

**CRYSTALLIZATION OF A MARTIAN MAGMA OCEAN AND THE FORMATION OF SHERGOTTITE SOURCE REGIONS: A LESS FE-RICH MARS?** D. S. Draper, L. E. Borg, and C. B. Agee, Institute of Meteoritics, 1 University of New Mexico, MSC03-2050, Albuquerque, NM 87131, david@draper.name

**Introduction:** In a recent paper, we modeled the formation of martian basalt (shergottite) source regions via crystallization of an early, extensive magma ocean on Mars [1; BD03 hereafter]. The modeling provided reasonable matches to both isotopic and trace element compositions of martian meteorites while providing an explanation for their broader major element compositions in general and of their superchondritic CaO/Al<sub>2</sub>O<sub>3</sub> ratios in particular. An important inference of the major-element section of the model was that the martian mantle crystallized from an initial composition that was somewhat less Fe-rich than had been previously supposed. Separately, high pressure experimentation on ultramafic compositions used as analogs for the martian interior led Agee and Draper [2, 3] to a similar conclusion. Here we revisit the BD03 model using a less Fe-rich starting composition.

The new model uses the same procedures as in BD03, but replaces the starting composition, which originally was the silicate fraction of the Homestead L5 ordinary chondrite, with that of the silicate fraction of the Farmville H chondrite. The bulk composition of the silicate fraction of Homestead is very similar to Mars compositions such as that proposed by Dreibus and Wänke [4]. The silicate fraction of Farmville has a nearly identical composition to that of Homestead except that its Mg# (molar Mg/Mg+Fe) is 80.4 instead of 76.6. This slightly higher Mg# is the value suggested by both the numerical modeling of BD03 and the experimental results of Agee and Draper [3].

**Approach:** In our model, Mars is essentially fully molten very early in its history, and has a bulk composition of Farmville H chondrite. We assume that the silicate portion of Mars after core formation corresponds to the silicate portion of the Farmville chondrite without its metal, as we did with Homestead in the original work. We then model crystallization of a liquid having that composition, using high-pressure phase relations [4] as a guide to the crystallization sequences that might form. This is analogous to our use of phase relations from Draper et al. [5] in guiding our original choice of crystallization sequences. Each “step” of the sequence consists of the crystallization of a given mineral assemblage over a prescribed range of total extent of crystallization, e.g. the assemblage olivine + orthopyroxene from 20 percent solid (PCS) to 50 PCS. In each such step, we calculated progressive melt compositions using equilibrium and fractional (at melt fractions <20%) crystallization formulations and the mineral assemblage corresponding to that step of

the sequence. Coexisting solid bulk compositions were calculated by mass balance.

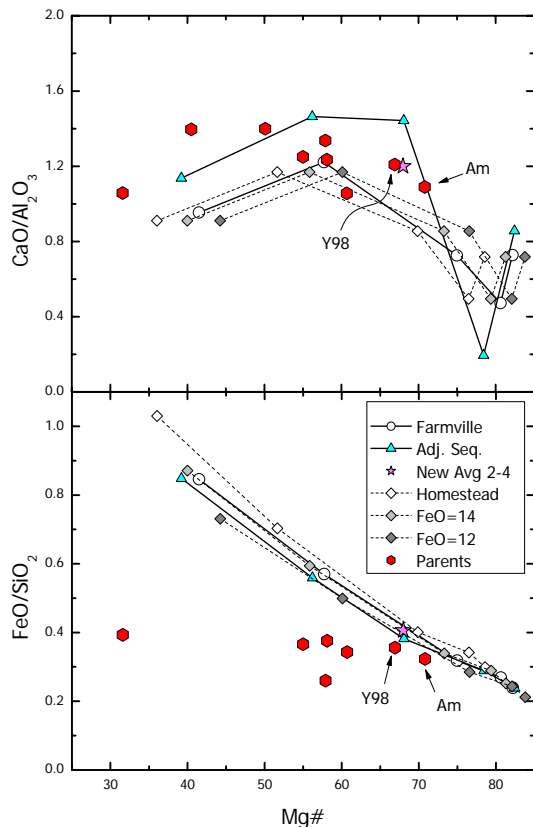
The goal in both the original BD03 modeling and this work is to show conditions under which source regions could form whose partial melts match important major element features of the most primitive liquids, thought to be parental to the shergottites, like Am of McSween et al. [6]. Here we add to the comparison the most primitive shergottite thus far reported, Yamato 980459 [7] (Y98 hereafter). In all models, only sequences in which garnet was an early crystallizing phase produced ranges of cumulate melt compositions similar to these target primitive liquids.

BD03’s original modeling using Homestead L5 as the starting composition suggested a crystallization sequence that yields cumulate packages whose partial melts are the best matches to Am. This sequence (“BD03 sequence”) consisted of these five steps: (1) Crystallization of majoritic garnet until 5 PCS; (2) olivine + majorite (80:20 by weight) to 20 PCS; (3) olivine + orthopyroxene (50:50) to 60 PCS; (4) orthopyroxene + clinopyroxene (60:40) to 90 PCS; (5) clinopyroxene + ilmenite (90:10) to 98 PCS. Here, we first recalculate the major element compositions of cumulate packages using the BD03 sequence and the Farmville starting composition. We then use a slightly different crystallization sequence to illustrate important controls on major-element features of shergottite source regions. The main differences between the two sequences are in the first two PCS steps; steps 3-5 are virtually identical. The five steps in this adjusted sequence are: (1) Crystallization of majoritic garnet to 10 PCS; (2) olivine + majorite (95:5) to 35 PCS; (3) olivine + orthopyroxene (50:50) to 65 PCS; (4) orthopyroxene + clinopyroxene (60:40) to 90 PCS; (5) clinopyroxene + ilmenite (90:10) to 98 PCS. In the adjusted sequence, the overall amount of garnet formed after 98% crystallization is 8% in the original model and 11.3% in the adjusted-sequence version, which also features early garnet crystallization.

For each of the two new sequences, the model yields five separate cumulate packages after 98% crystallization of the starting magma ocean composition. We then calculate 10% batch partial melts of each of these packages and compare them with the primitive liquid compositions noted above. Because the changes from the original model are small, both in terms of the different starting composition and the second, slightly different crystallization sequence used, there is virtually no effect on the trace element calculations as pre-

sented by BD03. Thus by definition these results also satisfy the trace-element and isotopic requirements of the original work.

**Results:** Figure 1 plots compositions of partial melts of the cumulate packages produced by crystallizing a martian magma ocean, in terms of the five most abundant major oxides ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{FeO}$ ,  $\text{MgO}$ , and  $\text{CaO}$ ). Also plotted in red symbols are compositions of calculated parent liquids for shergottite meteorites, with Am and Y98 indicated (see BD03 for references for calculated parent compositions). Diamonds connected by dashed lines show the results of the original modeling using Homestead, plus the adjustments to 14% and 12% FeO that we applied to that composition. Open circles connected by solid lines are results from the BD03 sequence using Farmville, and the blue triangles connected by solid lines are from the adjusted sequence, also using Farmville. As expected, the trend produced using the BD03 crystallization sequence and



**Figure 1.** Results of major-element modeling of 10% batch partial melts of cumulate packages formed during magma ocean crystallization. See text for discussion.

the Farmville starting composition lies close to the lower-FeO trends we generated in our original modeling. Liquids produced from melting cumulate packages from steps 2-4 approach the compositions of likely shergottite parent melts such as Am and Y98.

Phase relations from melting experiments on Farmville [3] suggested the adjusted crystallization sequence whose melts are shown on Fig. 1 (“Adj. Seq.”). These liquids produce an even better match to Am and Y98 and emphasize that early garnet crystallization in a martian magma ocean to give rise to shergottite source regions that have the requisite elevated  $\text{CaO}/\text{Al}_2\text{O}_3$  ratio at the appropriate Mg# is an essential aspect of any successful model of shergottite source regions.

The pink star on Fig. 1, designated “New Avg 2-4,” is the average composition of liquids generated by melting the cumulate packages from steps 2 through 4 of the adjusted crystallization sequence given above (PCS 2-4 was the preferred source lithology in the original models, and was designated *depleted martian mantle*). Its composition is extremely close to those of Am and Y98; the main differences (not visible on Fig. 1) are that it is slightly richer in  $\text{MgO}$  and  $\text{FeO}$ , and slightly poorer in  $\text{CaO}$  and  $\text{Al}_2\text{O}_3$  (although these are present in the correct ratio,  $\sim 1.2$ ), than are Am and Y98. Simple mass-balance modeling shows that the “New Avg 2-4” composition produces a very close match to Am and Y98 after removal of olivine ranging in composition from  $\text{Fo}_{75}$  to  $\text{Fo}_{85}$ ; 15 to 35% olivine removal is required depending on olivine composition and which target liquid is modeled. Orthopyroxene may also be fractionated; mass balances including opx call for only small amounts of that mineral.

**Discussion:** This new modeling supports our earlier suggestion that a slightly less Fe-rich mantle can satisfy major element requirements for shergottite source regions. We conclude that the best overall explanation for the body of geochemical features exhibited by the shergottites is that Mars had an extensive, early magma ocean, with a composition like that of the silicate fraction of H chondrite, that underwent nearly complete crystallization in the first few tens of millions of years of the planet’s history. Much later, melting of the cumulate packages generated by magma ocean crystallization, probably followed by olivine ( $\pm$  orthopyroxene) fractionation, gave rise to the liquids that ultimately were parental to the shergottites. Subsequent processes of mixing with late-stage products of magma-ocean crystallization give rise to the mixing arrays shown by SNC geochemical data [1].

**References:** [1] Borg L. E. and Draper D. S. (2003), *MAPS*, 38, 1713-1731. [2] Agee C. B. and Draper D. S. (2004) *EPSL*, 224, 415–429. [3] Agee C. B. and Draper D. S. (2005), this meeting. [4] Dreibus, G. and Wänke, H., (1985) *H. S. Festschrift*, 20, 367-381. [5] Draper D. S. et al. (2003) *PEPI*, 139, 149-169. [6] McSween et al. (1988), *LPSC XIX*, 766-767. [7] McKay G. A. et al. (2004), *LPSC XXXV*, 2154.