

CONSTRAINING THE DEPTH OF MARTIAN MAGMA OCEAN CRYSTALLIZATION: ROLE OF GARNET COMPOSITION. D. S. Draper, Institute of Meteoritics, 1 University of New Mexico, MSC03-2050, Albuquerque NM 87131, david@draper.name.

Introduction: A diagnostic major-element compositional feature of all basaltic martian meteorites (shergottites) is superchondritic $\text{CaO}/\text{Al}_2\text{O}_3$, with values ranging from ~ 1.0 - 1.7 compared to ~ 0.8 for chondrites. If it is assumed that bulk Mars is essentially chondritic, these ratios imply that martian basalt source rocks were depleted in primordial Al by up to 60% [1]. Several studies have suggested that this depletion was accomplished by early garnet crystallization from a martian magma ocean [2, 3] although it seems clear that martian basalt source regions are not garnet-bearing [4]. Models of martian magma ocean solidification have invoked crystallization sequences in which garnet is an early-formed phase, imparting the elevation in $\text{CaO}/\text{Al}_2\text{O}_3$ to residual liquids, followed by crystallization dominated by phases such as olivine and pyroxene that leave this ratio essentially unperturbed [5-8]. But garnet undergoes important compositional changes depending on pressure, and thus it may be possible to use the effect of early garnet fractionation to constrain the minimum depth of the initial martian magma ocean as described herein.

Effect of pressure on garnet composition: Garnet undergoes a transformation to its higher-pressure form, majorite, at elevated pressures. With increasing majorite content, Si increases from the canonical 3.0 atoms per formula unit (pfu) typical of lower-pressure, pyrope garnets, while Al decreases from the canonical 2.0 pfu. These changes reflect the enhanced solubility with increasing pressure of a pyroxene component in the Y site of garnet via the substitution $^{\text{VI}}[\text{R}^{2+} + \text{Si}^{4+}] = 2^{\text{VI}}\text{R}^{3+}$. These changes are not the same, however, between the more magnesian mantle compositions ($\text{Mg}\# \sim 90$) typical of terrestrial magmatism and the more Fe-rich ($\text{Mg}\# \sim 80$) systems relevant to the martian mantle. This difference is illustrated in Fig. 1, which plots Al pfu vs. pressure for experimental garnet compositions from 23 studies in the literature, including several from our group. For data from typical terrestrial systems (labeled *Mg-rich*), the shift to majoritic compositions is fairly abrupt, and takes place at pressures ~ 15 GPa (dashed schematic curve). In contrast, the changes in garnet Al pfu in more Fe-rich lunar and chondritic compositions are more gradual (red schematic lines); similar features, although less pronounced, are evident in Si pfu vs. pressure (not shown). Note that garnets in most experiments plotted have very low contents of Cr, the main cation that also enters the garnet Y site. This change in Al content attending the shift to majoritic garnet will in turn affect

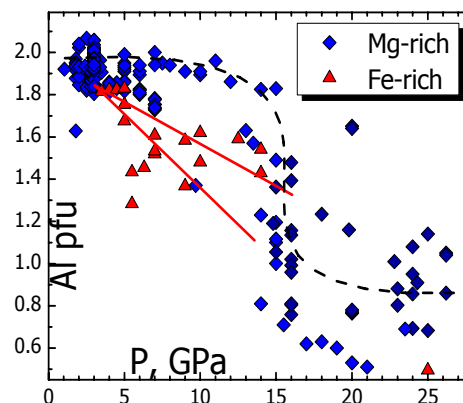


Figure 1. Garnet stoichiometry from 23 experimental studies as function of pressure.

$\text{CaO}/\text{Al}_2\text{O}_3$ of liquids residual to early garnet removal in a martian magma ocean. The more gradual change in Al pfu with pressure may allow constraints to be placed on the depth at which initial garnet removal took place.

Effect of majorite content on $\text{CaO}/\text{Al}_2\text{O}_3$: Figure 2 summarizes the effect of changing garnet majorite content on $\text{CaO}/\text{Al}_2\text{O}_3$ of residual liquids as a consequence of early garnet fractionation during magma ocean crystallization. All calculations were done assuming equilibrium crystallization of garnet having constant Mg-Fe-Ca composition ($\text{Py}_{80}\text{Alm}_{15}\text{Gr}_5$) and varying only in Al and Si; this is justified given the small extents of crystallization being modeled. Furthermore, these compositions are close to those of garnets formed in experiments using chondritic compositions similar to those thought to be close to model martian magma oceans [8, 9]. On this figure, ranges of $\text{CaO}/\text{Al}_2\text{O}_3$ are shown for all the shergottites (~ 1.1 - 1.7 , grey box), and for parent liquids calculated for them by various authors [10-15] (~ 1.05 - 1.3 , blue box). Also, the virtually identical values for the two martian basalts thought to represent liquid compositions, QUE94201 and Yamato 980459, are denoted by the narrow red band (arrow with QUE, Y98). The green band shows the narrow range occupied by chondrites.

The black curves on Fig. 2 represent loci of $\text{CaO}/\text{Al}_2\text{O}_3$ in liquids remaining after removal of garnet having a particular Al content, as a function of the fraction crystallized denoted on each curve. For example, a residual liquid matching the $\text{CaO}/\text{Al}_2\text{O}_3$ of QUE and Y98, ~ 1.2 , will be produced by 5% crystallization of garnet having ~ 1.65 Al pfu, or by 6% crystal-

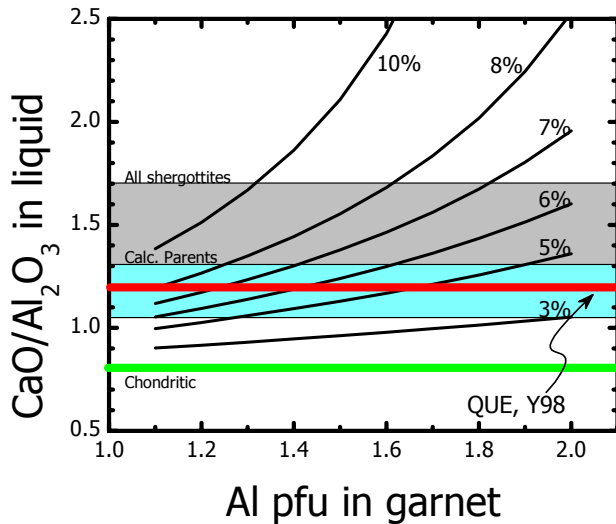


Figure 2. $\text{CaO}/\text{Al}_2\text{O}_3$ of liquids remaining after removal of garnets having range of majorite contents. Curves labeled with percent garnet removed. Grey box denotes $\text{CaO}/\text{Al}_2\text{O}_3$ range of all martian basalts; blue box, that of calculated parent melts; red band, that for QUE94201 and Yamato 980459; green band, that for chondrites. See text for discussion.

lization of garnet with just over 1.4 Al pfu, or by 7% crystallization of garnet with 1.25 Al pfu, and so forth. In general, the more majoritic the garnet composition, the larger percent crystallization required to produce a liquid of a given $\text{CaO}/\text{Al}_2\text{O}_3$.

$\text{CaO}/\text{Al}_2\text{O}_3$ of martian basalt source regions: Although there is a significant range of $\text{CaO}/\text{Al}_2\text{O}_3$ values for martian basaltic meteorites, it could be argued that the value of ~ 1.2 for QUE and Y98 is particularly significant. These two compositions are thought to represent liquids of their own composition [16, 17] rather than crystal accumulates as are all the other shergottites. Because they were likely the products of melting at pressures below the stability of garnet (and of a garnet-free source, as mentioned above), their $\text{CaO}/\text{Al}_2\text{O}_3$ values should reflect those of their sources. In addition, these two compositions occupy opposite ends of the spectrum of martian basalt compositions, with Y98 being the most primitive and QUE one of the most evolved. That they share identical $\text{CaO}/\text{Al}_2\text{O}_3$ also suggests that this value is characteristic of the upper-mantle source for martian basalts.

Magma ocean models [5-7] imply that none of the processes of cumulate crystallization and overturn that followed the early crystallization of garnet significantly affected the $\text{CaO}/\text{Al}_2\text{O}_3$ of the shergottite source regions. That is, once having been set by early garnet crystallization, these later processes leave that value essentially unchanged, and the $\text{CaO}/\text{Al}_2\text{O}_3$ of the shergottite source is a signature of that crystallization.

Thus, having settled on the QUE and Y98 value of ~ 1.2 as characteristic of their sources, we can evaluate the range of garnet majorite contents, and hence pressures, over which this signature was imparted.

Magma ocean depth constraints. To estimate pressures of early garnet formation, Al pfu contents that produce liquids having $\text{CaO}/\text{Al}_2\text{O}_3 \sim 1.2$ (Fig. 2) can be matched with the changes in that parameter with pressure (Fig. 1). Admittedly, the correlation of Al pfu with pressure on Fig. 1 is not highly robust. But if those trends are approximately correct, then the minimum depth at which early garnet crystallization occurred is ~ 9 -10 GPa (~ 900 km depth) with $\sim 5\%$ crystallization of garnet having ~ 1.65 Al pfu, and the maximum would approach 20 GPa (~ 1500 km) with 7-8% crystallization of garnet having ~ 1.15 Al pfu.

These depths probably do not correspond to the base of the magma ocean, however. Convection could be highly vigorous in these early stages, leading to an inertial zone capable of suspending early-formed crystals in much the same manner as suggested for the Moon by Spera [18]. It is also possible that even deeper crystallization could occur in which gamma olivine is an important early phase [6], but that phase would not perturb the chondritic $\text{CaO}/\text{Al}_2\text{O}_3$. But the depths inferred here obviously correspond at least to a minimum depth of a martian magma ocean.

It is also possible to predict the rare earth element (REE) contents of residual liquids after early garnet fractionation using recently published thermodynamic and statistical models [19, 20]. The conditions that are most in accord with the combined major and trace element models of a martian magma ocean [5] are in about the middle of the range outlined here, at ~ 15 GPa with 6-7% crystallization of garnet having Al pfu = 1.2-1.4.

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