The Martian Mantle is Convecting: Preservation of Isotopic Heterogeneity in a Convecting Martian Mantle

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Introduction

There is compelling isotopic and crater density evidence 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. On the other hand, martian meteorites preserve evidence for high levels of isotopic heterogeneity, some of which must have developed in the first 100 million years of Solar System history. This has sometimes been interpreted as evidence for the absence of mantle convection on Mars for most of martian history, 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 geographic separation of isotopic reservoirs and inefficient mantle mixing, may preserve isotopic heterogeneity on Mars in an actively convecting mantle.

Young Volcanism on Mars

The shergottites are igneous martian meteorites whose radiometric ages indicate formation in the last 180-500 million years [1]. A number of these meteorites have concordant ages measured in multiple isotopic systems, including Sm-Nd, Rb-Sr, Ar-Ar, and Lu-Hf [2-5]. This observation, coupled with the preservation of igneous zoning profiles within mineral grains, implies that these systems have not been seriously reset by post-crystallization events. Thus, the concordant ages date the igneous formation of these meteorites, not withstanding some interpretations of the U-Th-Pb system [6]. U-Pb ages of baddeleyites and zircons, which are resistant to isotopic resetting, also confirm igneous activity on Mars in the last 200 million years [7,8]. Cratering density ages indicate that several volcanic constructs, including Olympus Mons, Arsia Mons, Ascraeus Mons, Pavonis Mons, and the Elysium Planitia plains were volcanically active less than 200 million years ago, and perhaps less than 50 million years ago in some cases [9-11].

The two primary locations for creating volcanism on Earth, mid-ocean ridge spreading centers and subduction zones, are not relevant for understanding recent volcanism on Mars because there is no evidence of either large-scale rifting or subuction in the last 500 million years on Mars. Decompression melting in hot, rising mantle plumes explains a variety of martian observations, including the recent magma production rate, the observed range of melt fractions in the shergottites, and the geophysically inferred lithospheric thickness [12]. An alternative invokes a "top down" model, in which decompression melting in upwellings is initially triggered by cold convective downwellings rather than by boundary layer instabilities at the core-mantle boundary [13]. Small amounts of melting may also be possible if delamination occurs at a convective downwelling, similar to a model proposed for Venus [14]. The details vary, but active convective upwelling and downwelling are necessary in all of these models for melting to occur. A thick, low thermal conductivity crust may contribute to magma production in some locations on Mars [15]. However, it can not be the sole process for producing young volcanism, because some volcanos such as Olympus Mons and Elysium Mons are in regions of near-average crustal thickness [16].

Preserving Isotopic Heterogeneity

The silicate portion of Mars preserves high levels of heterogeneity in many isotopic systems, including Sm-Nd, Rb-Sr, Lu-Hf, Hf-W, and Re-Os [17-21]. Measurements of the short-lived isotopic systems ^{146}Sm-^{142}Nd and ^{182}Hf-^{182}W require that portions of this heterogeneity have been preserved for 4.5 billion years [17,18,22]. At least 3 distinct isotopic reservoirs are required [18,28]. It has sometimes been argued that the long-term preservation of this heterogeneity requires that the martian mantle has not convected for most of its history [8,23,24], but such proposals are inconsistent with the observation of young volcanism on Mars. A better solution is to consider methods for preserving isotopic heterogeneity, either by geographic separation of reservoirs or by inefficient convective mixing.

Geographic Separation: The Crust

It is highly likely that part of the martian crust formed very early in its history, at the time of core formation and a possible magma ocean [17,25]. Given the apparent absence of subduction on Mars, isotopic heterogeneity could be isolated in the crust and protected from convective mixing throughout martian history. Interaction between ascending mantle melts and the crust could then contaminate the magma with crustal isotopic heterogeneity. This scenario is supported by apparent mixing lines among

isotopic variability, trace element abundances, oxygen fugacity, and oxygen isotopes [e.g., 26].

Geographic Separation: Mantle Sources

On Earth, the reorganization of mantle convection cells is an important process for mixing and destroying isotopic heterogeneity [27]. On Mars, the volcanic record suggests that convective upwelling has been limited to a few regions for most of martian history and is at least consistent with the possibility that reorganization of the convective pattern has not occurred. Most post-Noachian volcanism on Mars has occurred in four widely separated regions: Tharsis, Elysium, Syrtis Major, and the rim of the Hellas basin. It is possible that each of these separate volcanic systems represents an isotopically distinct convective system. For example, the nakhlites and chassignites have a narrow range of formation ages and initial isotopic ratios, suggesting that they come from a single magmatic system. They are also isotopically distinct from all other martian meteorites [17], which could result if their source is geographically isolated from the sources of other martian meteorites. Future sample return missions to characterize the isotopic composition of the four major volcanic zones on Mars could test this hypothesis.

Geographic Separation: A Layered Mantle

Another method of separating isotopic reservoirs involves a chemically layered mantle, as in Jones' model of a shergottite mantle overlying a nakhlite mantle [28]. Layering in the middle of the mantle would require a large aspect ratio (horizontal length/depth) for convective upwelling beneath Tharsis, which may be difficult to achieve. However, this would not be a serious problem if the lower layer occupies only a small fraction of the total mantle depth. This model may be testable in the near future with seismic observations from the Insight mission.

Inefficient Mantle Mixing

Even if multiple isotopic reservoirs occur within a single mantle convection cell on Mars, it is possible that they could remain distinct for several billion years if convective mixing is inefficient. There are several reasons for thinking that convective mixing is inefficient on Mars. First, Mars has very few strike-slip faults and thus convective flow must be predominantly poloidal (vertical overturning driven by thermal buoyancy) with little toroidal (horizontal spinning) flow [29]. Toroidal flow velocities are 30-50% of the poloidal velocities in the Earth's mantle [30] and are known to substantially increase the efficiency of convective mixing [31, 32]. Second, the thick lithosphere on Mars results in what is known as stagnant-lid convection, with an immobile surface layer and less vigorous flow throughout the mantle relative to a planet with plate tectonics. Recent simulations indicate this will cause the martian mantle to have a convective mixing time several times larger than Earth's [33]. Both factors likely contribute to the inefficiency of convective mixing in the martian mantle.

Acknowledgements: This work was supported by NASA grant NNX09AL23G.

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