Formation and Preservation of the Depleted and Enriched Shergottite Isotopic Reservoirs in a Convecting Martian Mantle

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Introduction. There is compelling isotopic [1-4] and crater density evidence [5, 6] for geologically recent volcanism on Mars, in the last 100-200 million years and possibly in the last 50 million years. This volcanism is due to adiabatic decompression melting and thus requires some type of present-day convective upwelling in the martian mantle [7-9]. On the other hand, martian meteorites preserve evidence for at least 3 distinct radiogenic isotopic reservoirs [10, 11]. Anomalies in short-lived isotopic systems (^{146}Sm-^{142}Nd, ^{182}Hf-^{182}W) require that these reservoirs must have developed in the first 50 to 100 million years of Solar System history [11-13]. The long-term preservation of chemically distinct reservoirs has sometimes been interpreted as evidence for the absence of mantle convection and convective mixing on Mars for most of martian history [4, 14, 15], a conclusion which is at odds with the evidence for young volcanism.

This apparent paradox can be resolved by recognizing that a variety of processes, including both inefficient mantle mixing and geographic separation of isotopic reservoirs [7, 8, 16-17], may preserve isotopic heterogeneity on Mars in an actively convecting mantle. Here, we focus on the formation and preservation of the depleted and enriched isotopic and trace element reservoirs in the shergottites. In particular, we explore the possible roles of processes such as chemical diffusion and metasomatism in dikes and magma chambers for creating the isotopically enriched shergottites. We also consider processes that may preserve the enriched reservoir against convective mixing for most of martian history.

The Enriched and Depleted Shergottite Reservoirs. The shergottites are sub-divided into three distinct petrological types. The olivine-phyric shergottites all contain significant amounts of olivine and are the closest sub-type to primitive magma compositions, although most have gained some cumulate olivine [18]. Basaltic shergottites show greater degrees of magma evolution, possibly in a magma chamber, as shown by the nearly complete absence of olivine. Lherzolitic shergottites may have also experienced slow cooling in a magma chamber, as shown by pyroxene oikocrysts poikilitically enclosing olivine grains [19].

An alternative geochemical division of the shergottites is based on the slope of the rare earth element (REE) pattern (e.g., the La/Yb ratio). There is a strong but imperfect correlation between the petrological and geochemical classifications of shergottites. LREE depleted shergottites are mostly olivine-phyric, although basaltic shergottite QUE 94201 is also LREE depleted. On the other hand, the enriched and intermediate shergottites are mostly basaltic and lherzolitic, although olivine-phyric LAR 06319 is enriched. Figure 1 shows that trace element depletion or enrichment is strongly correlated with isotopic heterogeneity, in this case ε^{143}Nd. Trace element enrichment is also correlated with other isotopic ratios, such as the initial ^{87}Sr/^{86}Sr ratio, ε^{142}Nd, ε^{176}Hf, and ε^{182}W [20,21]. A striking aspect of Figure 1 is the relationship between igneous formation age and trace element and isotopic depletion or enrichment. The depleted shergottites range in age from 327 to 575 Ma, while the enriched and intermediate shergottites are mostly 165-200 Ma. The sole exception is intermediate basaltic shergottite NWA 1460, whose 346 Ma age [2] overlaps the young end of the depleted shergottite age range.
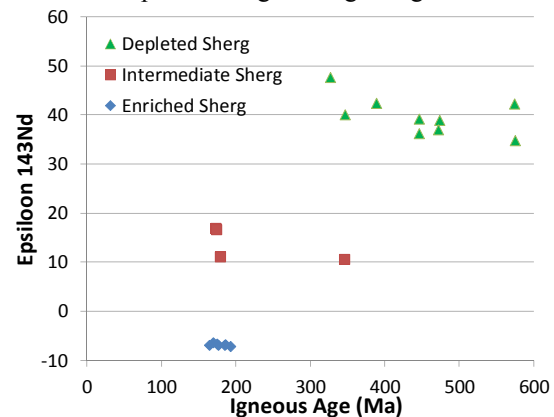

Figure 1: ε^{143}Nd as a function of igneous formation age for depleted, intermediate, and enriched shergottites. Data from [20] and references therein.

Reservoir Interaction and Enriched Shergottite Formation. The REE and all of the major radioactive isotopes are geochemically incompatible, so they will tend to be removed from the martian mantle by melting events, such as a magma ocean or later volcanic activity. We therefore assume that the depleted shergottite reservoir is in the convecting mantle. All shergottites likely formed initially as isotopically and trace element depleted, and the extent to which they became intermediate or enriched depended on the

extent to which the shergottite melts interacted with geochemically more enriched material in the crust or lithosphere while ascending to the surface. One compelling reason for locating the enriched reservoir in the crust is that it is much easier to preserve it there over the age of the Solar System (see below). In addition, the radioactive isotopic anomalies are correlated with oxygen fugacity [22] and, sometimes, with atmospheric sulfur isotopes [23], both of which may be related to surface chemical processes and thus also favor a crustal reservoir for the enriched shergottite source. On the other hand, solidification of a magma ocean might concentrate some incompatible elements in late stage crystallization products in the magma ocean cumulate pile [24], and Re-Os mixing systematics are best explained by a non-crustal reservoir [25]. Because mantle decompression melts traverse both the crust and lithosphere on their way to the surface, it is possible that both the crust and the lithosphere contribute portions of the enriched reservoir material sampled by some shergottites.

Because the radioactive isotopes and REE are incompatible elements, they tend to concentrate in trace mineral phases such as phosphates that crystallize near the end of the igneous solidification sequence. When later basaltic melts (depleted shergottites) intrude the crust, these incompatible elements can interact diffusively with the melt. However, chemical diffusion is typically very slow (~1 meter for a 1 Ma residence time in a magma chamber). Thus, the extent to which a depleted shergottite melt can be enriched by the surrounding crust depends on the thickness of the magma chamber or dike. If the magma chamber is similar in thickness to the diffusion length scale, significant enrichment of the melt is possible. On the other hand, if the chamber is significantly thicker than the diffusion length, then mass balance implies that crust can produce little enrichment of the intruded magma. The magma production in mantle plumes varies episodically in time due to thermal boundary layer instabilities. Times of high magma production rate are likely to result in greater amounts of magma chamber inflation, thus minimizing the enrichment of the magma. On the other hand, at times of low magma production, magma chambers are likely to be thinner, permitting greater amounts of crustal enrichment in the magma. Thus, if mantle plume magma production was higher 300-600 million years ago than at 160-200 million years ago, this mechanism can explain the age dependence of enrichment and depletion shown in Figure 1.

Stating this in a different, but complementary way, primitive melts coming from a peridotitic source are expected to have olivine on their liquidi. Almost all the depleted shergottites meet this criterion, whereas most enriched shergottites do not. We interpret this observation to mean that the enriched shergottites had the opportunity to pond and assimilate crustal materials, whereas the depleted shergottites did not.

Reservoir Preservation. If the enriched reservoir is in the crust, crustal buoyancy will protect it from being convectively mixed into the underlying mantle throughout the history of Mars (there is no evidence for crustal subduction preserved in the geologic record of Mars). Late stage magma ocean crystallization cumulates are expected to be iron-rich and thus dense with respect to the underlying mantle, which could trigger a mantle overturn event, dragging the associated incompatible elements into the deep mantle [26]. Although the enriched material in such a model is consistent with the composition of enriched shergottites, the location of the enriched cumulate pile deep in the mantle is not optimal for serving as the enriched reservoir.

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