

HYDROUS MELTING OF THE MARTIAN MANTLE PRODUCED BOTH DEPLETED AND ENRICHED SHERGOTTITES. F. M. McCubbin¹, E. H. Hauri², S. M. Elardo¹, K. E. Vander Kaaden¹, J. Wang², and C. K. Shearer Jr.¹ ¹Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131. ²Department for Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd., N.W, Washington, DC 20015 (fmccubbi@unm.edu).

Introduction: The search for water in our solar system is one of the primary driving forces for planetary science and exploration. Water plays an important role in many geologic processes and is required for biologic processes as we currently understand them. Besides Earth, Mars is the most promising destination in the inner solar system to find water, as it is undoubtedly responsible for shaping many features observed on the martian surface; however, there is significant debate as to the presence of water in the martian interior [1-6]. Much of our information about the martian interior comes from studies of the basaltic martian meteorites (shergottites), which have bulk water contents of 50-150 ppm [1, 7]. From these values, the martian mantle would have on the order of 5-15 ppm H₂O [1, 4], which is as dry or drier than the lunar mantle [8-9]. Others have argued that magmatic degassing is responsible for the low water contents, and correction for degassing results in mantle water contents that are similar to the terrestrial mantle [3]. The shergottites are a group of fairly young basaltic meteorites that crystallized on the surface and shallow subsurface of Mars. The parental magmas to the shergottites are believed to have been generated by partial melting of the martian mantle; therefore, the shergottites have geochemical signatures that can lend insight into martian mantle chemistry. The shergottites are typically divided into chemical groups referred to as depleted and enriched [10-12]. The most depleted shergottites are characterized by low initial ⁸⁷Sr/⁸⁶Sr ratios (~0.7013), low chondrite normalized La/Yb ratios (approximately 0.1), large and positive ε_{Nd} values (e.g., +48 for QUE 94201), and low magmatic oxygen fugacity (*f*_{O₂}) near the iron-wüstite (IW) buffer (ΔIW+1) [10-13]. The depleted shergottites are believed to represent a depleted mantle source region that has not seen significant alteration or melting since planetary differentiation at about 4.513 Ga [10-11]. The most enriched shergottites are characterized by more radiogenic initial ⁸⁷Sr/⁸⁶Sr ratios (~0.7225), chondrite normalized La/Yb ratios of ~1.5, slightly negative ε_{Nd} values (e.g., -8 for Shergotty), and higher magmatic *f*_{O₂} (ΔIW+2 to +3) [10-13]. The enriched shergottites are believed to be the result of either varying degrees of mixing or assimilation of an enriched source that could be within the crust or mantle. The role of water in these two shergottite types is very poorly understood, but some have suggested that the enriched component

has higher water contents than the depleted source [12].

In the present study we compare the water contents of magmatic apatites within a depleted (Queen Alexandria Range 94201) and an enriched (Shergotty) shergottite to determine whether degassing of martian magmas occurred and whether water was present within their respective magmatic source regions.

Results: Analysis of apatite in the Shergotty meteorite was conducted using secondary ion mass spectrometry (SIMS) and electron probe microanalysis (EPMA), and these data were combined with previously published SIMS analyses of apatite from QUE 94201 [14] as well as newly obtained EPMA analyses for QUE 94201 apatite. Apatites in the Shergotty meteorite have 0.47-0.87 wt% H₂O, whereas apatites in QUE 94201 have 0.22-0.64 wt% H₂O [14]. Based on the apatite-melt partition coefficient for water ($D_{\text{H}_2\text{O}}^{\text{apatite/melt}} \approx 0.3$ [9, 15]), the Shergotty magma contained between 1.55 and 2.88 wt% H₂O at the time of apatite crystallization, and the QUE 94201 magma contained between 0.73 and 2.13 wt% H₂O. These values imply much higher bulk water contents of the basaltic melt than is currently present in the meteorites, confirming the presence of significant pre-eruptive water contents in both depleted and enriched shergottite magmas.

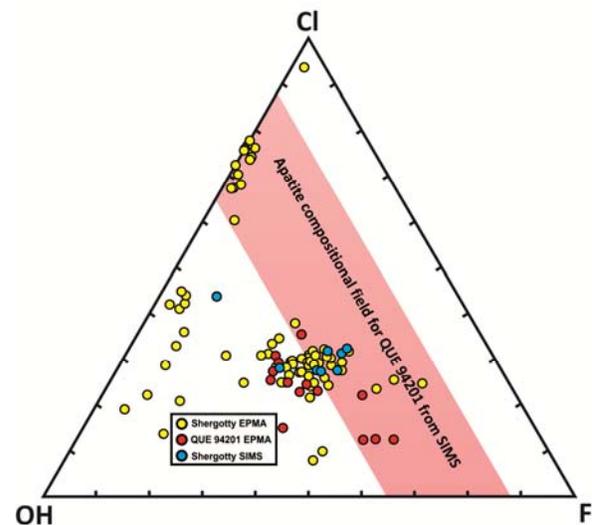


Figure 1. Ternary plots of apatite X-site occupancy (mol%) from the Shergotty and QUE 94201 meteorites using EPMA and SIMS data. The red field represents the range of apatite stoichiometry corresponding to the water contents obtained by SIMS from [14].

Interestingly, the apatite compositions for the two endmembers of the shergottite chemical groups display significant overlap (Figure 1), indicating that water may not correlate with the other chemical signatures that distinguish between depleted and enriched sources.

Discussion: The depleted shergottites are partial melts of the martian mantle that have not seen significant mixing with an enriched component [10-11]; therefore, the elevated pre-eruptive water content of QUE 94201 implies elevated water contents in the mantle source region. Using the same methods employed to estimate the water content of the martian mantle from the bulk rock water contents [1], and assuming apatite saturation occurred after approximately 90% crystallization of the QUE 94201 parent magma, water contents in the depleted martian mantle range from approximately 55 to 160 ppm H₂O. This range of values is similar to estimates of the martian mantle from kaersutite in the Chassigny meteorite [2], as well as estimates from Cl abundances on the martian surface determined by gamma ray spectroscopy (GRS) with the Mars Odyssey spacecraft [5]. Importantly, this range of values overlaps with estimates of the water content in the terrestrial mantle [16-17], showing that plate tectonics may not be required to store water in a planets interior.

For the enriched shergottites, it is unknown whether the source of enrichment is from a mantle or crustal reservoir. If the enriched source is in the mantle, then at least 120-220 ppm H₂O would be required in the enriched mantle source, which overlaps with the high end of the estimated range for the depleted source.

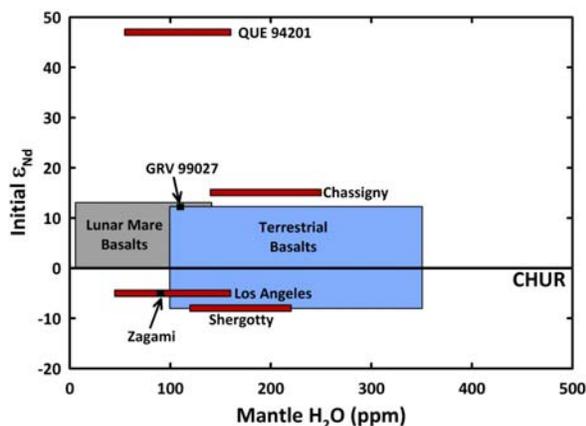


Figure 2. A plot of the initial ϵ_{Nd} vs. calculated mantle water content for various martian lithologies (red rectangles and small black rectangles), KREEP-poor lunar mare basalts (grey rectangle), and various terrestrial basaltic provinces (blue rectangle). The chondritic undifferentiated reservoir (CHUR, $\epsilon_{Nd} = 0$ by definition) shown for reference (black line). Water contents for martian rocks calculated from previously published apatite data in [14, 18-20].

However, if the previously published water contents of apatite from other enriched shergottites are considered, there is complete overlap for the water contents of apatite from depleted and enriched shergottites [14, 18-20]. Therefore, water does not appear to correlate to the typical chemical signatures that distinguish between enriched and depleted shergottites, as illustrated when water is plotted against ϵ_{Nd} (Figure 2).

These results show definitive evidence that martian magmas were not universally dry. Coupled with evidence from the chassignite meteorites [2], the geochemistry of the SNC meteorites as a whole indicate elevated water contents in the martian mantle. Consequently, magmatism on Mars was likely a significant source for surface and near-surface water, and the hydrosphere of Mars may have been at least partially supported by magmatic degassing of water. Given the young ages of the SNC meteorites, volcanism may have been the primary source of water during the Amazonian epoch.

The presence of water in the martian interior has implications beyond the geologic history of Mars. There is little consensus on the origin of water in the terrestrial planets, with groups arguing for either storage of water during primary accretion and differentiation or late addition via comets and meteorites [17, 21]. The Sm-Nd isotopic system indicates that prior to the melting event that formed the QUE 94201 parental magma, the depleted mantle source region from which it formed did not see mixing or melting since the time of Mars' differentiation at about 4.513 Ga [10]. Therefore, the elevated water content of the QUE 94201 source region provides strong evidence that water was incorporated during Mars' formation. These data indicate that Mars was able to store water within its interior during differentiation despite the low f_{O_2} environment during core formation ($\Delta IW = -1.25$) [22]. This is the first evidence of hydrogen storage in a planetary interior during differentiation, and this process could support elevated H abundances in the interiors of other terrestrial bodies like the Moon, Mercury, large differentiated asteroids, and early Earth.

References: [1] Filiberto and Treiman (2009) *Geology* 37. 1087. [2] McCubbin et al. (2010) *EPSL* 292. 132 [3] McSween et al., (2001) *Nature*, 409. 487. [4] Mysen et al., (1998) *Am Min* 83. 942. [5] Taylor et al. (2010) *GRL* 37. [6] Wanke and Dreibus (1994) *TRSL* 349. 285 [7] Leshin et al. (1996) *GCA*. 60. 2635 [8] Hauri et al. (2011) *Science*. 333. 213 [9] McCubbin et al. (2010) *PNAS*. 27. 11223 [10] Borg et al. (1997) *GCA*. 61. 4915 [11] Borg et al. (2003) *GCA* 67. 3519 [12] Herd et al. (2002) *GCA* 66. 2025 [13] Wadhwa (2001) *Science* 291. 1527 [14] Leshin (2000) *GRL* 27. 2017 [15] Vander Kaaden (2012) *LPSC* 43. *This volume* [16] Saal et al. (2002) *Nature* 419. 451 [17] Albarede (2009) *Nature* 461. 1227 [18] Greenwood et al. (2011) *Nature Geoscience*. 4. 79. [19] Watson et al. (1994) *Science* 265. 86 [20] Guan et al. (2003) *LPSC* 34. [21] Drake (2005) *MAPS* 40. 519 [22] Righter and Drake (1996) *Icarus* 124. 513.