HYDROUS MAGMATISM ON MARS: A SOURCE FOR WATER ON THE ANCIENT MARTIAN SURFACE AND THE CURRENT MARTIAN SUBSURFACE?

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Introduction: Water undoubtedly played a crucial role in Mars' geologic history and in any potential biologic history of the planet. Although evidence for surface and subsurface water is strong [1-7], the possible origin of this water from magmatic degassing of the planet remains in question. Current accepted estimates for water contents in the martian mantle range from about 1 to 36 ppm [8, 9]. Such low values appear incompatible with any significant amount of water in mantle-derived magmas and suggests that martian surface water was extra-planetary, brought in post magma-ocean by meteorites and comets [10]. In the absence of plate tectonics, such extra-planetary water would result in a shallow and short-lived Martian hydrosphere, both of which would severely inhibit the formation of a sustainable Martian biosphere [11-14]. But how well constrained is this low water content for the martian mantle? Here we re-examine the evidence for a dry martian interior using observations and analyses of minerals within the Chassigny martian meteorite.

Studies of this meteorite have led to two differing conclusions regarding the water budget of the parental magma. McCubbin and Nekvasil [15] studied maskelynite (shocked feldspar) in melt inclusions and in the regions interstitial to the cumulus grains and concluded that water-rich fluids were responsible for maskelynite and alkali-maskelynite compositions in the melt inclusions, indicating the trapped melt likely had elevated water contents. Yet, Watson et al. [16], in their SIMS study of OH- in kaersutite and Ti-biotite in Chassigny melt inclusions, obtained low water contents, values that are incompatible with formation from a water-rich magma.

The observation of Watson et al. [16] that the Chassigny melt inclusion kaersutite and biotite are water-poor is of such importance that it deserves detailed evaluation. Such water contents may reflect either the water content of the original hydrous minerals that crystallized in the melt inclusion or a post-crystallization process [exclusive of shock dehydration [17, 18]]. If these water contents reflect the primary water contents of kaersutite and biotite, then these water contents should satisfy the general crystal chemical constraints of the mineral structures. However, McCubbin et al. [19] have shown that there are strong crystal chemical arguments indicating that the measured low water contents cannot be an inherent igneous signature. Given the importance of such measurements and the disparate conclusions regarding the water content of the melt inclusion magma, we have reanalyzed, by secondary ion mass spectrometry (SIMS), OH-, F, and Cl in both kaersutite and Ti-biotite in Chassigny melt inclusions.

SIMS data for Chassigny kaersutite and Ti-biotite: Three kaersutite grains and one biotite grain were analyzed for H_2O, F, Cl, and S by secondary ion mass spectrometry (SIMS) on 2 thin sections of the Chassigny meteorite (slide P8064 from the Vatican Observatory, and one slide from the collection of Dr. Robert Dodd). The kaersutite showed a range in water content from 0.41 to 0.74 wt.% (Table 1). These water contents are approximately four times higher than the previously published values [16] and within the predicted range needed to satisfy amphibole stoichiometry [from 19]. The kaersutite grains analyzed had fluorine abundances which ranged from 0.4-0.72 wt.%, and chlorine abundances which ranged from 0.12-0.15 wt.%, consistent with previously published EPMA analyses [20].

The Ti-biotite analyzed contained 1.24 wt.% water, an abundance 2.5 times greater than the previous analysis [16]. Fluorine and chlorine were 0.72 and 0.03 wt.% respectively, which was considerably lower than values obtained by Johnson et al. [20] and Righter et al. [21] by EPMA; yet, due to the higher water contents, the volatile-site sum of our analysis is the same as that reported by Righter et al. [21] (OH + F + Cl = 0.8 afu), indicating a high amount of oxy-component in the volatile-site of all analyzed Chassigny Ti-biotite (1.2 afu O^{2-} in the volatile site).

Table 1. Ion microprobe data for amphibole and biotite in the Chassigny meteorite

Wt%	Kae 1	Kae 2	Kae 3	Biot
H_2O	0.59	0.41	0.74	1.24
F	0.40	0.72	0.48	0.72
Cl	0.12	0.12	0.15	0.03
S	0.02	0.01	0.01	0.01

Implications for the water content of Chassigny parental magma. Published partition coefficients for water between amphibole and silicate melt indicate that the water content of the melt must be greater than the water content of the amphibole that crystallizes from

the melt by about a factor of two (i.e., $D_{H2O}^{amph/silicate\ melt}$ ≤ 0.5) [8, 20, 22, 23]. Assuming a similar value for kaersutite, the range in measured water contents for the amphibole indicates a melt water content of 0.82 to 1.5 wt% H_2O once amphibole appears (approximately double the values from Table 1).

In order to estimate the water content of the melt parental to the Chassigny meteorite, the extent of crystallization before amphibole appeared must be approximated. The martian surface rock Humphrey [from 24] was proposed as a possible parental liquid composition for the Chassigny meteorite [25]. Therefore, experimental phase equilibrium data on the Humphrey rock composition crystallized at 9.3 kbar and 1.67 wt.% water content were used here to get a first-order approximation of the extent of crystallization that occurred before amphibole first appeared [data from McCubbin et al. [26]]. Experimentally, the onset of amphibole crystallization occurred once 44% crystallization had taken place. This indicates a minimum water content of the parental melt ranging from 0.5 to 0.8 wt% H_2O, assuming that no hydrous minerals crystallized prior to amphibole crystallization.

Implications for the water content of the magmatic source region: Work by McSween et al. [27] and Monders et al. [28] have suggested that the Humphrey composition is a primitive melt formed by partial melting of the martian mantle at depth. Moreover, it is thought that the parental magmas of the Chassigny meteorite are the result of partial melting of the martian mantle [8, 29]. If this is the case, then the water content of the parental magma reflects the water content of the martian mantle source region and is a function of the amount of partial melting that occurred to produce the parental liquids to the meteorite.
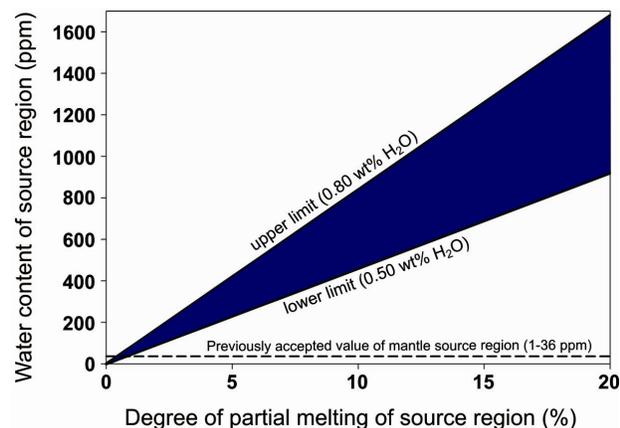

Figure 1. Possible range of water contents for the source region that produced the magma parental to the Chassigny meteorite as a function of the percentage of partial melting. The upper and lower lines for each range represent the possible range in parental magma water contents calculated for the Chassigny meteorite.

If the martian mantle produced a Humphrey-like liquid from about 10% partial melting [after 8, and 30], and water behaves incompatibly, the mantle source water content must range from ~460 to 840 ppm H_2O (Figure 1). This range is more than an order of magnitude higher than previously proposed values (1-36 ppm) for Mars and on the same order as those estimated for the terrestrial mantle [as summarized by 31].

Conclusions: New analyses of water contents of the hydrous minerals in the Chassigny meteorite provide the first direct evidence that Mars experienced hydrous magmatism. Furthermore, based on the young crystallization age of the Chassigny meteorite (~1.3 Ga), hydrous magmatism likely occurred over much of the planet's active igneous history. The elevated water contents of the minerals found in the Chassigny melt inclusions suggest that primary melts from the martian mantle have water contents similar to those of terrestrial tholeiites [32] and that the martian mantle may contain significantly higher water contents than previously deduced. This opens up the possibility of a large magmatic contribution of water to the martian atmosphere, the martian surface, and the martian subsurface. Furthermore, these results indicate the possibility of relatively young water-rich hydrothermal activity on the surface and subsurface, creating environments that may have been suitable for developing and sustaining life.

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