

EXPLORING MARTIAN MANTLE HETEROGENEITY: MULTIPLE SNC RESERVOIRS REVEALED.

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Introduction: Earth- and Moon-like mantle and crustal reservoirs have long been proposed to play a role in the petrogenesis of the martian meteorite suite [1, 2]. The parental magmas for this suite are thought to represent mixing between *two* distinct geochemical reservoirs. One end of the continuum is represented by a highly depleted source region with depleted trace-element and isotopic compositions, whereas the other end of the continuum is derived from a more-evolved source region [1, 3-8]. The latter source is either a distinct enriched-mantle source or contamination of depleted magma by a LREE-enriched crustal reservoir during ascent to the surface [8, 9-11].

It has, however, been long speculated that a third component has influenced the isotopic compositions of martian meteorites. This third component is potentially similar to the lunar KREEP (potassium–rare earth element–phosphorus) basalt source [6, 12-14]. If true, this could be associated with early planetary devolatilization. Conversely, this interpreted isotopic ‘heterogeneity’ could also reflect (i) contamination, (ii) *in situ* isotopic ingrowth with variable parent/daughter ratios (U/Pb, Lu/Hf, Sm/Nd, Rb/Sr) over Gyr time span [15], or (iii) secondary, near-surface components.

The objective of the present study is to: (a) assess how many mixing components can be recognized, and (b) address ongoing debates within the martian isotope community. In order to achieve this goal, an exploratory data analysis technique, i.e., Principal Component Analysis (PCA), was applied to the existing martian isotope dataset. Radiogenic isotopes are ideal for this type of study because they are unaffected by melting and crystallization, thus making them true tracers of mantle-source compositions. Upon inspection of the literature, this study represents the first such application of this statistical treatment.

Method: Principal component analysis [16-18] provides a method for reducing a multivariate system to a more manageable number of dimensions, without making any assumptions about the original data. Principal component analysis (PCA) reveals patterns of inter-correlations among variables by defining unique orthogonal directions, i.e., the eigen-vectors of the data that map the spread (or variance) in a dataset [19]. The eigen-vectors represent the fraction of the total variance of the data in the direction of that particular vector. The first eigen-vector accounts for as much of the variance in the dataset as possible; the second does the same for the remaining variability, and so forth. The extent to which the principal component represents the original dataset is indicated by the eigen-value. Data-

sets requiring only one principal component describe binary mixing between two end-members; two principal components describe three end-members that form a planar triangular mixing field; and so forth. Principal component analysis was carried out using Microsoft Excel-Stat software.

Data Sources: This work relies on published Sr-Nd-Hf-Pb radiogenic isotope analyses of shergottite meteorites. Our recompilation captures the entire spectrum of rocks found on Mars. Isotope data from the following meteorites are examined here: Chassigny, Queen Alexandria (QUE) 94201, Larkman Nunataks (LAR) 06319, Zagami, Los Angeles, Shergotty, Allan Hills (ALH) 77005, Elephant Moraine (EET) 79001, Dar al Gani (DaG) 476, Grove Mountains (GRV) 99027, Yamato (Y) 984028, Y980459, Y793605, Y000593, Y000097, Dhofar 019, Tissint, Lewis Cliff (LEW) 88516, Governador Valadares, Northwest Africa (NWA) 856, NWA1068, NWA1195, NWA480, Sayh al Uhaymir (SaU) 094 and SaU008, Roberts Massif (RBT) 04262, and Miller Range (MIL) 03346.

Results: The PCA results for six isotope ratios (²⁰⁴Pb/²⁰⁶Pb, ²⁰⁷Pb/²⁰⁶Pb, ²⁰⁸Pb/²⁰⁶Pb, ⁸⁷Sr/⁸⁶Sr, ¹⁴³Nd/¹⁴⁴Nd, and ¹⁷⁶Hf/¹⁷⁷Hf) for the martian meteorites are presented in Tables 1 and 2. Results for Sr-Nd-Hf are considered separately from the Pb isotopic system.

There are two components of significance for the Sr-Nd-Hf PCA results, which argues for three end-member mixing. The first (V1) and second (V2) component make up approximately 93 % and 6 % of the total variance, respectively, or 99 % of the total variation (Table 1). No significant changes are observed if ϵNd_i or $^{87}\text{Sr}/^{86}\text{Sr}_i$ are substituted.

In our results for the Pb-isotopic system, we present ²⁰⁶Pb-normalized ratios (i.e., ²⁰⁴Pb/²⁰⁶Pb, ²⁰⁷Pb/²⁰⁶Pb,

Table 1 - PCA results summary for Sr-Nd-Hf

Eigenvectors	V1	V2	V3
% of total	92.7	5.7	1.5
⁸⁷ Sr/ ⁸⁶ Sr	-0.58	0.43	0.69
¹⁴³ Nd/ ¹⁴⁴ Nd	0.56	0.83	-0.04
¹⁷⁶ Hf/ ¹⁷⁷ Hf	0.59	-0.36	0.73

Table 2 - PCA results summary for Pb

Eigenvectors	V1	V2	V3
% of total	95.6	3.9	0.5
²⁰⁴ Pb/ ²⁰⁶ Pb	0.58	-0.39	0.71
²⁰⁷ Pb/ ²⁰⁶ Pb	0.57	0.82	-0.01
²⁰⁸ Pb/ ²⁰⁶ Pb	0.58	-0.41	-0.70

and $^{208}\text{Pb}/^{206}\text{Pb}$), rather than conventional ^{204}Pb -normalized ratios, to minimize correlations between analytical errors related to measuring the low ^{204}Pb -isotope abundance [18, 20]. The first and second component make up approximately 95 % and 4 % of the total variance, respectively (Table 2). The lack of a significant contribution by a third component indicates that the data form a near perfect plane in three-dimensional Pb-isotope space, and requires three mixing end-members to account for the variance.

Discussion and Implications: The statistical review presented here suggests that *three* mantle reservoirs, with distinct compositions, are required to explain the observed geochemical variations in martian shergottites, consistent with recent evaluations of mixing within the martian mantle [Fig. 1; 5, 6, 21-23].

The elemental and isotopic compositions of mixtures between depleted and enriched parent melts for martian meteorites were calculated using protocols outlined by Hanan et al. [24]. The model is applicable to any isotope system, or combination of systems where the three end-members are expressed as isotope ratios [17]. The depleted (DMM) and enriched (EMM) martian mantle end-members are well-represented along the compositional continuum of meteorites in various isotope representations [2, 4, 7, 15, 23, 25, 26]. To this spectrum, we add isotopic and elemental concentrations for a martian KREEP-like component that is similar to lunar KREEP [Fig. 1; 5, 6, 27].

Our results show that approximately < 98 % of the depleted mantle component, < 16 % of the enriched mantle component, and < 38 % of the KREEP component are required for the meteorites from this study. Our model also illustrates that (1) depleted mantle was ubiquitous at > 1 Gyr; (2) enriched martian mantle is only a relatively recent phenomena; and (3) at ~ 0.2 Gya, the MKREEP end-member plays a stronger role in martian petrogenesis (Fig. 2). This implies a martian mantle that is not currently stratified.

Summary: The ability of our mixing model to reproduce the compositions measured for martian meteorites, while using a *lunar* end-member, supports the idea that the trace-element and isotopic variability observed in martian meteorites reflects interactions of compositionally diverse sources. Strongly depleted incompatible element sources on the Moon are thought to have been formed by crystallization and accumulation of mafic silicates from the lunar magma ocean, whereas KREEP is thought to represent highly fractionated late-stage magmatic influence. If the analogy between Mars and the Moon is appropriate, Mars consisted of a magma ocean, and remelting of its crystallization products has produced the compositional and isotopic ranges observed in the meteorites [6].

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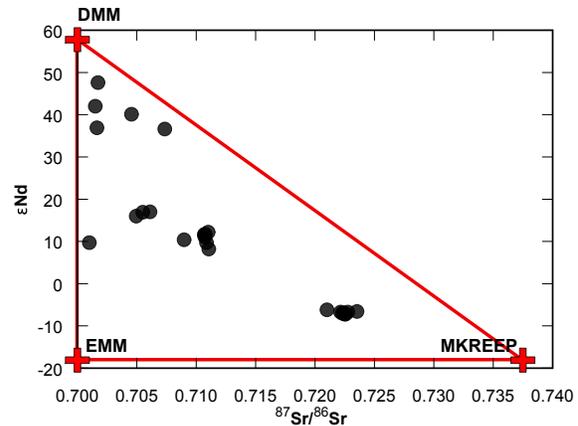


Figure 1. Sr and Nd isotopic compositions for martian shergottites, relative to proposed martian end-members: **DMM** = Depleted Martian Mantle; **EMM** = Enriched Martian Mantle; **MKREEP** = Martian KREEP

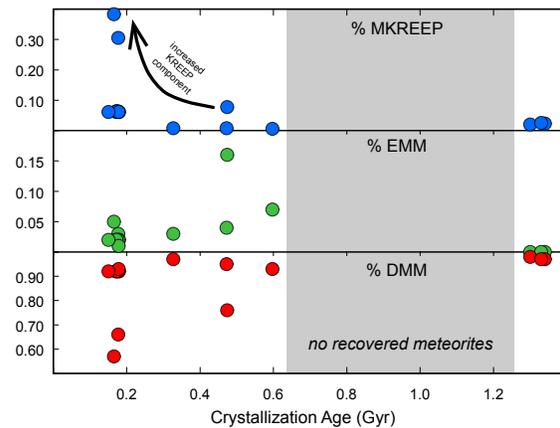


Figure 2. Model end-member mass fractions tracked through time. Each sample is represented by three points: % DMM, % EMM, and % MKREEP.

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