our model to represent the primitive shergottite parent magma most likely to have been in equilibrium with a depleted source. Although no Nd isotopic data are available for LEW88516, it is petrologically similar to ALH77005, which has an ϵ_{Nd} of +14.9 (this sample also anchors both the mixing trend and the assimilation trend shown in Fig. 1), indicating a long-term depleted mantle source with minimal crustal assimilation effects superimposed [5]. Modeling the shergottite source is simplified by assuming that garnet had been completely removed from the source at this late stage of melting when the shergottites were finally produced. Such an assumption is required by phase equilibria and experimental constraints, neither of which are compatible with equilibrium between a garnet-bearing source and these low Al magmas [1,2,10,13]. By modeling shergottite melt removal using a simple inverse equilibrium batch melting model (Fig. 2), it can be shown that the shergottite source REE pattern was virtually identical to that of the melt extracted from it. Since this calculated source composition is non-chondritic and LREE depleted, it is clear that a previous REE fractionation event must have affected the source region.

The effects of this earlier fractionation event can be duplicated using a three stage REE model (Fig. 3), beginning with a primitive, unfractionated mantle (2x chondritic). Stage one melting of this primitive mantle (at ca. 4.5 Ga) produces a moderately-LREE depleted source, consistent with that required by Nd isotope constraints [12]. During stage two (ca. 180 Ma), this source undergoes non-modal, fractional (Rayleigh) fusion, with garnet present during withdrawal of only the first 10% of melt. This is accomplished by the removal of incremental batches of infinitesimal melt fractions, and successfully reproduces one of the primary features of the shergottite source REE pattern in Fig. 2, which is the downward inflection between Dy and Er. The stage two pattern (Fig. 3) also mimics clinopyroxene REE patterns observed in some abyssal peridotites, and is in fact derived using a model developed by [15] for the REE evolution of MORB source regions. However, the extreme LREE depletion at this stage is not a

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characteristic of the model shergottite source REE pattern, which has an upward inflection between Nd and Ce (Fig. 2). In order to elevate the LREE to the levels of the shergottite source, a third stage (Fig. 3) is required involving the late addition of a LREE-rich component ($La/Yb_{[N]} = 10$) to the source. Stage three (Fig. 3) results in a successful match for the model shergottite source (Fig. 2). It is noted that late-stage LREE enrichment also appears to have affected MORB source regions, as reflected in the REE patterns of clinopyroxenes in some abyssal peridotites [15]. This has been variably attributed to the late influx of CO_2 rich fluids [15] or chromatographic fractionation effects of the kind described by [16].

This model offers strong evidence that Sm/Nd fractionation in SNC meteorites is a direct result of residual garnet present during earlier stages of melting in SNC source regions. Lack of fractionation in the Rb-Sr and U-Th-Pb isotopic systems since 4.5 Ga on Mars [8,17] may simply be attributed to the absence of any process, like subduction, that can recycle evolved crustal materials back into the martian mantle. This model also accounts for certain other non-chondritic refractory lithophile element ratios in SNC's, thus eliminating the need to appeal to primitive anomalies in the martian mantle.

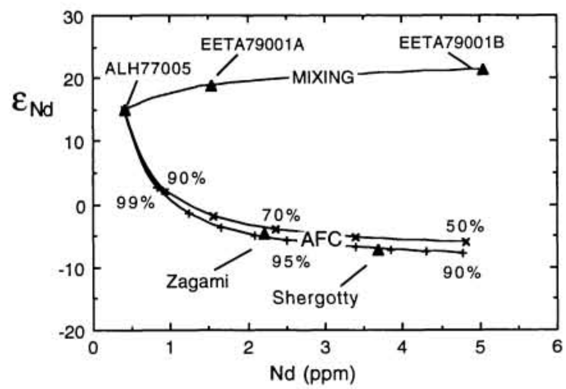

Fig. 1. ϵ_{Nd} vs. Nd diagram (values from [3,5,6]) showing possible AFC mixing relationships among shergottites. ALH77005 anchors both mixing trend (with EETA79001B) and AFC trend (with Zagami/Shergotty). Calculated ϵ_{Nd} of EETA79001B is +21.3, based on mixing relationship of [18]. Assimilant (crust?) has ϵ_{Nd} = -10, Nd = 10 ppm (assumed). AFC curves are for r values of 0.3 (upper) and 0.8 (lower), calculated from equations of [19]. Note that < 8% assimilation is required for a model based on r = 0.8.

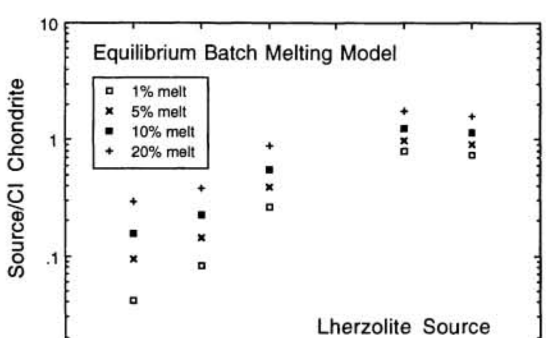

Fig. 2. Model REE patterns for shergottite source assuming garnet-free residue (20% cpx, 25% opx, 55% ol). Model calculated from equilibrium batch melting equation (with Kd's from [20]) using parent melt REE composition of LEW88516 [3]. Note that this requires the shergottite source to have been fractionated before the melting event that produced the shergottite magmas.

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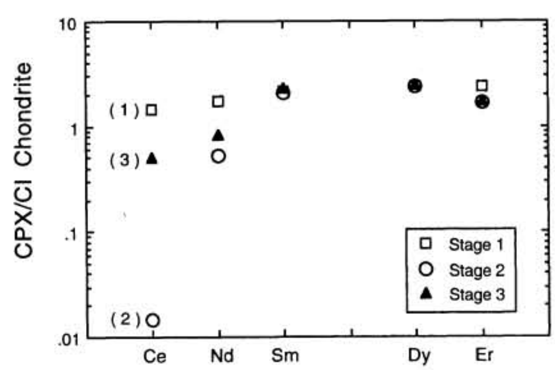

Fig. 3. Three stage REE evolution model for clinopyroxene in the shergottite source. Long-term depleted mantle source (Stage 1) undergoes complex melting at 180 Ma (Stage 2) with garnet present during early melt withdrawal. Stage 2 model is derived from equations developed by [15] for non-modal fractional fusion of MORB source regions. Stage three addition of LREE-rich component may account for variable LREE inflections which appear to correlate with ϵ_{Nd} in Antarctic shergottites.