REJUVENATED MAGMATISM ON MARS.

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Introduction: Direct and precise geochemical observations for Mars are possible by analysis of meteorites. These meteorites, which represent near-surface extrusive and/or hypabyssal intrusive rocks within the martian crust, including shergottites, nakhlites and chassignites, and ancient (4.1 to 4.4 Ga) crustal rocks (ALH 84001; NWA 7034/7533), are the ground truth for remote sensing (e.g., [1]). To date, however, no unified model has been proposed to explain the petrogenesis of these rock-types, despite their importance for understanding the accretion, differentiation and surface-process history of Mars.

Long-lived isotopic evidence for formation: The geochemical identity of shergottite source reservoirs is well-expressed in ^{87}Sr/^{86}Sr-^{143}Nd/^{144}Nd space, where samples are corrected for ingrowth from ^{87}Rb and ^{147}Sm decay since crystallization (**Fig. 1**). Shergottites define long-term Rb and Nd depleted-, intermediate- and enriched-groups and, collectively, span compositions a factor of ~4 greater than found in terrestrial basaltic rocks. The 1.34 Ga nakhlites and chassignites have isotopic compositions distinct from shergottites and long-term depleted Rb/Sr and Sm/Nd isotopic compositions. Nakhlite/chassignites are petrogenetically associated low-degree partial melts from the same depleted mantle source [2]. The relationship of shergottites to nakhlites/chassignites is not well understood. It has been proposed that late-incompatible element source enrichment must have occurred between major silicate differentiation at 4.504 Ga, and crystallization of the nakhlites at 1.34 Ga [3].

Methods: Data are presented for 25 shergottite meteorites and compared with data obtained for nakhlites/chassignites using identical analytical protocols using inductively coupled plasma mass spectrometry. Measurement under identical analytical conditions removes non-systematic bias from analysis of individual meteorites in different laboratories.

Results: Major- and trace-element results for shergottites and nakhlite/chassignites reinforce several previously identified characteristics of these rocks. Shergottite data highlights the incompatible-element depleted, intermediate and enriched compositions of samples. Intermediate shergottites are the most mafic, with enriched shergottites generally being more silica-rich. Nakhlites/chassignites have incompatible trace-element enriched signatures, with light REE enrichment relative to the heavy REE. Sample NWA 6963 is exceptional in that it has the major element geochemical composition of a shergottite, but the incompatible trace element composition of a nakhlite.

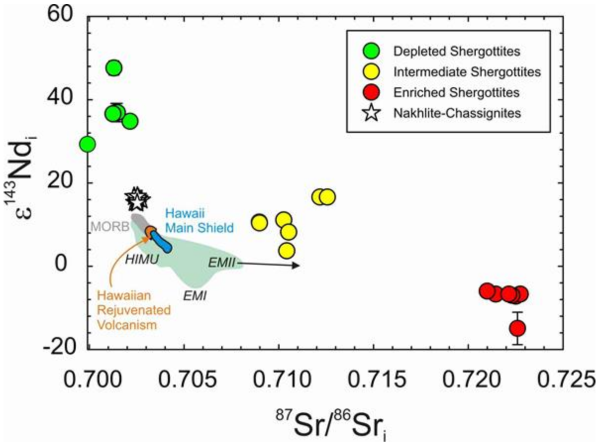

Figure 1: *Sr-Nd isotope compositions of basaltic volcanic rocks from Mars and Earth at the time of their crystallization. Terrestrial basalts include ocean island basalts (green field), mid-ocean ridge basalts (MORB; grey field) and Hawaiian Main Shield and rejuvenated lavas.*

The data also reveal fundamental differences in the geochemistry martian meteorites. Despite having similar Zr/Hf ratios (shergottites = 29.7±4.5; nakhlites/chassignites = 30.6±1.7), fractionation of Zr and Hf in shergottites is mirrored by nakhlite/chassignites. For example, calculated Zr* ($Zr_n/\sqrt{[Nd_n \times Sm_n]}$, where n is the normalized value to CI Chondrite) or Hf* ($Hf_n/\sqrt{[Nd_n \times Sm_n]}$) are distinct between shergottites (Zr* = 1.6±0.3; Hf* = 2.0±0.4) and nakhlites/chassignites (Zr* = 0.4±0.1; Hf* = 0.5±0.1). Similar differences also exist for Nb (Nb* = $Nb_n/\sqrt{[La_n \times Th_n]}$), and Ta (Ta* ($Ta_n/\sqrt{[La_n \times Th_n]}$) between shergottites (Nb* = 1.4±0.3; Ta* = 1.3±0.3) and nakhlites/chassignites (Nb* = 0.8±0.1; Ta* = 0.9±0.1). As expected for melts from depleted mantle sources, nakhlite/chassignites have generally lower absolute abundances of Nb, Y, Zr, and Ta than intermediate or enriched shergottites.

Discussion: A remarkable aspect of shergottite and nakhlite/chassignite compositions is their similarity to geochemical differences observed between Hawaii main shield stage and rejuvenated stage volcanic rocks. Hawaiian shield stage lavas form from the highest degrees of partial melting, above the plume conduit. Rejuvenated stage lavas occur after main stages of volcanism and erupted peripheral to the Hawaiian plume center (e.g., [4,5]). These alkalic lavas are incompatible-element enriched low degree partial melts, yet have Sr and Nd isotopic compositions requiring long-term depleted mantle sources relative to the shield source. These characteristics are like those for nakhlites/chassignites (**Fig. 2**). Such characteristics cannot be explained by crustal contamination of parental magmas, since both terrestrial and martian crust (represented by NWA 7034) have lower Nb/Y than nakhlites/chassignites or Hawaiian rejuvenated lavas.

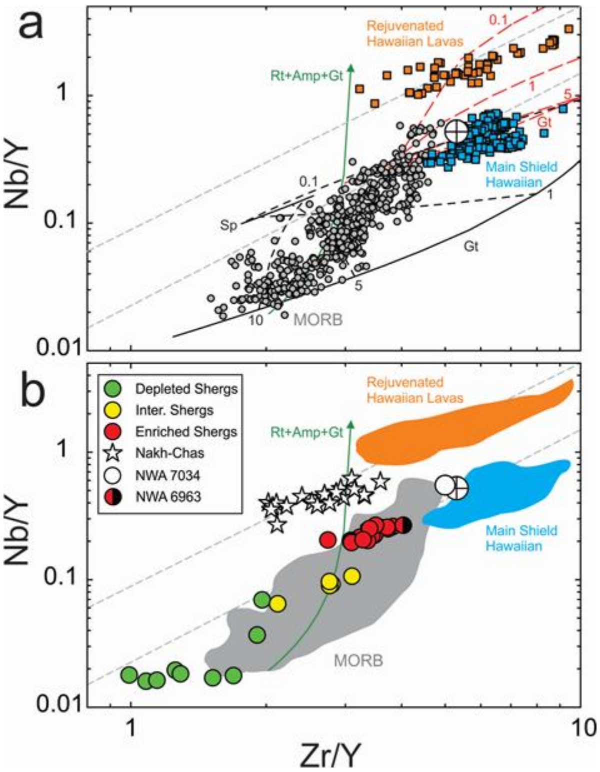

Figure 2: *Nb-Zr-Y discrimination diagrams showing (a) MORB and Hawaiian main shield and rejuvenated phases lavas. Models show partial-melting of different mantle sources (red = primitive mantle; black = depleted mantle; green = exhaustion of rutile [Rt], amphibole [Amp] and garnet [Gt] in a metasomatized martian mantle source). Numbers (0.1, 1, 5, 10) are partial melt increments, in percent and Sp is spinel. (b) Comparison of martial meterorites with terrestrial lavas. Crossed circle is terrestrial continental crust.*

A hallmark of Hawaiian rejuvenated stage volcanism is that it begins after a volcanically quiescent period, requiring a mechanism to engender further melting. The most popular model invokes a depleted source as an intrinsic part of the Hawaiian plume that has been pervasively metasomatized by low-degree melts [4,5]. Maximum extents of rejuvenated melting occur during decompression of the mantle by lithospheric flexure, reaching a maximum ~200 km downstream from the plume [5]. For Mars, joint analysis of gravity and topography has been used to estimate effective elastic thickness of the lithosphere. It has been shown that thickness of the martian lithosphere increases with age and decreased radiogenic power from K, Th and U decay [6]. In detail, the region of massive magmatism – Tharsis – appears to be dynamically supported, suggesting the presence of a mantle plume [6].

We interpret shergottites to represent shield-stage, whereas nakhlites/chassignites are rejuvenated stage igneous rocks from a generally earlier period of activity. In the absence of plate tectonics, stationary plume-generated melting would be expected to strongly deplete portions of the martian lithosphere and mantle. During plume impingement and maturation, eruption of large volumes of basaltic magmas would occur. To generate parental magmas to nakhlites/chassignites, metasomatism of portions of depleted mantle is required. Evidence for a water-bearing lithosphere is provided from its rheology [6], and from addition of fluids into nakhlite/chassignites [7]. Nb-Zr-Y systematics of nakhlites/chassignites support a model of partial melting of depleted but metasomatized mantle. The presence and complete exhaustion of limited quantities of hydrous phases (amphibole, mica) and rutile can generate high Nb/Y nakhlites/chassignites.

Interpretation of nakhlites/chassignites as rejuvenated lavas provides predictive power. Martian rejuvenated volcanism should occur where lithosphere thickened and stabilized and where flexural uplift engendered partial melting. Nakhlite/chassignites comes from a source that has seen prior melt depletion, and the previously extracted melts must have been similar to shergottites to explain elemental abundance patterns. Observations of 2.4 Ga shergottite magmatism supports continued and persistent magmatism for at least 2 Ga [8]. The link is strengthened further by the observation that NWA 6963 - a shergottite - has trace element abundances like nakhlites. The current suite of martian meteorites represents at least two phases of plume magmatism. Nakhlite/chassingnites represent melting of metasomatized mantle from early magmatic events, and could have been ejected from deep craters, or are from regions distinct from young shergottites.

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