

New Bulk Sulfur Measurements of Martian Meteorites – Implications for Sulfur Cycle and Crust Formation on Mars. S. Ding^{1*}, R. Dasgupta¹, C-T. A. Lee¹, M. Wadhwa², ¹sd35@rice.edu, Dept. Earth Science, Rice University, MS126, 6100 Main Street, Houston, TX 77005, USA, ²School of Earth and Space Exploration, Arizona State University, AZ, USA.

Introduction: Sulfur is thought to be a dominant volatile element in Mars. Understanding the fate of sulfur in various magmatic processes is important for constraining the differentiation history of Mars. The primary source of surficial sulfur on Mars is volcanism and the amount of S released to the martian atmosphere depends on (1) the S content of the mantle-derived magma and (2) the magmatic S budget of the basaltic crust. The former could be estimated by S contents of basaltic melts at sulfide saturation (SCSS) [1,2], assuming mantle derived magma is sulfide saturated. The latter can be approximated by S content in martian meteorites, although bulk S concentration data for martian meteorites are limited [3]. However, both assumptions above are questionable. Firstly, it is unknown whether sulfide, if present in the martian mantle, can remain in the residue during partial melting; Secondly, most martian meteorites contain cumulus minerals and some have experienced secondary alteration (weathering/ impact effects), which could either deplete or enrich S in these samples. These two questions (related to the S content of mantle-derived magma and the magmatic sulfur budget of martian basalts) are fundamental to understanding S distribution among martian mantle, crust and the atmosphere and the fate of sulfur during partial melting in the mantle, crystallization of basalt and formation of the crust. However, no study has combined bulk S data of martian meteorites with their petrology and interpreted them in the context of magma differentiation.

In this study we measured bulk S contents of 7 martian meteorites and modeled the fate of S in differentiating martian magmas. By comparing bulk S data for martian meteorites and the modeling results, we have attempted to estimate the plausible S budgets of the martian mantle, crust, and atmosphere.

Methods: Bulk S contents of 7 martian meteorites (the shergottites Los Angeles, Zagami, NWA 856, NWA 1068, and Tissint, and the nakhlites NWA 998 and Nakhla) were measured using high mass-resolution solution ICP-MS following the method in [4]. Interior chips of each of these martian meteorites were obtained from the meteorite collection in the Center for Meteorite Studies at Arizona State University. Fractions, ranging from ~13 to ~60 mg, were taken from each of these interior chips. For three of the samples (NWA 856, NWA 1068 and NWA 998), two

separate fractions were taken to assess sample heterogeneity. Each of these fractions was then dissolved and processed separately. Sulfur in the bulk rock fractions was dissolved and converted to the S⁶⁺ species in the form of SO₄²⁻ which is analyzed with the ThermoFinnigan Element 2 magnetic sector ICP-MS at Rice University. To check the accuracy of the sulfur analyses, several terrestrial rock standards including one basalt (United States Geological Survey, BHVO-2), one gabbro (Japanese Geological Survey, JGb-1) and one marine mud (United States Geological Survey, MAG-1) were run as external standards in the same sequence.

Results: Within the analytical errors, the two different fractions each from NWA 856, NWA 1068 and NWA 998 yielded identical results. Therefore, the S concentrations reported here for these samples are the averages of the data for the two different fractions for each meteorite. Basaltic shergottites Los Angeles, Zagami and NWA 856 have S contents of 2865±224, 1954±91 and 1584±10 ppm, respectively. Olivine-phyric shergottites NWA 1068 and Tissint have S contents of 1280±48 and 2120±68 ppm. Clinopyroxenites Nakhla and NWA 998 yield the lowest S concentrations of 690±60 and 253±42 ppm S, respectively. Our measurements agree with the range of sulfur contents reported in previous studies of the martian meteorites [3].

Discussion and Implications: The bulk sulfur concentrations for the martian meteorites (reported in this study and in previous studies [3]) correlate with the estimated fraction of melt that the meteorites likely contain (Fig. 1). These S abundances are compared with the modeled S concentration along liquid line of descent (LLD) of three potential primary martian basalt compositions (Y980459 [5], LAR [6], and average Gusev basalt [7]) at 1.0 and 0.1 GPa, at sulfide saturation and under saturation. The major element composition of differentiating magma was estimated using pMELTS algorithm [8] and the SCSS of magma as a function of *P*, *T*, *f*O₂, and composition was calculated using the parameterization developed in [2]. This comparison suggests various possibilities to reconcile the difference between SCSS and the measured S contents of the martian meteorites if volcanic degassing is not the chief mechanism for lowering the S content of the basaltic crust. Firstly, starting compositions with higher FeO* or higher

liquidus temperature gave higher SCSS while shallow crystallization yields low SCSS (Fig.2a,b). S contents of some basaltic shergottites (e.g., Los Angeles) are at or close to SCSS at shallow depth. Secondly, S contents of some basaltic and olivine-phyric shergottites, which contain certain amounts of cumulus minerals, can be obtained by mixing between sulfide-saturated differentiated melts and equilibrium sulfide-bearing cumulates if primary magma is sulfide-undersaturated. Thirdly, some cumulate martian meteorites with or without trapped liquids (e.g., lherzolithic shergottites) match, or are close to, the modeled S content in cumulates, which implies that significant quantity of S could originate in martian crust as cumulus sulfides. To reproduce S contents in the shergottites by mixing of equilibrium melts and cumulates requires that primary magma derived from the shergottite source regions are not sulfide-saturated. Otherwise, precipitated cumulates would contain too high S contents to satisfy both major element compositions and bulk S data of the martian meteorites (Fig. 2). This also suggests that the mantle source reservoirs of the analyzed meteorites likely contain low S (<500 ppm) such that sulfide gets exhausted during partial melting in the martian mantle.

The discussion above does not rule out sulfur degassing, but calls for caution in the estimation of the amount of S outgassing via young martian basaltic volcanism. If meteorite sulfur data are any indication of the sulfur budget of ancient martian crust, S-degassing to the late Noachian and early Hesperian atmosphere could also be limited. Direct measurements of more ancient martian crustal samples will be necessary to test this hypothesis.

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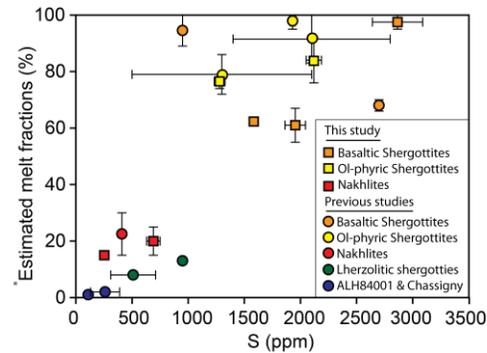


Figure 1. Correlation between bulk S contents of martian meteorites and estimated melt fraction. *Cumulate fractions of Ol-phyric shergottites are from [9]; the rest are calculated using mineral modes reported in [10] and references therein.

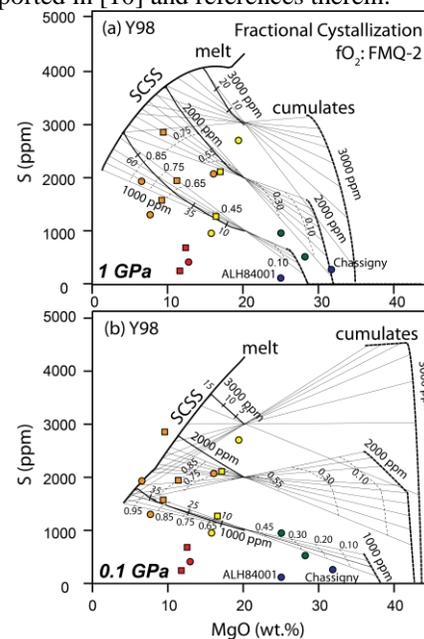


Figure 2. Comparison of the bulk S concentrations in the martian meteorites to the modeled S abundances in melt during fractional crystallization of Y980459 at (a) 1 GPa, and (b) 0.1 GPa. Symbols for the meteorite concentration data are the same as those in Fig. 1. Thick solid lines indicate SCSS along LLD. Intermediate solid curves with numbers (1000 and 3000 ppm) represent liquids that are sulfide undersaturated to begin with. S concentrations in these latter magmas first increase until they reach SCSS, i.e., S behaves as a perfectly incompatible element. Extent of fractional crystallization is shown by tick marks along the intermediate solid curves with italicized numbers. The thick dashed lines with numbers show S concentration increase in the cumulates. The thin solid lines are tie lines between liquids and corresponding cumulates. Thin dashed lines with numbers mark the melt proportions in cumulate-magma mixtures.