AN OVERVIEW OF VOLATILES IN BULK SILICATE MARS. G. Jeffrey Taylor, Hawai‘i Institute of Geophysics and Planetology, SOEST, University of Hawai‘i, Honolulu, HI 96822, and NASA Astrobiology Institute; gjtaylor@higp.hawaii.edu

Introduction: Knowing the bulk chemical composition of Mars is essential to understanding how volatile elements were redistributed during primary differentiation, magmatic construction of the crust, evolution of the crust by aqueous processes, and creation of the atmosphere. Fig. 1 shows a recent revision [1] of the Martian bulk composition compared to Earth [2], but with the addition of carbon and nitrogen. The basic geochemical approach is to assume that refractory elements are in the same relative abundances as in carbonaceous chondrites (this actually seems to work [1]) and then use correlations between a refractory element and a volatile element that have the same geochemical behavior (e.g., both are strongly incompatible). Knowing the abundance of the refractory element then allows us to determine the concentration of the more volatile element. This review focuses on abundances of volatile elements, not isotopic compositions. For isotopes, see the excellent review by Halliday [3].

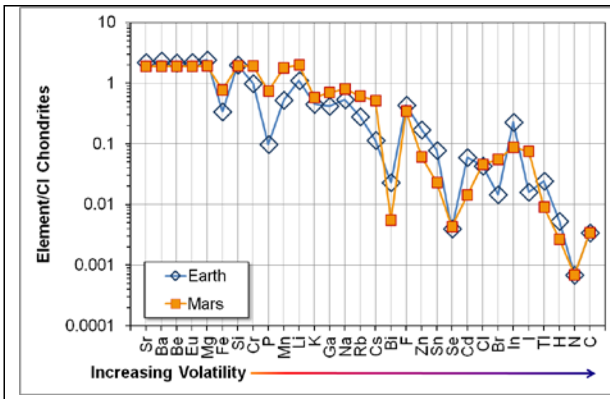

Fig. 1. Bulk compositions of silicate Earth [2] and Mars [1]. Elements listed in order of 50% condensation temperatures [4]; only a few refractory elements are shown for context. See [1] for uncertainties. Both planets are depleted in volatiles.

One-Way Street to the Crust: All our information about volatile elements comes from analysis of crustal materials (meteorites, surface rocks, orbital measurements), so it is important to understand the fractionation between the crust and the mantle. Isotopic studies of Martian meteorites [e.g., 5] suggest that only minimal recycling of the crust takes place. Thus, elements that go into the Martian crust stay in the Martian crust. This removes one mechanism of element cycling, confining all the recycling to the crust and atmosphere.

Half the Inventory of Incompatible Elements is in the crust: Using Th data from the Mars Odyssey Gamma-Ray Spectrometer (GRS), Taylor et al. [6] show that for a crust 57-km thick on average [7] and the Wänke-Dreibus [e.g., 8] Th concentration (no change in my update [1]), that ~50% of the total Th in Mars resides in the crust (Fig. 2). This means that 50% of the total inventory of incompatible volatiles (e.g., Sb, Tl, Bi, H_2O, Cl-Br, C, N) is also in the crust.

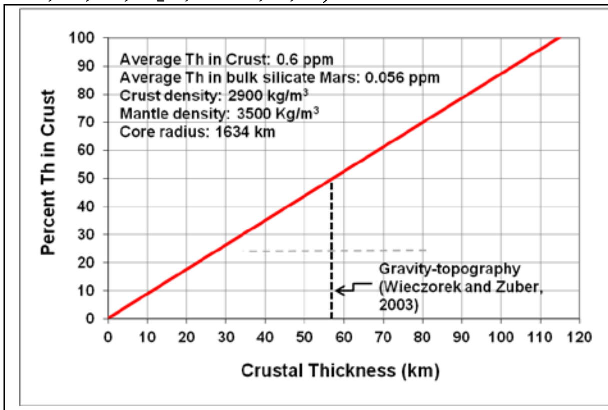

Fig. 2. Calculation of the percentage of Th (hence other similarly incompatible elements) in the Martian crust, using data at top left. Average Th from GRS measurements; bulk Th from [1,8]. The mean crustal thickness from [7] indicates that ~50% of the Martian bulk Th is in the crust. Taking uncertainties in the crustal thickness into account (gray dashed line) the percentage of Th in the crust could range from 29 to 70%.

Volatile Element Abundances: I summarize here the volatile element abundances inferred from elemental ratios (details except for C and N are in [1]), divided into groups of elements of similar volatility, as assessed by 50% condensation temperatures [4]. Results are in Table 1. Division into groups is useful in tracking the overall volatile depletion patterns and because relative fractionations are surprisingly similar within each group.

Moderately-volatile elements. This set of elements condense in the range 800-1000 K [4]. They are only slightly depleted compared to CI chondrites and within uncertainties have CI relative abundances. They are about double in abundance in Mars compared to Earth.

Halogens. The halogens Cl, Br, and I are highly volatile elements. (F is much less volatile, with a 50% condensation temperature close to that of Zn.) Cl is sufficiently abundant to affect magma properties [9] and all are useful for tracking aqueous processes in the crust [e.g., 10]. Martian meteorite data show that the Cl/Br ratio is close to chondritic (Fig. 3). Cl is quite high on the surface, as shown by orbital and lander data [e.g., 11], implying that there is a strong concentration of Cl in the upper crust, presumably caused by aqueous processes. The standard 50% condensation temperature for Cl is 948 K, similar to that of potassium [4]. If this were correct, the bulk Cl normalized abundance in Mars would be similar to that of K, but this does not appear to be the case [1]. I suggest that Cl, Br, and iodine have chondritic relative abundances and concentrations of ~0.06 x CI and similar condensation temperatures of ~540K. (Cl might have a higher condensation temperature, but was lost by impact erosion during during accretion [12].)

Table 1. Mean volatle element abundances (concentration normalized to CI) grouped by volatility.

Volatility Group	Elements	Abundance
Moderately volatile	Na, K, Rb, Cs, Ga	0.6
Halogens (highly volatile)	Cl, Br, I	0.06
Highly volatile elements	Bi, Zn, Sn, Se, Cd, In, Tl	0.03
Ultra volatile elements	H, N, C	0.002

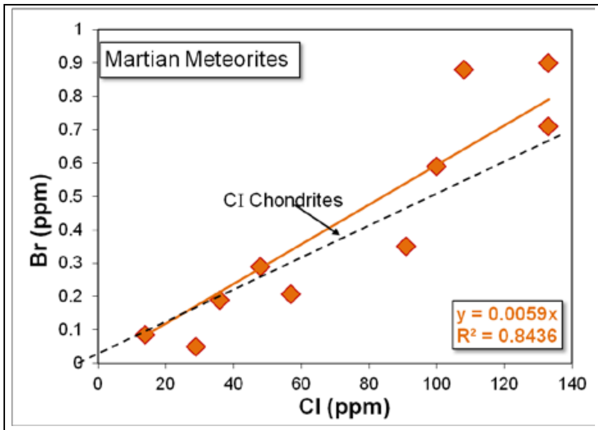

Fig. 3. The Br/Cl ratio appears to be chondritic (modified from [13]).

Highly-volatile elements. This group have condensation temperatures in the range 750-532 K (Hg is 252K, but little data are available for Martian meteorites). They are dominated by chalcophile elements, although in magmas not saturated in S, they generally behave as lithophile elements [e.g., 14]. Correlations with refractory elements have mean CI-normalized abundances of ~0.03. Abundances are roughly similar in Earth and Mars.

Ultra volatile elements. This group of elements (H, C, and N) is important for magmatic behavior, alteration of the crust, and for life. All have complex cycles on both Mars and Earth, though as noted above, the Martian H, C, and N cycles do not include recycling back into the mantle. H is constrained the best by far. As summarized in [1], the bulk Mars H_2O abundance is >300 ppm and likely not much different from the mantle sources of terrestrial MORBs [15]. Fig. 1 assumes 500 ppm for Mars and 1000 ppm for Earth (highly uncertain, see [16]). The δD of Martian interior water is similar to that of the terrestrial mantle [17]. In contrast to isotopic data [2] analyses of elemental C and N concentrations in Martian samples are sparse. Concentrations of C and N in the few samples of igneous rocks suggest that Mars contains approximately the same concentrations of C and N as does Earth. In turn, C and N are among the most depleted elements in Earth [2]. Thus, I use the abundances of C and N in Earth [2] as surrogates for abundances in Mars, ~0.002 x CI concentrations.

Inferences: Holding Fig.1 at arm's length, one gets the impression that Earth and Mars do not differ significantly in composition among volatile elements. The biggest bulk compositional difference is in the far greater FeO abundance in Mars (see details in review by [1]), which affects mantle melt production.

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