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The Hf/Sm Fractionation in Basalts and the Evolution of the Terrestrial, Lunar, and Martian Mantles

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Hf and Sm are two incompatible elements that should fractionate to an extent comparable to other incompatible elements such as La, Nd, Sr, Zr, etc. It is, however, well established that all systematic searches for covariance in databases invariably return excellent correlation coefficients for the Hf/Sm pair. The Hf/Sm ratio obtained in this way is constant and normally chondritic (0.6-0.7). Outside of the continental realm, where sedimentary zircon sorting fractionates this ratio, the extremely rare exceptions to this rule are (1) the EMII basalts from Polynesia, (2) The high-Ti lunar basalts, and (3) the SNC (Martian) meteorites.

This simple observation has a first implication for the origin of the EMII basalts, which are known to contain a sedimentary terrigenous component. The departure of their Hf/Sm ratio from the chondritic value indicates whether or not the source is enriched in pelagic clay (low Hf/Sm) or terrigenous sand (high Hf/Sm).

The constancy of the Hf/Sm ratio in basalts also poses a formidable challenge to experimental geochemists and modelers. So far, all experiments indicate that both garnet and pyroxene fractionate this ratio during melting. None of the experimental investigations is offering a satisfactory explanation for the Hf/Sm conundrum: even if this ratio in the melt can remain constant for a given set of pressure, temperature, mineral proportions, and degree of melting, it will be susceptible to subtle changes in these parameters. A constant Hf/Sm ratio during melting has to be considered a very stringent criterion for successful experiments as well as for melt extraction models.

Because Hf is compatible in ilmenite, accumulation of this mineral must have contributed to the mantle source of the lunar high-Ti basalts. The strength of geochemical effects that clearly reflects large-scale ilmenite fractionation from its parent magma is one of the key arguments in support of the magma ocean concept for the early Moon. The chondritic, homogeneous Hf/Sm ratios of terrestrial basalts may reflect that either a magma-ocean episode did not occur on Earth or that plate tectonics and mantle convection redistributed the ilmenite layer within the mantle. It is unfortunate that Hf is too mobile in metamorphic rocks to permit the Hf/Sm ratio in Archean rocks to be determined in order to assess the possible presence of abundant ilmenite in the early terrestrial upper mantle. The Hf/Sm ratio in shergottites is superchondritic (ca. 1.5) while it is subchondritic (0.3) in the nakhlites and Chassigny. Within each group, the ratio remains constant irrespective of large variations of other melting-sensitive ratios (e.g. Sm/Nd). We consider such a sharp dichotomy as a strong indication that ilmenite fractionation in a magma ocean shaped the mineralogical composition of the Martian upper mantle very early in the history of the planet. This composition has remained essentially undisturbed by later mantle convection. The bimodal distribution of Hf/Sm ratios in SNCs also implies that the parent magmas of the nakhlites and Chassigny originated from a part of the mantle that was different (deeper) from the source of shergottite magmas.