ISOTOPIC CONSTRAINTS ON THE PETROLOGY OF MARTIAN METEORITTES.

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Introduction: The SNC (martian) meteorites exhibit complex isotopic characteristics that yield information both about the ages of individual meteorites as well as information about the petrogenetic processes that produced both individual samples and about the origins of suites and sub-suites within the SNC clan. Here I review these data, reiterate earlier interpretations, and offer some new conclusions.

The Nakhlites: The nakhlites are a suite of augite-olivine cumulates that are almost identical in their ages and isotopic characteristics. They are 1.3 b.y. old and are LREE-enriched [1]. Because the petrography of these rocks is dominated by cumulate augite, which excludes LREE, it may be inferred that the nakhlite parent magmas were even more LREE-enriched than the nakhlites themselves. Oddly, the initial $\varepsilon(^{143}\mathrm{Nd})$ of the nakhlites is ~+16 [1]. This means that, between 4.5 and 1.3 b.y., the source region of the nakhlites had a time-integrated LREE-depleted signature ($^{147}\mathrm{Sm}/^{143}\mathrm{Nd}$ = 0.24 [2]) and was probably depleted in incompatible elements generally. Further, it is unlikely that the nakhlite source was simply mixed with LREE-enriched materials penecontemporaneously with the melting event that produced the nakhlite parent magmas. Such mixing should bring in Nd that is indicative of LREE enrichment [i.e., with negative $\varepsilon(^{143}\mathrm{Nd})$] and the initial $\varepsilon(^{143}\mathrm{Nd})$ of the nakhlites themselves should reflect this. Therefore, the nakhlites require that a chemical fractionation of Sm and Nd occur just before or during the nakhlite parent-magma melting event.

Using D(Nd) = 0.07 and D(Sm) = 0.24 for garnet/liquid [3] a simple model illustrates the situation. Suppose a source region with a Sm/Nd of 0.24 is partially melted such that the only significant REE-bearing phase in the residuum is ~2% garnet (garnet harzburgite). What percent partial melting is necessary to produce a liquid with Sm/Nd of 0.16? Mass balance calculations indicate that 1.8% melting will produce the requisite fractionation. This is somewhat higher than the degree of partial melting required to produce high-Ti mare basalts — a conclusion based on a similar calculation [4].

If the amount of garnet in the residuum increases so does the degree of partial melting necessary to effect the required change. However, even a factor of three increase in residual garnet will only raise the degree of partial melting to 5.4% — still a modest amount. If augite remains in the residuum (i.e., if the residuum approaches being lherzolitic), the situation is more complex. However, using the same situation as above with an additional 2% augite in the residuum (D(Nd) = 0.2; D(Sm) = 0.3 [5]), 0.56% melting is necessary to produce the observed change in (Sm/Nd). Based on other considerations related to heat production in the nakhlite source region, I consider the lherzolitic case to be the more viable of the two [6].

Therefore, simplified but reasonable models of nakhlite genesis seem to require that the nakhlites represent very small degree partial melts of a depleted source region. In addition, the LREE enrichment of the nakhlites and their parent magmas is a consequence of the degree of melting and is not a characteristic of their source regions. An alternative would be to have nakhlite melting be initiated by infiltration of a metasomatic fluid into the nakhlite source [7]. In which case the chemical fractionation between Sm and Nd could have occurred elsewhere (i.e., in the source of the fluid). However, because the fluid is required to be LREE-enriched, Nd is enriched (over Sm); and, therefore, the Nd isotopic signature is more difficult to change by mixing or re-equilibration. Thus, it is not clear that metasomatism offers any advantages over the simple partial melting model — particularly since high-Ti lunar mare basalts, derived from volatile-poor source regions require quite similar petrogenetic scenarios [4].

The Shergottites: The petrogenesis of the nakhlites is simple compared to that of the shergottites. The nakhlites could be simple partial melts of a depleted, but modestly fertile source. This cannot be true for most shergottites. The various processes that have affected most shergottites include: partial crystal accumulation, crystal fractionation, removal of melts from the shergottite source region before the formation of shergottite magmas themselves, and assimilation or mixing of "primitive" shergottite liquids and another material(s). The imprints of these processes greatly complicate interpretations of shergottite petrogenesis. Despite these difficulties, two shergottites deserve special mention: (i) QUE94201 (hereafter QUE) because of its very large $\varepsilon(^{143}\mathrm{Nd})$ ~+50 [8], which suggests that it may have come from an endmember source region; and (ii) Y980459 (hereafter Y98) because of its high liquidus temperature (~1450°C) and high Mg# [9]. However, in terms of "primitiveness," the short answer is that neither of these samples is perfect. QUE has a large positive $\varepsilon(^{143}Nd)$, but is evolved and has a low Mg#. Y98 has a high Mg# but its Nd isotopic initial is ~10 epsilon units below that of QUE.

Further, none of the shergottites, including Y98 and QUE give totally unqualified information about their source regions. At the time of this writing, there are no shergottites whose Sm/Nd ratios reflect that of their (time integrated) sources. "Enriched" shergotties appear to have gained LREE by assimilation of crustal or other LREE-enriched materials. High-Mg shergottites with LREE depletions have larger Sm/Nd than their sources, indicating that melt was removed from these source regions (which we have not sampled) prior to shergottite petrogenesis. Longhi [7] has noted the complementarity of some trace element patterns between nakhlites and shergottites, so possibly these missing melts resemble nakhlite magmas.

Implications for Crustal Assimilation vs. Mantle Heterogeneity on Mars: The original shergottites (Shergotty, Zagami, ALH77005, EET79001) formed a linear array on a standard Sm-Nd isochron diagram that was originally interpreted as a crystallization age (~1.3 b.y. [10]) but is now regarded as a mixing line (e.g., [2, 7]). It is now also generally agreed that these shergottites share a common crystallization age of 170-180 m.y. [7]. These shergottites also form a whole-rock Rb-Sr isochron that suggests mixing of source materials that were separated early in martian history.

What is still in dispute, however, is the physical process by which this mixing occurred. Jones [2] preferred crustal assimilation by mantle-derived magmas, by analogy with terrestrial lava series such as the Columbia River Basalts. In contrast, Borg and Draper [11] prefer that whole-rock linear arrays on isochron diagrams reflect processes that occurred as part of the differentiation of an early magma ocean. Choosing between these models is difficult because differentiating between a small-degree partial melt and a KREEP-like differentiate is hard.

However, as noted above, the shergottite source regions have not remained as closed systems. Melts were extracted before shergottite petrogenesis whose general properties are unknown. Therefore, if one prefers the crustal assimilation model three independent events need to occur: (i) pre-shergottite partial melting of the shergottite source, (ii) shergottite melting; and (iii) crustal assimilation/contamination by/of a shergottite magma. The first two of these three events are not under dispute.

If, instead, one prefers the mantle heterogeneity model, additional events must conspire. The pre-shergottite melting events of mantles of different compositions must now extract just enough Sm and Nd to produce a linear array that was good enough to originally be interpreted as an isochron [10]. In effect, in this model the whole-rock Sm-Nd mixing line should be regarded as coincidental. However, because all these rocks have the same crystallization age, this seems unlikely. And it is also true that all subsequently-discovered shergottites that have a 170-180 m.y. age, also fall along this Sm-Nd array.

References: [1] Shih C.-Y. et al. (1999) *Meteoritics & Planet. Sci.* **34**, 647-655. [2] Jones J.H. (1989) *Proc. Lunar Planet. Sci. Conf.* 19th, 465-474. [3] Draper D. et al. (2002) *Lunar Planet. Sci. XXXIII*, #1306 CD-ROM. [4] Beard B. L., et al. (1998). *Geochim. Cosmochim. Acta* **62**, 525–544. [5] Grutzeck M.S. et al. (1974) *Geophys. Res. Lett.* **1**, 273-275. [6] Jones J.H. (2003) *Meteoritics & Planet. Sci.* **38**, 1807-1814. [7] Longhi J. (1991) Proc. Lunar Planet. Sci. Conf. 21st, 695-709. [8] Borg L.E. et al. (1997) *Geochim. Cosmochim. Acta* **61**, 4915–4931. [9] McKay G.A. et al. (2004) *Lunar Planet. Sci. XXXVI*, #2154 CD-ROM. [10] Shih C.-Y. et al. (1982) *Geochim. Cosmochim. Acta* **46**, 2323–2344. [11] Borg L.E. and Draper D.S. (2003) *Meteoritics & Planet. Sci.* **38**, 1713-1731.