MAGMATIC PROCESSES ON MARS: INSIGHTS FROM SNC METEORITES; J. Longhi, Lamont-Doherty Geological Observatory, Palisades, NY 10964

The composition and petrology of the SNC (shergottites-nakhlites-Chassigny) meteorites reveal a surprising diversity of magmatic processes on their parent body, which the weight of evidence suggests is Mars (1). There is evidence for large scale mantle heterogeneities, multi-stage melting, extreme fractionation of REE, assimilation of a long-term light REE-enriched component (a 'granitic' crust?), mantle metasomatism, and possibly CO_2-fluxed melting. In some respects the style of martian magmatism is intermediate between that of the Moon and the Earth, with the terrestrial component having some of the geochemical character of hot-spot and arc basalts.

Estimates of the major element composition of the SNC parent magmas show them to be hpyersthene-normative, high-Fe, low-Al liquids (2). As might be anticipated, calculated densities of these liquids are high (2.75-2.96) and viscosities are low (4-128 poise). These compositions are consistent with the petrography: olivine and pyroxene crystallize early, plagioclase crystallizes late (1); this crystallization pattern is different from terrestrial MORB's and continental tholeiites in which plagioclase crystallizes early. These low-Al liquids require either large degrees (~50%) of partial melting of an undepleted source or smaller degrees of melting of a depleted source. Geochemical and isotopic data discussed below show the latter certainly to be the case for Nakhla and probably to be the case for the shergottites. This depletion may be accomplished by the accumulation of olivine and pyroxene (lunar style) or extraction of basalt (terrestrial style).

Figure 1 illustrates some important aspects of SNC trace element and isotopic composition. Figure 1A shows the REE concentrations of two calculated parent liquid compositions for Nakhla. Chassigny parent liquids have similar patterns. Nakhla is an unusual rock consisting of large cumulus augite and minor olivine crystals set in a rapidly crystallized matrix (5). The 'closed system' calculation assumes that no net changes in the intercumulus liquid took place after accumulation of the pyroxene, but does allow for partial equilibration of the cumulus crystals and trapped liquid. The 'open system' calculation is a direct calculation based upon the composition of Nakhla augite (6) and the partition coefficients of (7); this calculation allows for the possibility of migration of intercumulus liquid. Both patterns are similar and show dramatic light REE enrichment. This fractionation is truly remarkable in light of the ε_{Nd} value of +16 (6) which requires that the source had a long term pattern of light REE depletion, i.e. something similar to the EETA79001A pattern in Fig. 2B. Compounding the situation is the low Al content of the Nakhla parent liquid (N) evident in Fig. 1 (Pl is the Al bearing component). The Al content is sufficiently low that garnet, which is the most effective REE fractionating agent, cannot have been a residual phase in the parent magma's source region; niether is there much allowance for removal of augite at low pressure. The problem of deriving strongly light-REE enriched magmas from light-REE depeleted source regions is common to terrestrial hot spots, such as Hawaii (8). Single-stage models require prohibitively small degrees of partial melting (<1%), so multi-stage melting models have been invoked to spread the REE fractionation over two or more steps (e.g., 9). Some sort of multi-stage melting process thus seems necessary to explain the Nakhla parent magma composition with the condition that garnet not have been a residual phase in the last stage of melting. In addition to low-Al the Nakhla parent magma also had an unusually high concentration of CaO (~14 wt% (2)). The combination of low-Al and high-Ca requires either that the source was dominated by augite or that CO_2, which has the potential of drastically increasing the CaO content of melts coexisiting with olivine and pyroxene, fluxed the melting at pressures > 25 kb (2). Since partial melting of pyroxene dominated sources produces small negative Eu anomalies in the liquid (10) and since there is no evidence of such an anomaly in Fig. 2A, the presence of CO_2 in martian melting processes must be seriously considered. CO_2 is also an effective carrier of light REE (11), so CO_2 may have affected both trace and major elements during melting.

Fig. 1B illustrates very different REE patterns for the shergottites. The Shergotty pattern is the 70% ICM model taken from (12). The EETA79001A pattern is the bulk rock analysis of (13). EETA79001A is a fine-grained basaltic rock with 10-15 % mafic xenocrysts (14). These xenocrysts will likely have only a minor diluting effect on incompatible elements, so the pattern in Fig. 1B is believed to close to, albeit slightly lower and steeper than, the true parent liquid pattern. The crystallization ages of the shergottites are controversial because of variable shock effects on the isotopic systems and consequentlythe values of ε_{Nd} are model dependent. The values shown in Fig. 1B are consistent with the 180 m.y. age advocated by (15). This age is chosen here because only the younger ages, which yield $\varepsilon_{Nd} > 0$, are petrologically reasonable, and because the 350 m.y. age reported by (16) has been shown to be a mixing line (12). Given these qualifications, the low-Al content, the depleted light-REE pattern, and $+\varepsilon_{Nd}$ of EETA79001A have a straightfoward explanation: partial melting of a low-Al source region with a long term light-REE depletion. In this regard, the source region was similar to that of Nakhla although the EETA79001A magma genesis was apparently much simpler. The ε_{Nd} values for Nakhla and EETA79001A are much higher than typical terrestrial basaltic values, but are more typical of lunar mare basalts. This similarity suggests that Mars was more like the Moon in its ability to maintain long term isotopic heterogeneities in its mantle. Lack of crustal recycling on Mars and/or less vigorous mantle convection than the Earth are probable explanations.

Given the similarity of mineral compositions in Shergotty to those in the groundmass of EETA79001A, it is likely that their parent magmas lay along similar liquid lines of descent, as suggested by Fig. 1, and hence they were derived from similar primary magmas and source regions. If so, then REE pattern and ε_{Nd} of the Shergotty

Shergotty parent magma in Fig. 2B are readily explicable as those of a magma derived from a depleted source region like EETA79001A, but subsequently contaminated by a low-temperature, long-term, light-REE enriched component. The slight U-shape in the light REE is especially indicative of such a contamination. This component probably is crustal, but whether it is older basalt, like the Nakhla parent magma (Fig. 2A), or 'granitic' is not clear; the physics of assimilation favors an evolved composition with a low melting point, however. One thing that is clear is the absence of a negative Eu-anomaly in the Shergotty REE pattern. Consequently, this crustal component was unlike lunar KREEP, which has a prominent negative Eu-anomaly (17).

Fig. 2A contains REE concentrations for the Nakhla parent ('closed system') and the bulk data for EETA79001A taken from Fig. 1 plus additional calculated and measured concentrations of some high-field-strength elements (HFSE) arranged in order of incompatibility. Fig. 2A shows that there are complementary anomalies for Ta, Hf, and Zr in the Nakhla and EETA79001A patterns, thus supporting the hypothesis that the shergottites were generated by remelting a source depleted in a Nakhla-like component. Fig. 2B schematically illustrates typical incompatible element patterns for basalts from terrestrial oceanic islands (OIB), volcanic arcs (ARC), and mid-ocean ridges (MORB). Despite the fact that there is no evidence of plate tectonics on Mars, the Nakhla parent magma pattern appears more similar to the ARC pattern than to OIB or MORB. This similarity is probably due to similar fractionations of the REE from the HFSE during transport by a CO_2-rich vapor phase, rather than similar tectonic styles.

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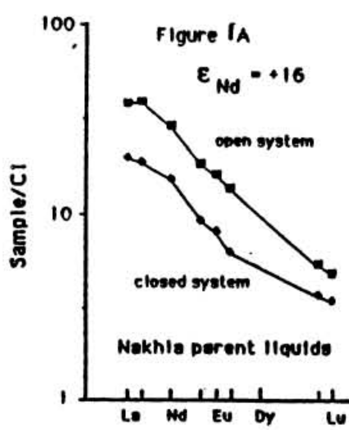
Figure 1. REE in Nakhla and shergottite parent magma compositions. Nakhkla - calc.,this study; Shergotty - calc(12); EETA79001A - bulk (13).



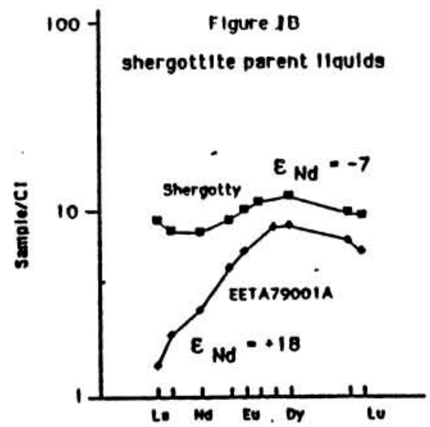


Fig. 2 A. Calculated REE and HFSE in Nakhla parent magma and bulk EETA79001A. B. Typical (schematic) patterns for terrestrial basalts.