

**Lu-Hf AND Sm-Nd ISOTOPIC STUDIES OF SHERGOTTITES AND NAKHLITES: IMPLICATIONS FOR MARTIAN MANTLE SOURCES.** V. Debaille<sup>1</sup>, Q.-Z. Yin<sup>2</sup>, A.D. Brandon<sup>3</sup>, B. Jacobsen<sup>2</sup>, A.H. Treiman<sup>1</sup>, <sup>1</sup>Lunar and Planetary Institute, 3600 Bay Area, Houston TX 77058 (debaille@lpi.usra.edu), <sup>2</sup>Department of Geology, University of California, One Shields Avenue, Davis, CA USA 95616-8605 <sup>3</sup>NASA-Johnson Space Center, Mail code KR, Houston TX 77058

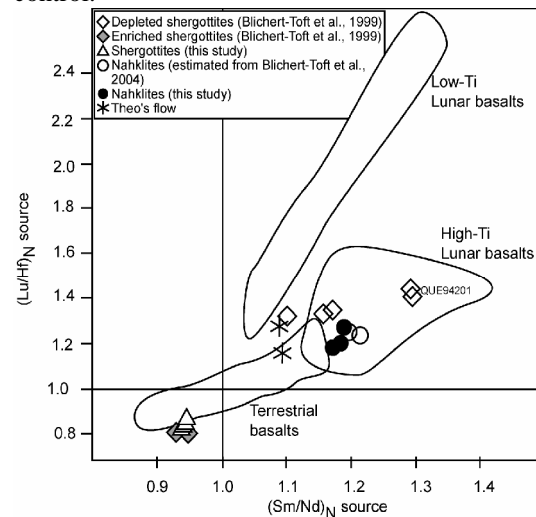
**Introduction:** We present a new Lu-Hf and Sm-Nd isotope systematics study of four enriched shergottites (Zagami, Shergotty, NWA856 and Los Angeles), and three nakhlites (Nakhla, MIL03346 and Yamato 000593) in order to further understand processes occurring during the early differentiation of Mars and the crystallization of its magma ocean. Two fractions of the terrestrial petrological analogue of nakhlites, the Archaean Theo's flow (Ontario, Canada [1]) were also measured. The coupling of Nd and Hf isotopes provide direct insights on the mineralogy of the melt sources. In contrast to Sm/Nd, Lu/Hf ratios can be very large in minerals such as garnet. Selective partial melting of garnet bearing mantle sources can therefore lead to characteristic Lu/Hf signatures that can be recognized with  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios.

**Results:** Both  $^{176}\text{Hf}/^{177}\text{Hf}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios of shergottites on one hand and nakhlites on the other hand are clearly distinct from each other:  $^{176}\text{Hf}/^{177}\text{Hf} = 0.282248\text{--}0.282334$  and  $^{143}\text{Nd}/^{144}\text{Nd} = 0.512314\text{--}0.512335$  for shergottites;  $^{176}\text{Hf}/^{177}\text{Hf} = 0.282998\text{--}0.283108$  and  $^{143}\text{Nd}/^{144}\text{Nd} = 0.512854\text{--}0.512873$  for nakhlites. The  $^{176}\text{Hf}/^{177}\text{Hf}$  values for Zagami and Shergotty perfectly overlap those previously measured [2]. The three nakhlites are also in good agreement with a previous study [3].

In a plot of  $(\text{Lu}/\text{Hf})_N$  vs.  $(\text{Sm}/\text{Nd})_N$  ratios (where subscript N stands for chondrite normalized) calculated for time-integrated sources (Fig. 1), all shergottites are in the enriched lower left quadrant while both nakhlites and the terrestrial analogues from Theo's flow are in the depleted upper right quadrant. One of the Theo's flow data point that lies outside of the terrestrial field corresponds to an aliquot of sample that has been leached with 1N HCl. This leaching process may have affected phases controlling the Hf and REE budget, such as phosphates. None of the SNC meteorites have been leached, except the desert meteorite Los Angeles, in 50% acetic acid.

The comparison between calculated lava source  $(\text{Lu}/\text{Hf})_N$  and  $(\text{Sm}/\text{Nd})_N$  and their measured  $(\text{Lu}/\text{Hf})_N$  and  $(\text{Sm}/\text{Nd})_N$  respectively can be used to test for fractionation between these parent-daughter ratios during partial melting. Samples having ratios near 1:1 line are believed to be the product of large degree partial melting, whereas samples with the measured ratios much less than the source ratios are likely resulting from small degree partial melting

[4]. All shergottites (both depleted and enriched) plot on the right side of a 1:1 line for Sm-Nd (Fig. 2b), while they plot on the left side of a 1:1 line for Lu-Hf (Fig. 2a). This indicates the lack of coherency between these two systems in shergottites, likely reflecting some mineralogical control.



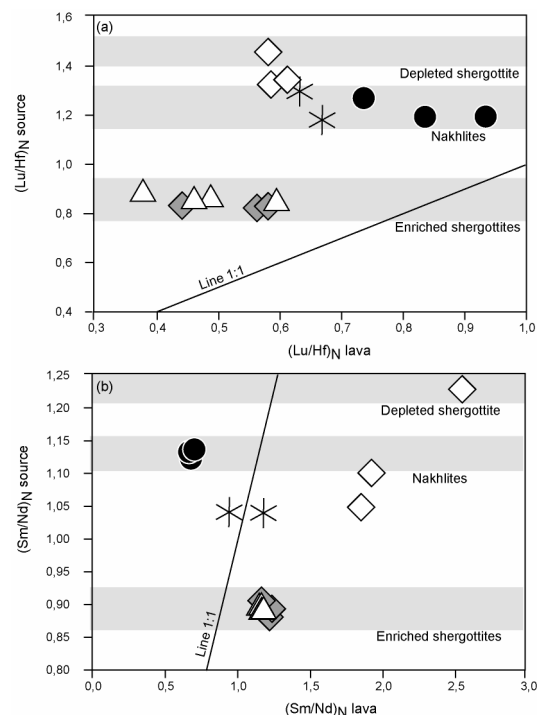
**Fig. 1:** Chondrite-normalized Lu/Hf vs. Sm/Nd ratios in the mantle source of basaltic rocks from Earth, the Moon and Mars, calculated based on their Sm-Nd and Lu-Hf isotope ratios.

**Discussion: Source of nakhlites:** Because of the positive initial  $\epsilon_{\text{Nd}}$  [5] of nakhlites, their source is believed to be long-term depleted in incompatible trace elements. However the clearly distinct calculated source  $(\text{Lu}/\text{Hf})_N$  of shergottites and nakhlites (Fig. 2a) confirm that the mantle source of nakhlites, is distinct from both depleted (represented by QUE94201) and enriched shergottite sources (represented by LA, NWA856, Shergotty and Zagami). The  $\epsilon_{\text{Hf}}/\epsilon_{\text{Nd}}$  ratios of all nakhlites range from 0.8 to 1.2. This is consistent with melts derived from residues with ancient garnet segregation [6]. The long-term depleted reservoir of nakhlites is therefore consistent with an early cumulate crystallized within a thick magma ocean (e.g., [7]) in the stability field of garnet, positioning the source of nakhlites deep in the Martian mantle. The presence of garnet in the residue of nakhlites source is consistent with their HREE depletion on a normalized REE concentrations diagram.

*Source of shergottites:* With respect to their measured versus source  $(\text{Sm}/\text{Nd})_{\text{N}}$  ratios, all shergottites have values that are greater than 1:1 (Fig. 2b), as previously shown [8]. This illustrates a discrepancy between the Lu-Hf and Sm-Nd systematics in shergottites, because it implies that behaviors of these parents/daughter ratios are decoupled in an unusual way, with  $(\text{Sm}/\text{Nd})_{\text{source}} < (\text{Sm}/\text{Nd})_{\text{lava}}$ , but  $(\text{Lu}/\text{Hf})_{\text{source}} > (\text{Lu}/\text{Hf})_{\text{lava}}$ . This contrast could be achieved by the presence of majorite in magma sources, because  $^{majorite/melt}D_{(\text{Sm}/\text{Nd})} > 1$  and  $^{majorite/melt}D_{(\text{Lu}/\text{Hf})} \sim 1$  [8]. This hypothesis has two implications: first that majorite is a major phase of shergottites mantle source(s) and second it thus follows that this reservoir must reside deep within the Martian mantle. The depth of the source region could be as deep as close to the core-mantle boundary within the stability field of majorite ( $>1300\text{km}$ , [9]), although some workers [10] suggested that majorite could appear as soon as 500 km in the Martian mantle. This hypothesis contradicts Blichert-Toft et al. [11] who proposed that low  $\epsilon_{\text{Hf}}$  compared to  $\epsilon_{\text{Nd}}$  in shergottite QUE94201 is inconsistent with a source that evolved in presence of high Lu/Hf residual phases such as garnet or majorite. Ilmenite crystallization in the magma ocean could also explain Lu/Hf-Sm/Nd decoupling. However, ilmenite is likely not relevant in the Martian mantle [12]. Hence, majorite may be the most likely phase that can fractionate these two parent/daughter ratios in the manner observed [8]. Such a depth of origin, either in the deepest portion of the Martian mantle or at shallower depth [10], would place the depleted shergottite reservoir below the also depleted nakhlite reservoir at the time of partial melting of their source rocks, if the cumulates from a magma ocean have not been overturned. The incompatible trace element depleted character of shergottite QUE94201 and its large  $^{142}\text{Nd}$  anomaly [13] are consistent with a source formed by the crystallization of earliest and most depleted cumulates within a magma ocean. This constrains the formation of the depleted shergottite reservoir as earlier than the formation of the nakhlite reservoir, consistent with the smaller positive  $^{142}\text{Nd}$  anomaly in nakhlites relative to QUE94201 [13,14].

The calculated  $(\text{Lu}/\text{Hf})_{\text{N}}$  source ratios for the enriched shergottites form a narrow range from 0.8258 to 0.8798. This implies that their enriched isotopic signatures may result from large scale source contamination (i.e., all the enriched shergottites reservoir) rather than sporadic crustal contamination affecting basaltic melts during their ascent. This raises the more general question of the location of the enriched reservoirs in Mars. If all

enriched shergottites are cogenetic, then a simple scenario reflecting their compositional features could be the mixing of depleted shergottite melt produced in the stability field of majorite with a shallower/more enriched source of the solidified magma ocean. The “flat” REE patterns for enriched shergottites (e.g., [15]) suggest that this shallow/enriched material hybridizing the shergottite melts are very unlikely KREEP in nature (no LREE enrichment vs. HREE). The presence of several shergottite reservoirs is in good agreement with the age discrepancies between depleted samples such as QUE94201 (~327 Ma, [13]) and all enriched shergottites erupted at 180 to 150 Ma (e.g., [16]).



**Fig. 2:** (a) Lu/Hf and (b) Sm/Nd chondrite-normalized time-integrated ratios for mantle sources (calculated from the Lu-Hf and Sm-Nd isotope ratios respectively) vs. the measured chondrite-normalized ratios in lavas. Shaded grey bands indicate the Lu/Hf source variation range for depleted shergottite (QUE94201), enriched shergottites (Zagami, Shergotty, Los Angeles, NWA856) and nakhlites, respectively. Symbols as in Fig. 1.

**References:** [1] Lentz R. et al. (1999) *MAPS* 34, 919-932. [2] Blichert-Toft J. et al. (1999) *EPSL* 173, 25-39. [3] Blichert-Toft J. et al. (2004) *LPS-XXXV*, abs. #1226. [4] Beard L. et al. (1998) *GCA* 62, 525-544. [5] Shih C.-Y. et al. (1999) *MAPS* 34, 647-655. [6] Vervoort J. and Patchett J. (1996) *GCA* 60, 3717-3733. [7] Shih C.-Y. et al. (2006) *LPS-XXXVII*, abs. #1701. [8] Beard L. et al. (2002) *LPS-XXXIII* #1933. [9] Bertka C. and Fei Y. (1997) *JGR* 102, 5251-5264. [10] Draper D. et al. (2003) *PEPI* 139, 149-169. [11] Blichert-Toft J. et al. (1998) *LPS-XXIX*, abs. #1074. [12] Righter K. and Shearer C. (2003) *GCA* 67, 2497-2507. [13] Borg L. et al. (1997) *GCA* 61, 4915-4931. [14] Harper C. et al. (1995) *Science* 267, 213-217. [15] Borg L. and Drake M. (2005) *JGR* 110, E12S03. [16] Nyquist L. et al. (2001) *Chronology and Evolution of Mars, Space Sci. Rev.* 96, 105-164.