Water Under-saturated Mantle Plume Volcanism on Mars

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Introduction

Mars has been volcanically active into the geologically recent past, as demonstrated both by the low impact crater densities on some volcanos as well as by concordant radiometric ages of igneous martian meteorites. For example, Arsia Mons, Olympus Mons, and Pavonis Mons all have mappable surfaces with cratering ages of 100-200 million years [1, 2]. Basaltic shergottite Zagami has an age of 160±12 Ma based on Rb-Sr, Sm-Nd, and U-Pb isotopes [3], while basaltic shergottite NWA 1460 has an age of 346±17 Ma from Rb-Sr, Sm-Nd, and Ar-Ar isotopes [4].

This evidence for young volcanism is an important constraint on the thermal structure of the martian mantle and is best explained by adiabatic decompression melting in an actively convecting mantle [5-7]. The approximately point-like nature of individual martian shield volcanos is consistent with an upwelling cylindrical plume beneath each volcano. Several plumes might be active in the Tharsis volcanic province at any given time, so it is appropriate to think of Tharsis as a cluster of plumes [5, 6] rather than as a single massive “superplume” [8, 9]. In some cases, the thermal effects of a mantle plume may be supplemented by the thermal effects of a thick, low conductivity crust [10]. However, some young volcanos such as Olympus Mons occur in regions of near-normal crustal thickness [11] and thus can not be explained by heating below a thick, insulating crust.

Recent studies have explored mantle plume magmatism on Mars under both dry [6, 12] and wet mantle conditions [13-15]. However, some aspects of the wet melting models are unphysical. For example, in [13] the core heats up by hundreds of degrees for periods of up to 2 billion years after formation despite the fact that the core has no radioactive heat sources. In [14], less than 25% of the initial water and radioactive elements escape to the crust despite the fact that these elements are highly incompatible; the observed volume of the crust [11] implies that at least 40-50% of the incompatible elements should now be in the crust [5]. These considerations suggest that additional modeling of the effects of water on martian mantle plume volcanism is needed. The focus here is on geologically recent melting at water-undersaturated (few hundred ppm) conditions.

Geochemical Constraints

Although the early martian mantle has been proposed to have melted under water-saturated conditions [16], it would have experienced substantial degassing during initial formation of the crust [17, 18], resulting in a water-undersaturated mantle at present. Recent measurements of water in martian meteorites imply several hundred ppm water in the mantle source regions for Chassigny (140-250 ppm, [19]), QUE 94201 (150-290 ppm, [20]), and Shergotty (70-210 ppm, [20]). An alternate estimate for the bulk martian mantle water is 100-500 ppm [21]. Some water (a few hundred ppm) in the mantle source region appears to be necessary to explain chemical trends in the shergottite meteorites [22], although this does not necessarily imply that all young Tharsis volcanism formed with this amount of mantle water.

Based on these considerations, this study compares decompression melting under dry conditions and with 200 ppm water in the mantle source region, using the Katz et al. [23] parameterization of the effects of water on the peridotite solidus. Chlorine and fluorine can also be important in lowering the solidus [24, 25] and may be more abundant than water in the martian mantle [26, 27]. Due to the limited amount of data on the effect of Cl and F on the mantle solidus, their effects are simulated here using the Katz et al. [23] hydrous melting model with an effective water abundance of 500 ppm.

Melting Results

The computational approach follows the dry mantle plume magmatism models of [6]. Plumes are modeled in spherical axisymmetric geometry with a finite element mantle convection code. Viscosity follows an Arrhenius model for olivine [28]. Radioactive heating uses the present-day abundances for the the Wänke and Dreibus [29] composition model, with half of the total radioactivity partitioned into the crust.

Figure 1 shows results for dry melting (dashed red line with diamonds) and for 200 ppm mantle water (blue line with triangles) as a function of the volume averaged Rayleigh number, Ra. Increasing Ra corresponds to increasing convective vigor and a thinner near-surface thermal boundary layer. Models with 200 ppm water have a lower solidus temperature and thus can begin melting with a smaller amount of adiabatic decompression. As a result, the onset of melting in the 200 ppm water case is at an Ra that is about half that of the dry mantle case. At higher Ra, the 200 ppm water cases produce about 50% more magma than the corresponding dry melting cases. Models for 500 ppm water are in development.

The plume model results can be tested using a variety of geological and geochemical results. Based on the results of geologic mapping, the late Amazonian magma production rate is in the range $1.5 \cdot 10^{-4}$ to $2 \cdot 10^{-2}$ km^3 $year^{-1}$ [5], which is consistent with the results in Figure 1. Useful geochemical constraints come from the melt fraction, which can be estimated from measurements of trace element abundances in martian meteorites [e.g., 30], and the range of melting pressures. Dry melting in these models occurs primarily at 3-5 GPa, and the melting zone is expanded toward higher pressure by the presence of volatiles in the mantle source region.

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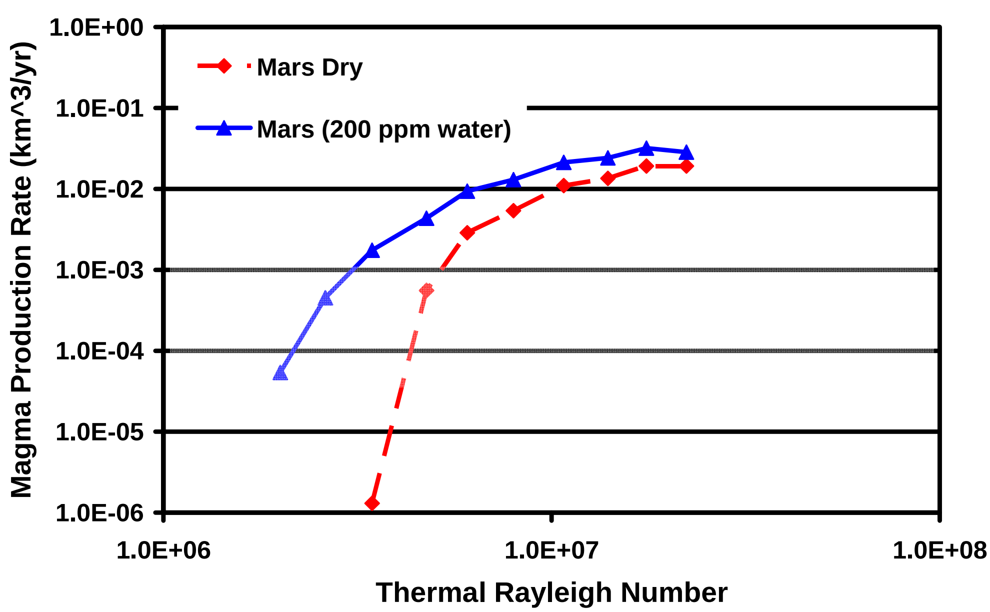

Figure 1: Comparison of magma production rate as a function of Rayleigh number (increasing Ra corresponds to increasing convective vigor). The dashed red line with diamonds corresponds to melting under dry conditions and the blue line with triangles is for a mantle with 200 ppm water.