GEOCHEMICAL SUBCLASSIFICATION OF SHERGOTTITES AND THE CRUSTAL ASSIMILATION MODEL

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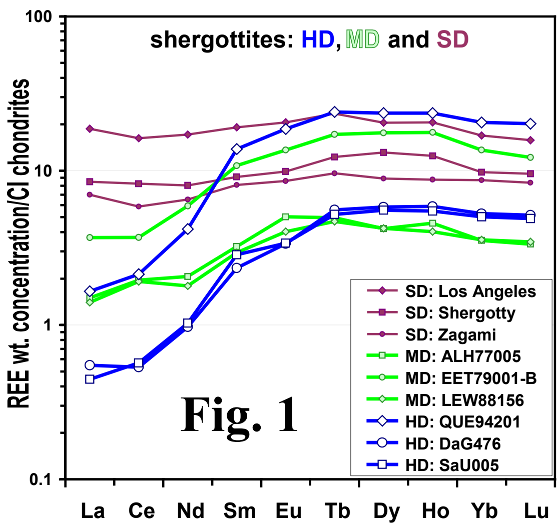
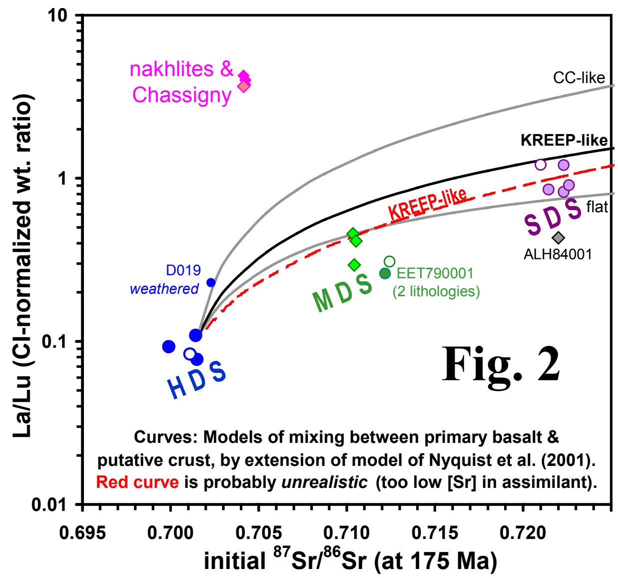
Shergottites are customarily subclassified on mineralogical grounds. To date, about 9 basaltic shergottites have been discovered, 8 olivine-phyric shergottites, and 6 peridotitic (“lherzolitic”) cumulates. We [1] have recently suggested a more genetically significant way of subclassifying shergottites based on geochemistry. There are again three groups, which we define as highly depleted shergottites (HDS), moderately depleted shergottites (MDS), and slightly depleted shergottites (SDS). Even the SD shergottites (which constitute the most numerous subclass) are in some respects depleted vs. chondrites, but the depletions are only very mild in comparison to HD shergottites. These geochemical subclasses correlate only loosely with the mineralogical subclasses. Most HDS are olivine-phyric; but HDS QUE94201 is a basaltic melt-rock [2]. Most MDS are cumulate peridotites; yet EET79001 contains two lithologies (basaltic and phyric-xenocrystic), both MD. Most of the SDS are basaltic without conspicuous phenocrysts; yet NWA1068 [3] is olivine-phyric.



The ratio La/Lu (Lu being the heaviest REE) is particularly diagnostic. Fig. 1 shows CI chondrite-normalized REE patterns for a representative selection of shergottites (literature data; for sources, cf. [1] and [4]). The HDS subtype have La/Lu consistently close to 0.12×CI; the SDS subtype have La/Lu consistently close to 1.0×CI. Despite their cumulate nature, the MD peridotitic shergottites have REE patterns (including La/Lu) lower but roughly parallel to the patterns of their parent melts [5].

These trace-element signatures of highly diverse extents of depletion are paralleled by isotopic

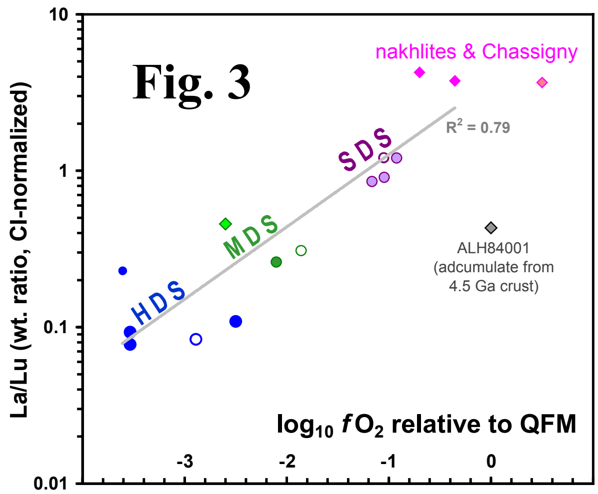


Curves: Models of mixing between primary basalt & putative crust, by extension of model of Nyquist et al. (2001). Red curve is probably *unrealistic* (too low [Sr] in assimilant).

variations. For example, initial $^{87}Sr/^{86}Sr$ ratio, normalized to the typical shergottite age of 175 Ma, is consistently close to 0.701 among highly depleted shergottites, close to 0.722 among SD shergottites, and close to 0.711 among the MD shergottites (Fig. 2; literature data, open symbols denote samples whose bulk compositions closely resemble parent melts, non-circular symbols denote cumulates). A very similar pattern is manifested using εNd (at 175 Ma) in lieu of $^{87}Sr/^{86}Sr$ [6]. These systematic depletion variations among shergottites correlate only loosely with key mineralogical traits.

As noted by Wadhwa [7] and Herd et al. [8], the shergottite depletion signatures also correlate with oxygen fugacity (Fig. 3; data mainly from [9] and [10]). This correlation even extends to the nakhlites and Chassigny. Several separate craters launched shergottites, versus just one for nakhlites + Chassigny [11]. It is generally assumed that the shergottites are the more representative rock type in relation to the upper mantle [e.g., 7, 10]. If the relationship between depletion and fO_2 reflects a general feature of the martian mantle-crust system, then most of the martian upper mantle is at ~ QFM – 4 and also highly depleted.

The diversity of depletion characteristics among shergottites (Fig. 2) has often been interpreted as a manifestation of varying extents of assimilative mixing between primary, HD-type basalt and a putative enriched (high La/Lu, REE-rich, Sr-rich, etc.) material [e.g., 11,13,6]. The setting for the assimilative mixing and the detailed composition of



the enriched component are speculative; the assimilated material is often referred to simply as "crust." Nyquist et al. [13] proposed a roughly quantitative model in terms of Sr and Nd, including isotopic ratios. However, these authors did not model La/Lu (or any analogous ratio such as La/Yb). The red curve in Fig. 2 shows a mixing model based on the assumptions of [13] for Nd, Sr and $^{87}Sr/^{86}Sr$ in the crust and HD-basalt components, augmented with an assumption that the La/Lu of the crust component was equivalent to lunar KREEP in terms of REE pattern, i.e., La/Lu = 2.28 × CI chondrites [14]. This extension of the [13] model yields a reasonably satisfactory fit to most of the shergottite compositions, the main exception being EET79001.

However, the Nyquist et al. [13] model yielded (by extrapolation from all the other assumed parameters) a dubiously low Sr concentration for the HD-basalt component (specifically, 11.5-26.2 µg/g; note: only the average of 19 µg has been employed for our Fig. 2), which translates into relatively high (crust-dominated) $^{87}Sr/^{86}Sr$ at any given La/Lu position along the Fig. 2 mixing curve. No known shergottite analysis has Sr <20 µg/g. The mass-weighted mean of two precise analyses for QUE94201 [15] is 48 µg/g, and the only other applicable result (most HD shergottites have suffered warm-desert weathering) is 20 µg/g for Y980459 [16]. Fig. 2 also includes a set of three curves based on the more realistic assumption that the average HD composition has Sr = 35 µg/g. The thick black curve is otherwise analogous to the red (19 µg/g) one, but the other two 35 µg/g curves illustrate the sensitivity of the mixing parabolas to the assumed La/Nd and Lu/Nd (and thus La/Lu) ratios of the enriched component. In the case of the upper curve, the enriched component's REE pattern is assumed to parallel the pattern of the Earth's continental crust, with La/Lu = 6.6 × CI. In the case of the lower curve, the enriched component's REE are assumed to be unfractionated ("flat") with respect to La/Lu. In all these 35 µg/g models, the proportion of the enriched component that has to be added to the HD end-member to reach the SD shergottites is ~ 17 wt%; in the 19 µg/g model, it is ~10 wt%. Note that only the model with flat La/Lu comes close to matching the combination of low La/Lu and relatively high initial $^{87}Sr/^{86}Sr$ observed in the two distinct (but similar) EET79001 lithologies. An approximately flat REE pattern for an otherwise highly enriched component is hardly expected as a typical outcome from planetary igneous differentiation.

Another parameter that might be at play is the enriched component's Sr level, but the 204 µg/g assumed by Nyquist et al. [13] agrees with an estimate of 180 µg/g, based on martian meteorite Sr/K systematics coupled with the Pathfinder soil K concentration, by [17], albeit new data from the Gusev and Meridiani sites show only half as much soil K as was found by Pathfinder [18]. Appeal might also be made to a higher $^{87}Sr/^{86}Sr$ in the crustal component. However, Dreibus and Jagoutz [17] argue that the $^{87}Sr/^{86}Sr$ assumed by [13] was already too high to represent the average crust.

In summary, it appears that a Nyquist et al. [13] style 2-component mixing model yields a marginal fit to the MD shergottite data, but only if La/Lu in the enriched component is assumed to be surprisingly mild (KREEP-like or flatter), despite the extreme La/Lu fractionation manifested across the spectrum of martian meteorite compositions. Also worrisome is the high proportion of the enriched component that must be assimilated into the HD starting material (probably >>10 wt%) to reach the average SD composition. It seems more likely that the model itself is over-simplified; MD and SD shergottites are not simple dilutions of HD matter by a single, uniform "crust" component.

References: [1] Bridges J. C. & Warren P. H. (2005) In Mitchell K & Rothery D. A., eds., Geol. Soc. Lond. Spec. Pub., in press. [2] Wadhwa M. et al. (1998) MaPS 33, 321. [3] Barrat J. A. et al. (2002) GCA 66, 3505. [4] Meyer, C., Jr. (2003) *Mars Meteorite Compendium*. [5] Wadhwa M. et al. (1994) GCA 58, 4213. [6] Borg L. E, et al. (2002) GCA 66, 2037. [7] Wadhwa M. (2001) Science 291, 1527. [8] Herd C. D. K. et al. (2002) GCA 66, 2025. [9] Goodrich C. A. et al. (2003) MaPS 38, 1773. [10] Herd C. D. K. (2003) MaPS 38, 1793. [11] Nyquist L. E. et al. (2001) Space Sci. Rev. 96, 105. [12] McKay G. A. et al. (2002) LPS 33, #2051. [13] Nyquist L. E. et al. (2001) LPS 33, #1407. [14] Warren P. H. (2004) In A. M. Davis, ed., *Treatise on Geochemistry, Vol. 1, Meteorites, Comets, and Planets*, pp. 559-599. [15] Borg L. E, et al. (1997) GCA 61, 4915. [16] Shih C-Y. et al. (2003) NIPR Symp. Ant. Met., 125. [17] Dreibus G. and Jagoutz E. (2003) LPS 34, #1350. [18] Rieder R. et al. (2004) LPS 35. #2172.