Mantle Plume Magmatism in Elysium Planitia as Constrained by InSight Seismic Observations

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Introduction: Based on cratering statistics, there has been active volcanism in the last 100 Ma and possibly the last 1 to 10 Ma in both central Elysium Planitia and in the Cerberus Fossae region of southeastern Elysium [1-4]. Seismic measurements by the InSight mission show a strong concentration of seismicity in Cerberus Fossae which are interpreted as due to magma transport along dike systems [5]. Together, these observations strongly support the existence of geologically recent and possibly of currently active magmatism in Elysium.

InSight seismic observations were also used to construct seismic velocity models for the martian mantle. These models are effectively a regional average of the seismic velocity structure for the Elysium region, where both the InSight lander and most of the measured seismic events are located. These seismic velocity models have been interpreted in terms of the lithospheric thickness and mantle potential temperature. Khan et al. found a lithospheric thickness of 400 to 600 km and a mantle potential temperature of 1325 to 1425 °C [6]. Durán et al. found a lithospheric thickness of ~450 km and a mantle potential temperature of 1375-1475 °C [7]. Drilleau et al. found a thermal lithosphere of 420-660 km and a mantle potential temperature of 1380-1560 °C [8]. In this study, we combine these InSight seismic observations with finite element mantle plume magma production models to place new constraints on the properties of the mantle beneath Elysium Planitia.

Melting Models: The best constraints on melting of the modern martian mantle comes from studies of the olivine phyric shergottites. Olivine phyric shergottite Yamato 980459 (hereafter Y98) is interpreted as an unfractionated mantle melt [9, 10]. As a result, extensive melting studies have been performed on the Y98 composition [9, 11-13]. Following standard practice [14, 15], we parameterize the melting temperature as a quadratic function of pressure using experimental results from 1 bar to 4 GPa,

$T(P) = 1450\ °C + 80*P - 5*P^2$ (1),

where P is expressed in GPa. This is shown as the green line in Figure 1, which is dotted where extrapolated below 4 GPa. Equation (1) fits all experimental data points to 10-15 °C or better, consistent with the likely accuracy of the experimental measurements. Future work may also consider melting experiments on the basalt Fastball from Gusev Crater, which has also been interpreted as a mantle melt [16].

The red box in Figure 1 shows the range of possible mantle temperatures below the thermal boundary layer from [8]. The InSight potential temperatures are converted into physical temperatures and projected downward in the mantle using an adiabatic gradient of 0.18 K/km [17]. The regionally averaged mantle conditions in Elysium are colder than the olivine phyric shergottite melting curve, but this does not rule out the possibility of localized melt sources.

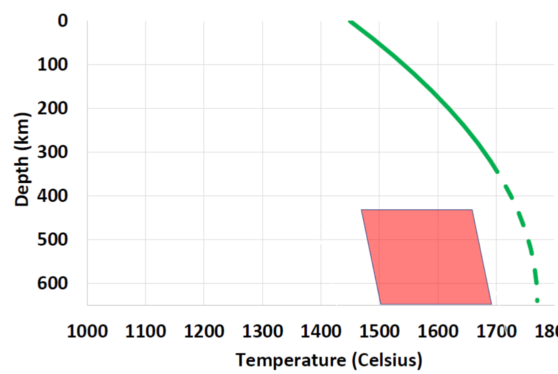

Figure 1: The melting temperature versus depth for the Y98 olivine phyric shergottite source region (green line, dotted below 4 GPa pressure). The red box shows the range of upper mantle temperatures allowed by the InSight mantle seismic model of [8].

Mantle Plume Models: Mantle plumes have been widely invoked as an explanation for young volcanism in Tharsis [17, 18] and Elysium [19]. In these models, melting is limited to a small region around the axis of the upwelling plume (see, for example Figure 1 in [18]). Thus, it is expected that most of the mantle is sub-solidus, as is the case for the regionally averaged seismic model in Figure 1.

In order to more thoroughly explore the role of mantle plumes in producing geologically young Elysium volcanism, we use a series of finite element models of mantle plume magma production [18]. These models span thermal Rayleigh (Ra) numbers between $1.1 \cdot 10^6$ and $2.2 \cdot 10^7$ (increasing Ra corresponds to increasing convective vigor). The temperature dependence of viscosity is based on an olivine flow law [20, 21]. Ra is calculated using volume-averaged, strain-rate weighted viscosity. Total radioactivity is based on bulk mantle composition of 305 ppm K, 16 ppb U, and 56 ppb Th [22], with half of the total radioactivity in a 50 km thick crust and the rest uniformly distributed within the mantle. Each model is run until it is in a statistical steady state. It is then run for several additional convective overturn times to fully sample the temporal variability of the mantle plume thermal structure. Scaling the plume results to physical mantle temperatures depends on the super-adiabatic temperature difference, ΔT, between the surface and the core-mantle boundary. For each model, we calculate the minimum ΔT that is required to achieve melting for that plume model.

The InSight mantle velocity model is based on seismic events at epicentral distances of 18 to 54 degrees from the seismic station [8] and thus constitute a regionally averaged seismic model. We therefore horizontally average the temperature fields for each of our plume models. The base of the thermal lithosphere is determined by the depth at which the advective flux and convective flux are equal; below this depth, convection dominates the thermal structure. We also determine the potential temperature for each model at the base of the lithosphere.

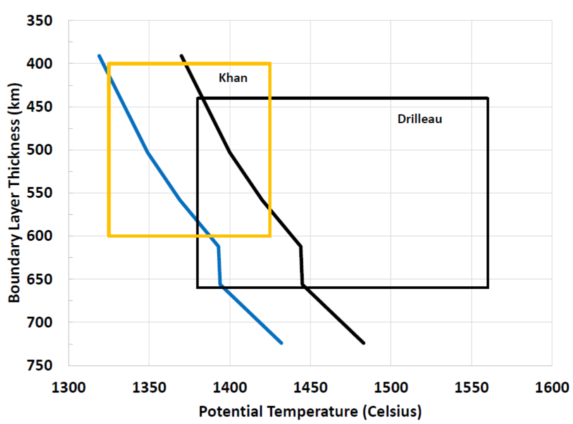

Figure 2: The black line is the combination of potential temperature and boundary layer thickness required for dry melting of the olivine phyric shergottite source region. The blue line is for melting with 50 ppm water. The black and yellow boxes show the allowed range of these parameters from InSight seismic observations [6, 8].

The black line in Figure 2 plots the boundary layer thickness and mantle potential temperature required to achieve dry melting of the olivine phyric source region. The blue line represents similar results for a source region with 50 ppm water. We calculate water undersaturated melting using the method of [23]. Water is known to have a larger effect on the melting of MgO rich systems, such as the olivine phyric shergottites, than it does on other basaltic systems [24]. For this reason, we assume that the liquidus depression in our calculations is twice that calculated by [23] based on results for olivine phyric shergottite melting compiled in [25]. Along both lines, Ra increases from lower right (10^6) to upper left (10^7).

Conclusions: Based on these results, we reach the following conclusions. (1) A hot, upwelling mantle plume in Cerberus Fossae is consistent with both geologically young volcanism and InSight seismology. (2) The range of thermal Ra for the Elysium plume that is allowed by the InSight results is $2 \cdot 10^6$ to $2 \cdot 10^7$. (3) The Elysium mantle is quite dry, with a maximum water concentration of slightly more than 50 ppm, consistent with measurements of water in martian meteorites [25].

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