MANTLE METASOMATISM IN MARS: EVIDENCE FROM BULK CHEMICAL COMPOSITIONS OF MARTIAN BASALTS. A.H. Treiman, Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston TX 77058. <treiman@lpi.usra.edu>

Bulk compositions of martian meteorite basalts suggest that they formed from a highly depleted mantle that was variably metasomatised and enriched in incompatible elements. These results are consistent with radio-isotope results

Bulk chemical compositions of basaltic rocks retain clues and tracers to their origins and histories. Interpretations of bulk compositions are not so straight-forward as once envisioned [1], because real-world magmatic processes can be far from theoretical simple models like one-stage partial melting or closed-system fractional crystallization [e.g., 2]. Yet, bulk chemistry can shed a broad (if dim) light on Martian basalt petrogenesis that complements the sharply focussed illumination of radio-isotope systematics.

History: Starting ~20 years ago, bulk compositions of martian basalts have been used to constrain the composition of the martian mantle and its basalt petrogensis [3,4]. Treiman [5] delineated two groups of incompatible elements; abundances of elements in each group are strongly correlated, but abundances between groups are not correlated (Table, Fig. 1). Group 1 elements are highly incompatible in silicate mineral/melt fractionation; and Group 2 was inferred to be moderately incompatible. Several peculiarities (notably P, S, and Se being in Group 2) were inexplicable.

Table 1. Incompatible Element Groups [5].

Group 1	Group 2
La, Ce, Nd, Th, U, Ta, Nb, W, K, Rb, Cs, Ba	Ti, Sm, Eu, HREE, P, Al, Ga, Na, S, Se, Cu, Sc, Hf

Fig. 1. Element correlations in shergottites. (a) Ti and Al are Group 2 elements, and their abundances correlate well. (b) P is Group 2, and La is Group 1, and their abundances are not correlated. Dashed lines mark clans of shergottites with relatively constant P/La abundance ratios.

Data Sources: For most SNC meteorites, data are excerpted from [5-7]. Data for Saharan and Omani SNC meteorites are from [8-10].

Group 2 Elements: Unlike in [5], Group 2 (G2) elements are considered first because of the (now) rec-ognized possibility that Group 1 elements were affected by metasomatic or complex igneous process. Abundances of G2 elements are strongly correlated, Fig. 1a, 2a [5], although NOT necessarily linearly. The non-linearities are consistent with pyroxene/basalt fractionation, i.e. $^{Sc}D>^{Al}D>^{Ti}D\approx^{Na}D>^{Lu}D>^{Hf}D>^{P}D$ (Fig. 2b). Because most of the SNCs have similar Fe*, partial melting is an appropriate 0th order model. If $^{P}D \equiv 0$ for the solid mineral assemblage, the trends of Fig. 2a can be modeled by partial melting with $^{Ti}D \approx 0.1$ and $^{Sc}D \approx 0.3$. These D values suggest a restite assemblage with Gp 2 element partitioning dominated by opx [see 11,12] (with the remainder likely being olivine ± minor

Fig. 2. Variation Diagrams, Group 2 elements in shergottites. (a) Sc (blue) and P (red) vs. Ti in Martian basalts. Sc in Shergotty and Zagami is high because they contain cumulate pyroxene. (b) Schematics of expected variations between elements Q and R for mixing (black lines) and fractionations for several sets of D values (orange).

augite).

Group 1 Elements: Group 1 (G1) includes high field strength elements (Th, U, Ta, Nb, W), large ion lithophiles (Cs, Rb, Ba), and LREE. It is clear now that their abundances relative to G2 cannot be explained by

Fig. 3. Group 1 elements. (a) The Ta/Th ratio is identical, and equal to the CI ratio, in shergottites and nakhlites. (b) The Th/La ratio is shergottites is larger than in nakhlites. The three analyses of Los Angeles give a sense of how variable a single rock can be.

simple processes [13].

Many G1 elements have nearly constant abundance ratios in across all the SNC basalts and mesocumulates [5]: Th, U, Ta, Nb, Ba, K, Rb (Fig. 3a); the first five of these are in CI-relative proportions. In other ratios, like

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Th/La, the nakhlites and Chassigny are distinct from shergottites (Fig. 3b). Much of the variability in Gp 1 element abundance ratios can be ascribed to analysis of non-representative samples (small sample masses compared to the abundance of phases that carry the incompatible elements). Abundance ratios for G1 elements that are carried by the same mineral (e.g., La & Nd) show much less scatter that ratios of elements carried by different phases (e.g., La & K).

Group 1 vs. Group 2. Abundances of elements in Groups 1 and 2 are decoupled – one cannot predict the abundance of a G1 element from the abundance of a G2 element. However, abundance ratios G1/G2 are not random, but are restricted to several distinct values (Figs. 1b, 4). These abundance-ratio clans correspond to groupings of the Martian meteorites by Sm-Nd iso-
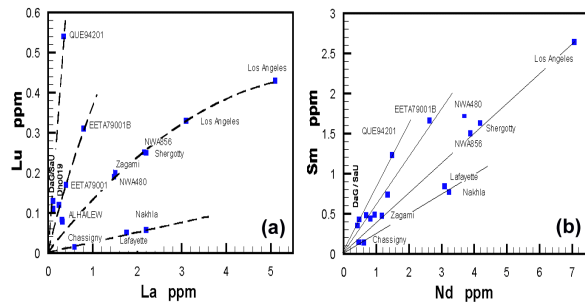

Fig. 4. Group 1 versus Group 2. (a) La (G1) and Lu (G2). Straight lines are constant La/Lu. (b) Nd (G1) and Sm (G2). Straight lines are constant Sm/Nd.

topic ratios and by oxygen fugacities [13,14]

Interpretations. Constraints from bulk chemical compositions are complementary to those from radio-isotopic systematics.

Group 2 Diversification. Element-element variations among G2 elements are consistent with silicate mineral/melt fractionations. Most of the meteorites have similar Fe* values, suggesting variation through mantle partial melting (or otherwise buffered in Fe*). Some basalts (Los Angeles, QUE94201) have elevated Fe* which is consistent with fractional crystallization as a source of diversity.

Group 2 Source Mantle. G2 element-element variations are consistent with mantle partial melting leaving solid residua of opx+(ol±aug). The residua cannot include aluminous phases (garnet, spinel, plagioclase), because Al abundances vary significantly among the SNC basalts. Likewise, the residua cannot contain ilmenite (Ti varies), phosphate (P varies), zircon (Hf varies), or sulfides (S and Se vary).

The absence of an aluminous phase is surprising (compared to the Earth), but the sub-chondritic Al/Ti ratios of the SNC basalts [5] implies that their source region had been previously depleted in aluminum. This

depletion can be consistent with an early magma ocean, but does not require one.

Group 1 Diversification. The distribution of G1 elements is likely controlled by a fluid phase, as it is difficult to imagine a solid that would carry such a variety of elements. The nature of the fluid is not obvious. An aqueous fluid is unlikely, as it would have to transport Ta and Th as readily as K and Ba. Silicate and carbonate melts are possible, as both can extract G1 elements from a lherzolite mantle. However, the absence of several magmaphile elements from G1 is problematic: P, LREE, Ti, Hf, S, Se. On one hand, no fluid (known to me) can accept G1 elements and reject these others into a mantle of ol+opx+aug. On the other hand, a silicate or carbonate melt could lack these elements if they had been sequestered into residual solids, e.g. phosphate (P) and sulfide (S, Se, Cu) and garnet (Ti, Hf, HREE). This would be an unusual mantle assemblage, and it is not even clear that it could produce adequate degrees of fractionation [13].

Group 1 Origin. The origin of the fractionations inherent in the G1/G2 dichotomy were explored at a recent workshop with two favored processes involving enrichment in G1: crustal assimilation, and mantle metasomatism [15].

Mantle metasomatic enrichment of G1 elements is strongly favored by results here. The observation that G1/G2 element abundance ratios are not random, but cluster at a few values (Figs. 1b, 4) is readily explained by metasomatism of highly depleted mantle. Basalts in each G1/G2 'clan' would be derived from a single mantle reservoir that was metasomatized to some degree – different reservoirs experienced different degrees of G1 enrichment. For assimilation to yield this result, each 'clan' of independently formed mantle melts must have co-incidentally assimilated the same proportion of crustal material.

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