VOLCANO TOPOGRAPHY AND APPARENT VISCOSITY OF THE CRUST ON MARS.

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Introduction: The lithosphere of Mars experiences little deformation and forms a single plate. However, observational evidence, including extensional grabens and slope change of crustal dichotomy, indicate non-zero crustal deformation [1, 2]. It is highly likely that volcanoes, the largest topographic features on Mars, experience substantial crustal deformation. This research project seeks to explore the potential viscous deformation of the crust on Mars and put constraints on the average apparent crustal viscosity by assuming either no detectable or significant viscous volcano flattening.

Volcano Topography and Viscous Relaxation: The two end scenarioes related to the volcano topography on Mars include: 1) there is no significant or detectable deformation occurring on the volcanoes of Mars. The topographic differences among the volcanoes are due to their varying lava compositions and the increasing of lithosphere thickness through Martian history [3]; 2) there has been continual viscous relaxation of the crust, regardless of volcano composition, beginning with the formation of the volcanoes. In this study, we are going to explore both scenarios.

In many previous Mars lithosphere dynamics studies, the lithosphere, including the crust, is assumed to be elastic or elastic-frictional [4, 5]. Viscous deformation on Mars has been considered in a few studies but mostly in relation to the crustal dichotomy of Mars and for several giant basins [2, 6]. The changes in crustal thickness and lower crustal flow between the southern highlands and northern lowlands have been considered, but whether there is significant viscous deformation is under debate [2, 6].

With volcanoes, high topographic features, there is a large gravitational load on the crust and lithosphere and considerably high deviatoric stress. According to a stress-dependent viscosity law, higher stress may cause lower apparent viscosity. Consequently, with a higher stress and lower viscosity, we are more likely to have detectable viscous deformation on volcanoes than other regions such as the crustal dichotomy or impact basins.

Modeling: Using a digital elevation program, GRIDVIEW, the present-day topographic profiles of fifteen major volcanoes on Mars are obtained with MOLA elevation data. For each volcano, we take profiles along 8 orientations, which have 45° uniform spacing. The topographic slope for each profile is measured. The averages of the profiles and slopes of each volcano are used as contraints in the following viscous and visco-elastic models.

A semi-analytical viscous flow model, assuming uniform linear viscosity in the crust, is used to investigate viscous deformation with varying parameters, including volcano width, height, crustal thickness, and viscosity. Specifically, the model is to determine the evolution of crustal thickness under gravitational forces, assuming Airy's isostasy. The formula we use is similar to Nimmo's formula [6]:

$$\frac{\partial D}{\partial t} = \frac{\Delta\rho g}{12\eta} \frac{\partial (r \frac{\partial D}{\partial r} D^3)}{r \partial r},$$

where D is the crustal thickness, g is the gravitational acceleration, η is the viscosity of the crust, Δρ is the density difference between the crust and mantle, and r is the radius from the volcano center.

Both elastic and viscous crustal properties may affect volcano deformation on Mars. In order to investigate how elasticity affects viscous crustal deformation, a 2D axi-symmetric visco-elastic finite element model is applied to simulate topography change through time. The model assumes a Maxwell visco-elastic rheology, in which

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{\kappa} + \frac{\sigma}{\eta},$$

where $\dot{\varepsilon}$ is the strain rate, κ is rigidity of the crust, σ is stress, and $\dot{\sigma}$ is the stress rate. Airy's isostasy is assumed for the initial volcano configuration while it becomes a dynamic approximation over time [7].

Results: We set a conceptual volcano, which has a linear-slope configuration, and simulate its deformation under gravitational forces with the viscous flow model. The model predicts topography sinking at the volcano's summit and uplifting at volcano's foot. The deformation magnitude depends on several model parameters, including volcano width, crustal thickness and viscosity. Increasing volcano width and crustal viscosity decrease viscous deformation and vice versa. An increase in crustal thickness yields a higher rate of deformation.

We simulate viscous deformation of each major volcano, trying to place upper and lower bounds on the crustal viscosity. The initial shape of each volcano has a configuration similar to the above conceptual volcano, while it has varying slope and width. An upper bound is set to have 2-10% volcano height change in two billion years. If the viscosity is above the upper bound then there is no significant or detectable deformation occurring and vice versa. A lower bound is set to determine the point in which the volcano deforms from an initial shape to the present-day shape within two billion years. The initial shape here is assumed to have a slope equal to the largest volcano slope at present-day (7.8°, Tharsis Tholus). If the viscosity is below the lower bound, the present-day shape of a volcano could not have been sustained in the past few billions of years. The upper bound viscosities are found in the range of 10^{26} - 10^{28} Pa s (Figure 1) assuming a 50 km crustal thickness, whereas the lower bound viscosities are in the range of 10^{24} - 10^{26} Pa s (Figure 2). Assuming a 100 km crustal thickness, the upper and lower bounds increase slightly (less than one order of magnitude).

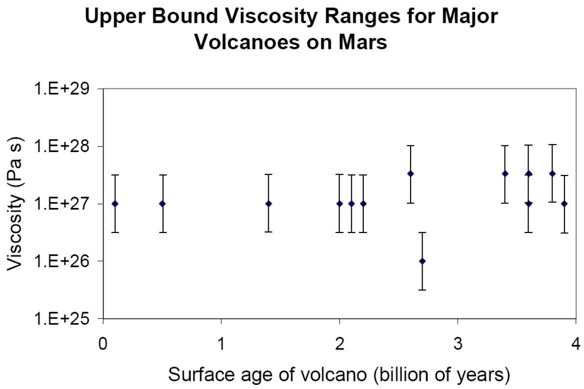

Figure 1: The upper bound viscosity constraints for major volcanoes on Mars assuming a 50 km crustal thickness. The surface ages of the volcanoes are from Carr [8].

Figure 3 shows the topography evolution of Ascraeus Mons predicted by the visco-elastic numerical model. The initial shape of the volcano is set by increasing its slope to the highest volcano slope at present (Tharsis Tholus). During three billion years, the slope of the volcano is continuously decreasing. As the volcano summit is sinking, however, the short-wave length feature of the volcano is well-preserved. As a comparison, the volcano summit and foot have large short-wave length deformation, and the volcano slope changes less with the solely viscous model.

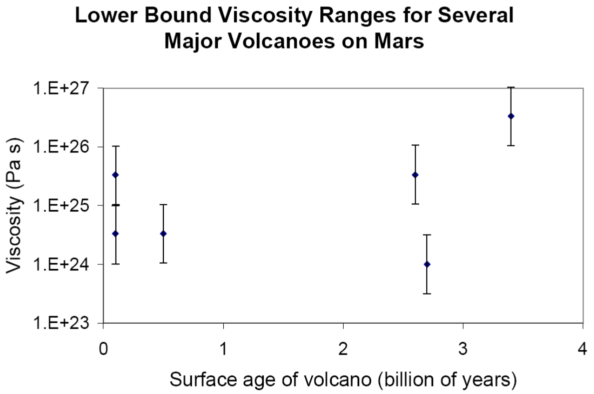

Figure 2: The lower bound viscosity constraints for several major volcanoes on Mars assuming a 50 km crustal thickness.

With the visco-elastic numerical model, we try to set lower viscosity bounds for several major volcanoes. The lower bounds are set to let volcanoes deform from an initial volcano topography, which is assumed to have the same slope as Tharsis Tholus, to the present-day shape in 3 billion years. The lower viscosity bounds based on the visco-elastic model are in the range of 10^{25} - 10^{26} Pa s. The viscosity bounds are close to those set with the solely viscous semi-analytical model.

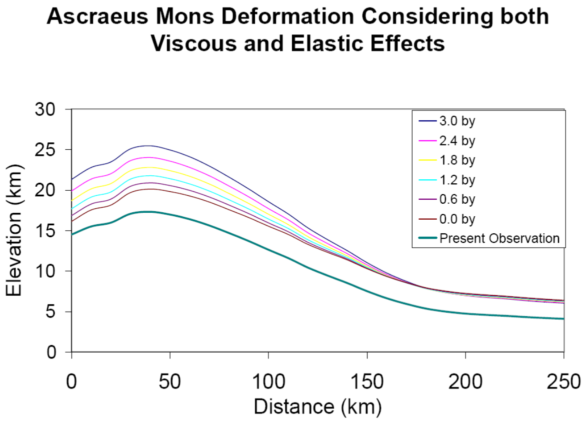

Figure 3: Predicted topography evolution of Ascraeus Mons showing relaxation from initial volcano topography over 3 billion years. Crustal thickness equals 50 km and crustal viscosity equals 5×10^{25} Pa s.

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