Lu-Hf isotopic compositions of SNC meteorites: Implications for Martian mantle evolution

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In contrast to the Earth, garnet is not stable in the lunar mantle and should not appear in the Martian mantle at shallow depth either. Clinopyroxene, however, is expected to be present in different proportions in the mantles of all three planets. The potential of Hf isotope geochemistry lies with a large parent-daughter Lu-Hf fractionation for garnet and clinopyroxene relative to other isotope pairs such as Sm-Nd and Rb-Sr. When these minerals form a substantial fraction of a rock and when the degree of melting is not too large, a large Lu-Hf fractionation takes place and a differential isotopic evolution of Hf in the melts and their residues ensues. In an attempt to better define mantle evolution on Mars, we have therefore begun a systematic study of the Lu-Hf isotopic compositions of the SNC meteorites. Until recently, such measurements were not possible because of the large sample sizes required and the analytical difficulties to be overcome. Our analyses are being carried out by multiple collector, magnetic sector inductively coupled plasma mass spectrometry on the Fisons Instruments Plasma 54 in Lyon, following a two-stage column separation for Hf and a one-stage column separation for Lu using a mixed ^{176}Lu-^{180}Hf spike.

Results

The results for four meteorites, all shergottites, are presented in Table 1. These data were obtained relative to a value of 0.28216 ± 1 for the ^{176}Hf/^{177}Hf ratio of the JMC-475 Hf standard. Zagami and Shergotty both have initial ε_{Hf} values of -18, corrected for an age of 180 Ma. EETA79001B has an initial ε_{Hf} of +33 (180 Ma), and QUE94201 has an initial $\varepsilon_{Hf} = +43$ (330 Ma).

Discussion

It is difficult to compare the isotopic information available from different planetary objects of different ages. This is most conveniently done by calculating the integrated source ^{176}Lu/^{177}Hf ratio at the time of magma extraction from the age of the rock and the chondritic initial ^{176}Hf/^{177}Hf ratio, for which we used the value of Blichert-Toft and Albarède (1997). Although the precise ages of the shergottites are still contentious, the uncertainty on the result is not an issue. The integrated source ^{147}Sm/^{144}Nd ratio was calculated in the same way using the Sm-Nd isotope data from Shih *et al.* (1982), Jagoutz and Wänke

TABLE 1. Lu-Hf isotopic compositions of SNC meteorites

Sample	Hf (ppm)	Lu (ppm)	^{176}Lu/^{177}Hf†	^{176}Hf/^{177}Hf*	ε_{Hf}(T)**	Age (Ma)
Zagami	1.5542	0.2043	0.01866	0.282203 ± 13	-18.3	180
Shergotty	1.7702	0.1825	0.01463	0.282199 ± 7	-18.0	180
EETA79001B	2.0067	0.2619	0.01852	0.283657 ± 5	+33.1	180
QUE94201	2.9877	0.4032	0.01915	0.283897 ± 9	+43.0	330

† 2σ errors for ^{176}Lu/^{177}Hf < 1.0%.
* Ratios normalized to ^{179}Hf/^{177}Hf = 0.7372. Errors are 2σ.
** ε_{Hf} values were calculated using ^{176}Hf/^{177}Hf CHUR(0) = 0.282772 and ^{176}Lu/^{177}Hf CHUR = 0.0332.

(1986), and Borg *et al.* (1997). The present-day $^{143}Nd/^{144}Nd$ value of lithology B of EETA79001, although not reported in the literature, has a calculated initial ε_{Nd} of +21 if one assumes a straightforward simple mixing relationship between lithology B and ALH77005 to produce lithology A. The integrated Lu/Hf and Sm/Nd source ratios were also computed for lunar rocks (Unruh *et al.*, 1984) and terrestrial basalts (too numerous to be referenced here) and plotted in Fig. 1 together with the shergottites. The terrestrial field is essentially equivalent to the mantle array in an ε_{Nd} *vs* ε_{Hf} diagram. As shown by Nyquist and Shih (1992), the low-Ti Moon basalts plot well above this array. Three SNC meteorites fall below the terrestrial trend, while EETA79001B plots on its extension toward more radiogenic values. The inferred source/melt Sm/Nd fractionation is inconsistent with known partitioning and reflects either the inadequacy of the two-stage assumption or the effects of variable cumulate fraction in the four SNC samples. The fact that the four shergottites do not form a linear array with CHUR in spite of relatively similar Lu/Hf ratios seems to indicate a relatively complicated pattern of fractionation.

Mars and the Moon are isotopically much more heterogeneous than the Earth. The four SNC meteorites suggest, at face value, magmas extracted from parts of the Martian mantle having very different histories. Strong mantle convection appears to have reduced the isotopic dispersion in the Earth relative to Mars and the Moon. However, the limited number of data and the possibility of sample heterogeneity urge us to consider several interpretations, all of which are tentative. First, the Martian upper mantle could represent the olivine-rich cumulate of an early global magma ocean. With minor clinopyroxene and garnet, it would form the complement of the protocrust which extracted most of the lithophile element inventory. The SNC meteorites would then represent liquids formed by remelting this cumulate, with Shergotty and Zagami being contaminated by a crustal component.

A difficulty with this scenario is that only trace amounts of pyroxene and garnet would be allowed in the mantle, in contrast with accepted Mars mantle mineralogies. An alternative model is a protracted history of mantle-crust fractionation on Mars, contrasting with the terrestrial evolution insofar as garnet is unimportant and convective mixing inefficient. If we leave aside EETA79001B, whose Nd isotopic composition is only inferred, the Mars

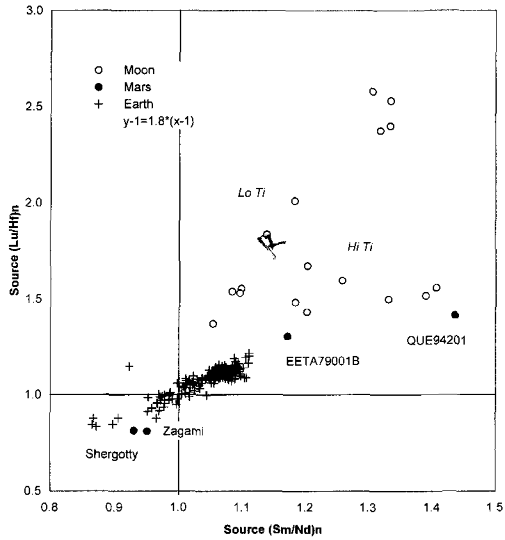

FIG. 1. Time-integrated chondrite-normalized Lu/Hf and Sm/Nd ratios of lunar, terrestrial and Martian mantle sources calculated for a 2-stage model (see text).

Hf-Nd systematics are not incompatible with the continuous extraction of melts leaving olivine and clinopyroxene in the residue (see Fig. 5 in Blichert-Toft and Albarède, 1997). QUE94201 would then be produced by remelting the depleted residue. In contrast, Zagami and Shergotty could be formed by remelting the pyroxenitic equivalent of these first liquids extracted and reinjected into the mantle by any form of recycling or convective overturn.

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