A GEOCHEMICAL MODEL FOR THE ENRICHED CRUST AND DEPLETED MANTLE OF MARS
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The terrestrial planets, Earth's moon, and many asteroids preserve geological records of their differentiation into metallic cores, ultramafic mantles, and mafic or felsic crusts. Core formation represents a primary segregation of metal from silicate. The primitive silicate mantles of Earth, Moon, and Mars appear to have differentiated into complementary enriched crusts and depleted mantles. Crust-mantle systematics of the Earth and Moon are well-studied, but investigations of the other planets are just beginning. This paper presents a mass balance model for the REE and Nd isotopic relations between the enriched crust and depleted mantle of Mars.

Although several assumptions are required, the model is robust and does not depend critically on any single parameter. The martian core is assumed to account for 30% of the planet's mass [1], and the silicate mass is calculated by difference. The entire silicate mass is allowed to differentiate into conjugate reservoirs of enriched crust and depleted mantle, resulting in upper limits to crustal thickness for a given concentration. The bulk Nd concentration of Mars (0.83 µg/g) is estimated assuming a chondritic Al/Nd and 3% Al2O3 [2]. The enriched crust of Mars appears to have a chondrite-normalized Nd isotopic composition (ENd) equal in magnitude but opposite in sign to that of the depleted mantle [3, 4]. If this is true, then the crust and mantle of Mars must contain equal numbers of Nd atoms, and concentrations can be calculated for various mass increments. Crustal thickness can be calculated assuming a density (3.0 g/cm3). REE patterns of the Martian crust are extracted from the meteorite compositions. The calculated concentration of Nd in the enriched crust and depleted mantle as a function of crustal mass and thickness is shown in Fig. 1. The composition of the crust is sensitive to small changes in volume, while the composition of the depleted mantle is buffered at these volumes. A depleted mantle of this composition would require very small degrees of melting to produce the magmas sampled as SNC meteorites [4, 5].

The SNC meteorites appear to represent magmas which contained components from both the depleted mantle and the enriched crust [3, 4]. Representative chondrite-normalized REE patterns for the Antarctic shergottite EETA79001A and Shergotty are shown in Fig. 2 (data from [6]). The Antarctic shergottites have LREE-depleted patterns, and Nd isotopic compositions that are taken as representing the Martian depleted mantle at 200 Ma [3, 4]. Other shergottites, including Shergotty, have the paradoxical characteristics of a relatively flat to slightly LREE-depleted pattern, but Nd isotopic compositions indicating long-term LREE-enrichment. For this model, Shergotty is assumed to represent a magma from the depleted mantle which has been mixed with enriched crust. The REE pattern of the crustal component is calculated assuming that the Shergotty composition reflects a binary mixture of crust and 79001A. The resulting crustal pattern is LREE-enriched, with a Sm/Nd very close to that obtained by [4]. It has no Eu anomaly, and a flat HREE pattern (Fig. 2).

The absolute abundances of REE in the crustal component depends on the amount of crust in the mix. The proportion of crust in the mix (Shergotty) was determined using the Nd isotopic compositions, and cross-checked using Nd concentrations (Fig. 3). For these calculations, the concentration of Nd in the crustal component was allowed to vary between 7-80 µg/g, which corresponds to a maximum crustal thickness of about 100 km. The isotopic composition of Shergotty can be reproduced with about 3-30% crust in the mixture. Nd concentrations tend to be underestimated by the model, but this depends somewhat on which Shergotty analysis is selected, and how phenocrysts are handled (phenocrysts are ignored here). If the mixing process was assimilation accompanied by fractionation rather than simple binary mixing, the concentration calculated for the mixture will be increased. These results suggest that a thick, low concentration crust is unlikely, with 10-12 µg/g Nd a likely lower limit for the bulk composition of the Martian crust.

An absolute upper limit of 150 km for the thickness of the Martian crust can be estimated using the hybrid Shergotty composition, and a more likely thickness of ≤50 km is implied for bulk compositions with ≥12 µg/g Nd (Fig. 4). This represents an average global thickness, and does not attempt to account for later geologic events. The calculated REE pattern of the Martian crust (Fig. 2) appears 'tholeiitic' in the broad sense, rather than highly alkaline with a steep slope. The effects of garnet fractionation such as might be expected for crystallization of a Martian magma ocean are not strongly apparent. The martian crust does not appear equivalent to lunar KREEP.

Fig. 1 Composition of Martian crust and mantle as a function of crustal mass

Fig. 2 Composition of the Martian Crust
\[ E_{\text{Nd}} = -20 \text{ Sm/Nd 0.25-0.28} \]

Fig. 3 Mixtures of Mantle Melt with Crust
- Mantle melt: +20, 1.4 ppm Nd
- Crust: -20, 7-80 ppm Nd

Fig. 4 Limits on Martian Crustal Thickness