High Mantle Viscosity Controls the Enormous Size of Martian Volcanoes: A Hypothesis based on Inferences from Rayleigh-Taylor Instability Theory

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Introduction: The exceptionally large size of Martian volcanos, as measured by their diameters and peak heights, was traditionally interpreted as a result of prolonged volcanism above a stationary hotspot with a constant magma source [1]. Although the longevity of a volcano is a contributing factor, it is proposed in this study that the role of the mantle viscosity on Mars has played a much more dominant role in controlling the size of Martian volcanoes This hypothesis is based on correlation between an increase in the size of Martian volcanos and an increase in volcano spacing with time. This is best shown by volcanism across the Tharsis province on Mars as outlined below.

(1) Stage 1: small (diameter < 40 km) central volcanoes at Syria Planum spaced between 20 and 30 km that were emplaced in the Late Noachian and Early Hesperian [2],

(2) Stage 2: moderately sized central volcanoes (peak elevation < 5000 m) on the northwestern flank (i.e., Biblis Patera and Ulysses Patera) and the northeastern flank (i.e., Uranius Patera, Ceraunius Tolus, and Uranius Tolus) of the Tharsis Montes that have a spacing 130-170 km and were emplaced in the Late Hesperian and Late Amazonian [3],

(3) Stage 3: the triplets of the Tharsis Montes spaced at ~750 km that were emplaced between the late Late Hesperian and early Late Amazonian [3], and

(4) Stage 4: the Olympus Mons and Alba Patera spaced at 1850 km and were emplaced mostly in the Amazonian [3].

Viscosity Evolution of Tharsis Mantle: The *dominant* spacing of coevally emplaced volcanos on Earth has been explained by Rayleigh-Taylor instability, which relates the distance between nearby volcanoes (d) to the viscosity ratio of melt (μ_1) and thee surrounding mantle (μ_2), and the thickness of the melt layer (h_2) in the following form [4]:

$$d = \frac{2\pi h_2}{2.15}\left(\frac{\mu_1}{\mu_2}\right)^{1/3}$$

The most important implication of the above relationship is the volcano spacing is proportional to the ambient mantle viscosity. Assuming Rayleigh-Taylor instability to have controlled the location and spacing of Tharsis volcanoes, we may use the temporal variation of volcano spacing to infer how the viscosity evolution of the Tharsis mantle. To do this requires the assumption that the thickness of the melt layer and the viscosity of the melt remained constant with time. This leads to the following simple relationship:

$$\frac{\mu_{mantle}^{Stage\,(i+1)}}{\mu_{mantle}^{Stage\,i}} = \left(\frac{d^{Stage\,(i+1)}}{d^{Stage\,i}}\right)^3$$

Using this relationship the following conclusions may be reached:

(1) Mantle viscosity in stage 2 volcanism is 216 times higher than that in stage 1;

(2) Mantle viscosity in stage 3 volcanism is 2.7 x 10^4 times higher than that in stage 1;

(3) Mantle viscosity in stage 3 volcanism is 4.1 x 10^4 times higher than that in stage 1;

The absolute value of Tharsis mantle viscosity may be obtained if we make an additional assumption that the melt viscosity and melt-layer thickness are the same as those on Earth in continental arc settings where dominant spacing between major volcanoes or volcano clusters is about 70-90 km ([4], [5], [6]). Assuming 10^{18} Pa s for terrestrial mantle viscosity, Tharsis mantle viscosity at stage 1, 2, 3 and 4 would have been 3.1 x 10^{16} Pa s, 6.9 x 10^{18} Pa s, 8.2 x 10^{21} Pa s, and 3.1 x 10^{22} Pa s, respectively, at the time of volcano-zone or volcano-group initiation. This implies that the mantle of Mars had cooled rapidly from 4.0 Ga at the Late Noachian to 3.0 Ga at the onset of Amazonian, causing its viscosity to increase accordingly.

Volcano Spacing, Volcano Size and Comparison to Terrestrial Examples: For the Tharsis Montes and Olympus-Alba volcanic chains, the spacing of the central volcanos is 9 to 23 times greater than that on Earth. Assuming simple cone geometry, the volume (V) of a volcano can be obtained from

$$V = \frac{1}{3}\pi R^2 h$$

where R is the radius of the base and h is the peak height. The volume ratio of two volcanoes with the same flank slope (α) or h/R ratio ($\tan\alpha$) can be expressed by

$$\frac{V_1}{V_2} = \left(\frac{h_1}{h_2}\right)^3$$

For the Tharsis Montes, the average elevation of the three central volcanoes is ~17.6 km and the length of the volcanic chain is ~2500 km. The highest arc volcano on Earth is located in the Andes, at an elevation of 6893 m (the Ojos del Salado volcano) along the Argentina-Chile border. As an example of comparison, it is assumed that the Tharsis Montes volcanoes were initially built from the mean elevation on Mars and the Andean volcanoes from the sea level on Earth. If the

Martian and terrestrial volcano geometry is similar and the effect of isostacy is neglected, the volume ratio between a single Tharsis Montes volcano and a single large Andean volcano would be ~16.5. That is, the total volume of the three Tharsis Montes volcanoes is equivalent to the total volume of about 50 (i.e., 3 x 16.5 = 49.5) largest volcanoes in the Andes. Using 80 km of volcano spacing in the Andes [6], the 2800-km long Tharsis Montes belt could have hosted 35 largest Andean volcanoes. This rough comparison, though with some uncertainties about the initial elevation of volcano construction, details of volcano shapes, and the effect of isostacy, has important implications for why the size of Martian volcanoes is so large. That is, closely spaced (80 km apart) Andean-sized volcanoes alone could account for ~70% volume of the Tharsis Montes volcanoes.

This simple consideration above did not account for two additional factors that would make the above estimate a lower limit: (1) the duration of volcanism and (2) the effect of much higher erosion rate on Earth. As summarized in [3], the development of individual Tharsis volcanoes may have lasted for over 500 Ma. In contrast, the formation of the modern Andean arc started only 115 Ma ago, after a major episode of back-arc extension [7]; this is less than a quarter of the total duration of any volcano construction in the Tharsis province. The current erosion rate across the Andes is between 0.2 to 1.2 mm/yr [8], which requires an average elevation reduction of 600 m per million years. Removing the effect of erosion would have increased significantly the elevation of the Andean volcanoes, which would be more than enough to account for additional 30% volume should they were developed on Mars.

Discussion: If locations of central volcanoes on Mars were controlled by Rayleigh-Taylor instability, then their spacing must have been controlled by ambient mantle viscosity assuming melt viscosity has remained constant with time. This inference is self-consistent with the inferred progressive cooling of Martian mantle with time, leading to an increase in mantle viscosity and thus an increase in volcano spacing from ~25 km in the Late Noachian time to ~1850 km in the Amazonian as observed across the Tharsis province. The increase in volcano spacing implies that an increase of six orders of magnitude of the mantle viscosity had occurred during a span of 1 Ga from the Late Noachian to the beginning of the Amazonian during the Tharsis evolution. Although the uncertainties melt-layer thickness and the details of melt viscosity as a function of mineralogy as a planet evolves with time time, these factors do not appear to affect the estimated ambient mantle viscosity as much as such a large temporal variation of 6 orders of magnitude as deduced from the simple approach adopted above.

Not only the volcano spacing increases but the volcano size also increases with time in the Tharsis province. The peak elevation of Alba Patera (~6.8 km) is about one third of the peak elevation of Olympus Mons (~21 km), but its base is about 3 times wider than that of Olympus Mons. Thus, the volume of the two volcanoes is similar. Olympus Mons is about 1.7 times larger in volume than a single volcano in the Tharsis Montes, which yields a volume ratio of 3.4:3.0 between the Olympus-Alba zone and the Tharsis Montes zone. As the total volume of the two volcanic zones is about the same, the increase in volcano size from the Tharsis Montes zone to the Olympus-Alba zone can simply be attributed to a change in volcano spacing, with both zones supplied by a similar amount of melt from below.

Conclusions: (1) Mantle viscosity of Mars has decreased with time as a result of cooling of the planet. (2) Its viscosity at the beginning of the Amazonian (~3 Ga) was on the order of 10^{22} Pa s, about four orders of magnitude higher than the viscosity of the current terrestrial mantle. (3) The enormous size of Martian volcanos was mainly caused by much wider spacing of volcanoes on Mars than that on Earth due to the high Martian mantle viscosity. That is, melt in Martian mantle was focused and then pumped out on much fewer volcanoes on Mars than those on Earth, allowing individual volcanoes to grow to their large sizes.

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