TIME-DEPENDENT MANTLE CONVECTION ON MARS: IMPLICATIONS FOR EPISODIC TECTONISM AND VOLCANISM IN THARSIS

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The Tharsis province on Mars is roughly 5000 km across, at least 8 km higher than the mean radius of Mars [1], and has a long-wavelength geoid anomaly exceeding 1 km [2]. Volcanic activity has occurred in Tharsis for most of the history of the Mars [3], including relatively recent times - the last 40 to 100 million years at Arsia Mons [4] and possibly the last 25 million years at Olympus Mons [3]. Extensional tectonism is widespread in the Tharsis region [5]. The Elysium province may be a small-scale version of Tharsis.

All of these observations are consistent with the occurrence of upwelling mantle convection in the Tharsis region during much of the history of Mars. There are two fundamentally different types of energy sources for convective flow in a planet's mantle: energy flowing from the core into the base of the mantle (termed bottom heating) and energy released within the mantle due to the decay of radioactive elements and the release of specific heat of cooling (termed internal heating) [6]. Bottom heating produces narrow upwellings (mantle plumes) and internal heating produces much broader convective upwellings. In terms of these two types of flow, the broad Tharsis swell is probably related to the internally heated portion of the convective flow. Individual shield volcanos within Tharsis, such as Olympus Mons or Arsia Mons, may be fed by mantle plumes. Mantle plumes form by the eruption of boundary layer instabilities out of the thermal boundary layer at the base of the mantle [7]. The eruption of such instabilities should occur most readily where the viscosity of the overlying mantle is lowest. The broad upwelling is warmer and therefore less viscous than other regions in the mantle of Mars. Thus, the concentration of shield volcanism and mantle plumes within the Tharsis region may be an indirect consequence of the broader upwelling.

More quantitatively, Kiefer et al. [8] analyzed the contribution of convective flow to the long-wavelength (up to spherical harmonic degree 10) gravity and topography of Mars. They found that convective flow dominates the geoid for all modeled wavelengths and that convection is an important although not dominant contributor to the long-wavelength topography. Moreover, the range of inferred mantle temperature anomalies is consistent with expectations for a convecting mantle. Model temperature anomalies are highest in the Tharsis region, with maxima near Olympus Mons and Ascraeus Mons, consistent with the observed volcanic history.

The observed tectonic history of Tharsis provides additional constraints on the nature of mantle convection in this region. It has often been recognized [e.g., 9, 10] that Tharsis is approximately axisymmetric in overall structure. With mantle upwelling beneath central Tharsis and radial outflow away from the symmetry axis, the geometric spreading associated with the outflow produces extensional stress. The resulting graben should be oriented radial to the center of Tharsis, in agreement with the observed graben orientation [5]. The implication is that mantle flow may have been important in developing the graben system observed in the Tharsis region. Crustal and lithospheric loads also probably played a role [11, 12] in producing these features.

Geologic mapping indicates that the graben system in the Tharsis region developed in a series of 4 to 6 main pulses of activity [5, 13, 14]. Volcanic activity also occurred in a series of pulses [13]. Mantle convection at moderate to high Rayleigh number is strongly time-dependent. The time-dependence of the flow is associated with the development of thermal boundary layer instabilities in both the upper and lower thermal boundary layers [e.g., 15]. Such boundary layer instabilities are a likely explanation for the observed episodicity of both tectonism and volcanism in Tharsis.

Stresses associated with mantle convection may contribute to episodic tectonic activity on two different time scales. On a time scale of 10 to 100 million years, the development of individual thermal boundary layer instabilities can be important. (This time refers to the ascent time of a single instability, not the time interval between successive instabilities, which is typically much longer.) Such instabilities can cause significant changes in the lithosphere's stress state. The loading time is short enough that the lithosphere can respond in a brittle manner, leading to faulting and graben formation. Adiabatic decompression melting of the rising thermal anomaly can also lead to enhanced volcanic activity. On a longer time scale, the cooling of the planet causes changes in the mantle buoyancy field (and hence the convective stresses) as the the Rayleigh number declines, and also causes thermal stresses in the cooling lithosphere. These latter types of stress may also contribute to tectonic deformation. However, the long loading time scale (of order 1 billion years) may cause these stresses to be partially relaxed by visco-elastic processes, thus reducing the importance of these long-term stress sources to the planet's tectonic evolution. Additional numerical modeling of time-dependent mantle convection at various Rayleigh numbers is needed. Such models will provide an essential connection between our current knowledge of the surface geology of Mars and an understanding of how the past mantle dynamics on Mars shaped the observed geology.

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