MANTLE PLUMES AND LONG-LIVED VOLCANISM ON MARS AS A RESULT OF MANTLE COMPOSITIONAL LAYERING. S. W. Zaranek[1] and M. Manga[1], [1]University of California Berkeley, Department of Earth and Planetary Science (szaranek@seismo.berkeley.edu)

Introduction: Previous studies of the Martian interior have highlighted the difficulty in forming and maintaining plumes throughout the history of the planet. A deep, gravitationally stable layer at the base of the mantle, possibly produced by magma ocean crystallization followed by an overturn event, could provide a heat source for plumes and therefore a source of long-lasting, localized volcanism. To address the influence of a layered mantle on the thermal evolution of the Martian interior, we have run a series of 1D numerical convection simulations with temperature-dependent viscosity in spherical geometry. The 1D models include melt generation, from both small-scale convection and plumes, to examine the effect on the magmatic history of Mars.

We explore the influence that the dense layer characteristics (thickness, initial temperature, concentration of heat production elements) have on the melt generated and duration of predicted melting and plume activity. Since our models assume a stable dense deep layer, we determine the densities necessary to have that layer stable over the history of Mars. 2D simulations are used to assess the accuracy of 1D thermal evolution for the layered cases. Additionally, we examine the effect that the chosen melt generation model and solidus and liquidus have on our results.

Numerical Models:

1D Models: Our 1D model (e.g. [1] and [2]) considers a spherical geometry and a temperature-dependent viscosity. The model solves for average core and mantle potential temperature, surface heat flux, core heat flux, melt generation, and crustal thickness as a function of time. The heating by radiogenic elements decays in time, and these radiogenic elements are partitioned between mantle and forming crust. Our models consider both the case of a single layer and a layered mantle.

The 1D thermal model involves three main components: (i) solving of the transient heat conduction equation for the non-convecting regions of the crust and mantle, (ii) solving of the thermal energy conservation equation for the convecting mantle and core, and (iii) solving for melt generation using melt models, considering both the influences of top-down convection (i.e. convection at base of the lithosphere) and buoyancy-driven plumes.

To calculate the volume of melt generated by top-down convection, we use a similar melting model as Breuer and Spohn [2] . We compare this model to the results of the melting model of Hauck and Phillips [1]. In both models, a melt fraction in the regions with temperatures above the solidus is calculated assuming a linear relationship between the solidus and liquidus, and the velocity of upwelling mantle flowing through that region is determined using velocity-Rayleigh number relationships. In the Breuer and Spohn model [2], total melt generation is calculated using this flux of upwelling mantle, the melt fraction, and a maximum potential depth of crust. The latter is calculated by considering the case where the entire mantle was depleted of its basaltic component.

To calculate the melt generated by plumes, we first calculate the thermal anomaly (radius and temperature) and average velocity of the plume as a function of depth using the model of Loper and Stacy [3]. We assume a constant number of plumes (2) over the history of the planet. Using these velocities, the plume radius and temperature, we can then calculate the melt generation by plumes. All melt is assumed to be transported to the surface. We also assume a constant radiogenic concentration in the crust of 5x bulk mantle (assumed to be that of Wänke and Dreibus [4]) and account for the partitioning of radioactive elements from the mantle into the crust by a batch-melting model.

2D Models: 2D simulations use the axially-symmetric spherical version of the convection code Citcom [5]. The code solves the non-dimensional conservation equations for mass, momentum and energy for an infinite Prandtl number, Boussinesq fluid. Density differences driving convective motions are a function of both composition and temperature. Particle methods are used to advect the non-diffusing composition.

Comparison Between 1D and 2D Models: To assess the validity of our 1D thermal models (Figure 1), we compare the results with 2D simulations. 1D and 2D simulations match well for both a compositionally layered (Figure 2) and non-layered interior. In these cases, the deep, dense mantle layer is given a compositional density such that it is stable throughout the run of the experiment. In the 2D models, there exists a sub-adiabtic gradient in the interior. Therefore, we compare both the maximum and minimum internal horizontally averaged temperatures.

Melting Estimates with and without a Dense, Deep Layer: For the conditions chosen (see Table 1), a layered mantle creates slightly less top-down convective melt but creates more total melt and the predicted melting lasts until present day (Figure 3). The crustal

thickness predicted is thicker than that estimated for Mars. However, since we assume all melt created reaches the surface our crustal thickness estimate is a maximum.

We have explored the influence of layer thickness, radiogenic element content, and initial temperature on these melting estimates. Thicker dense layers increase melt flux and result in an earlier development of plumes (Figure 4). A 200km thick layer does not result in current day melting. To achieve current day melting with thinner layers, the layers must have a heat production greater than that of the initial bulk Martian mantle. Increased enrichment of radiogenic elements in the dense layers results in an increased melt flux and an earlier development of plumes. Doubling heat production in the 400km dense layer, yields a ~20 km increase in crustal thickness (Figure 5).

Colder layers decrease net melt flux and result in later development of plumes (and perhaps predict a longer duration for the internally generated magnetic field). However, even a layer starting out at 1400 K results in current day plume activity (Figure 6).

Influences of Solidus and Melting Model: We compare the melting models of Breuer and Spohn [2]and Hauck and Phillips [1]. The overall effect on the rate and duration of melt generation is relatively minor (Figure 7-upper).

We explore the effect of the chosen solidus and liquidus by comparing models using the different estimates of Takahashi [6] and Longhi et al. [7]. Although more melt is created with the Longhi solidus (Figure7-lower), the duration of melt generation is not strongly affected. The total amount of crustal formation may not serve as an ideal criterion for distinguishing between viable thermal evolution models. Duration of melt generation, however, seems to be a more robust criteria for distinguishing between models.

Compositional Density Difference Required for Dense Layer Stability: In our thermal models for Mars, we assume a stable dense lower layer. We use the parameterized flux equations described in the 1D model section to determine the steady-state temperatures of the upper and lower boundary layers. From these, we calculate the compositional density difference necessary for the lower boundary layer to stay stable. We assume stability occurs when the ratio of the buoyancy due to composition to the buoyancy due to temperature difference between the upper and lower mantle is greater than 1, $\Gamma=\Delta\rho_c / (\rho_1\alpha(T_{m2}-T_{m1})) > 1$.

For an initial estimate, we use the values of T_{m1}(upper layer) and T_{m2} (lower dense layer) calculated for a planet in steady state (mantle experiences no net secular cooling). In this simplified model, we do not consider melting, the change of heating due to the decay of radiogenic elements, the cooling of the core, or a crustal component. We do however partition the radiogenic elements between the two layers, keeping the net heating by radiogenic elements constant. For simplicity, we also assume an exponential temperature dependence of viscosity corresponding approximately to a Q=300 kJ/mol.

We determine that the compositional density difference necessary to keep layers stable for a variety of thicknesses and heat productions (Figure 8) is less than that predicted by magma ocean crystallization and overturn [8].

Conclusions: The existence of a layered mantle permits volcanism over the entire history of Mars. Mantle layering increases both the amount and duration of melting. In our models, thinner layers (~200km) require enriched heat production to produce present day plumes. Initially colder layers can still produce plumes while possibly extending the duration of the internally generated magnetic field. The compositional density difference necessary to keep layers stable for a variety of thicknesses and heat productions is less than that predicted by magma ocean crystallization and overturn.

1D models accurately predict the large-scale thermal evolution (flux and average internal temperature) in the 2D models. Although changes in the preferred melting model and solidus may change the amount of melt and duration of melting, layered mantles still provide a viable way to extended volcanism on Mars. Plumes may be a transient effect and may not be seen in models that run to steady-state. Our 1D simulations do not reach steady state in 4.6 Byr.

References:

[1] Hauck S. A. and Phillips R. J. (2002) *JGR*, 107, doi: 10.1029/2001JE001801. [2] Breuer D. and Spohn T. (2006) *Planet. Space Sci*., 54, 153-169. [3] Loper D.E. and Stacy F.D. (1993) *PEPI*., 33, 192-3. [4] Wänke H. and Driebus G. (1994) *Philos. Trans. R. Soc. London, Ser. A*, 349, 2134-2137. [5] Roberts J.H. and Zhong S. J. (2004) *JGR*, 109, doi:10.1029/2003JE002226. [6] Takahashi E. (1990) *J. Geophys. Res*, 95, 15,941-15,954. [7] Longhi, J. et al. (1992) Mars, H.H. Kieffer (Ed.), 184-208.[8] Elkins-Tanton L.T, Parmentier E.M., and Hess P.C. (2003) *Meteor. Planet. Sci*, 38, 1753-71.

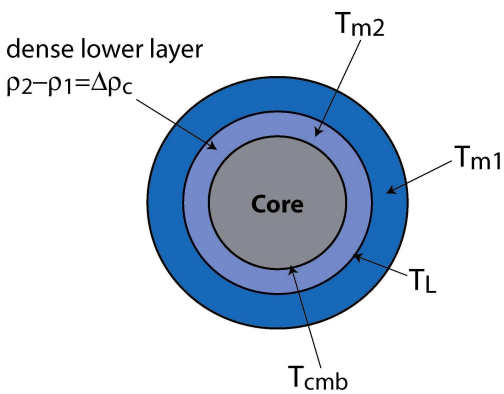

Figure 1: Illustration of initial conditions for the layered mantle models (not to scale). The nomenclature illustrated here will be used throughout the abstract.

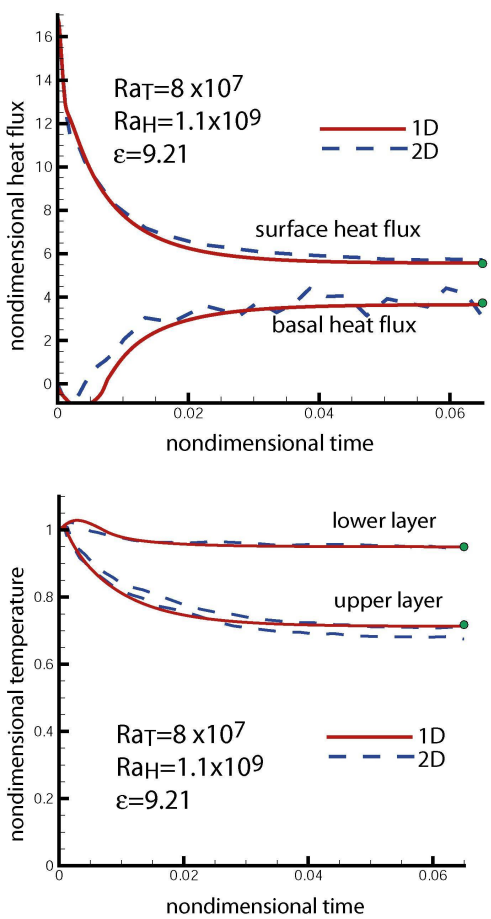

Figure 2: Comparison of 1D and 2D numerical results. Ra_T, Ra_H, Ra_C are the traditionally defined Rayleigh numbers for temperature (using initial temperature difference or internal heating rate, respectively) and for composition. ε is the non-dimensional temperature dependence of viscosity.

initial crustal thickness	50 km
μref (viscosity)	10^{21} Pa s
kmantle (conductivity)	4 W/Km
kcrust (conductivity)	2.4 W/Km
Q (activation energy)	300 kJ/mol
initial (Tcmb-Tm2)	200 K
initial Tm1=Tm2	1800 K
layer thickness	400 km
layer heating	1 x initial bulk mantle

Table 1: Model parameters for Figure 3, 4, 5, and 6.

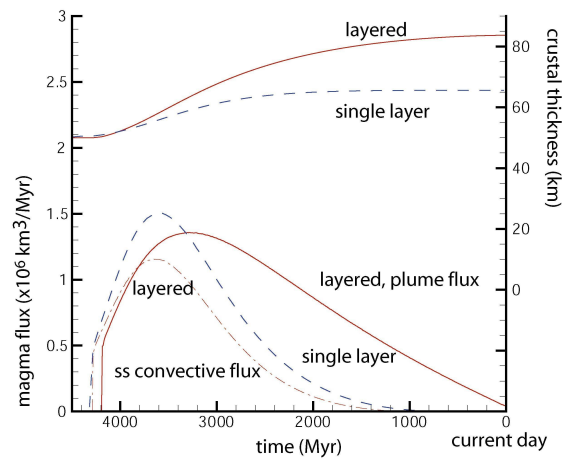

Figure 3: Magma flux and crustal thickness for layered and non-layered cases. Red and blue lines indicate layered and non-layered cases. Dashed and solid lines indicate melt generated from top-down convection and plumes (respectively).

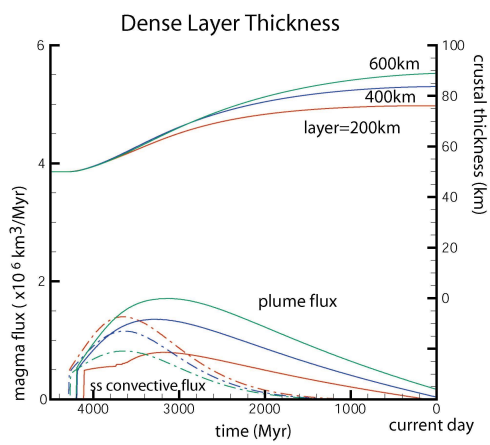

Figure 4: Magma flux from small-scale convection and plumes and crustal thickness for layered cases with different thickness of dense layer. Thicker dense layers increase melt flux and result in an earlier development of plumes.

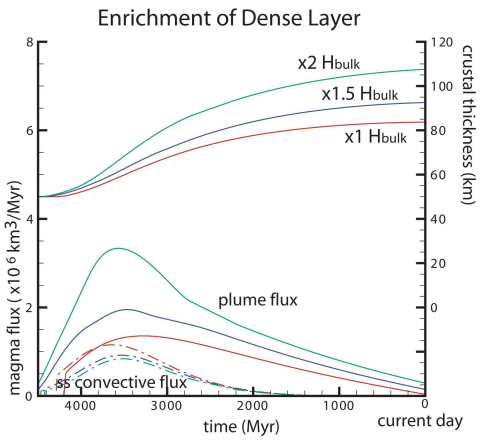

Figure 5: Magma flux from small-scale convection and plumes and crustal thickness for layered cases with different enrichments of radiogenic elements found in the dense layer. Increased radiogenic components in the dense layer result in an increase of melt flux and an earlier development of plumes.

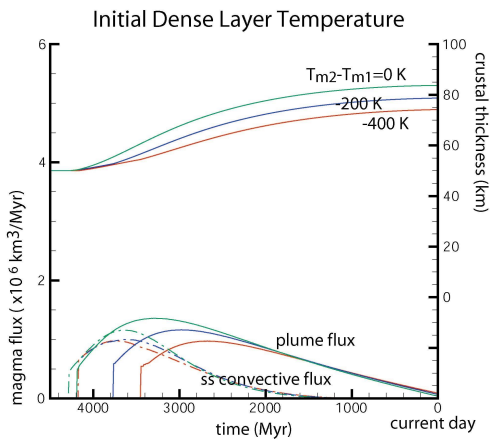

Figure 6: Magma flux from small-scale convection and plums and crustal thickness for layered cases with different initial temperatures of the dense layer. Initially colder layers decrease net melt flux and result in a thinner crust. Even a layer starting out at 1400 K results in current day plume activity.

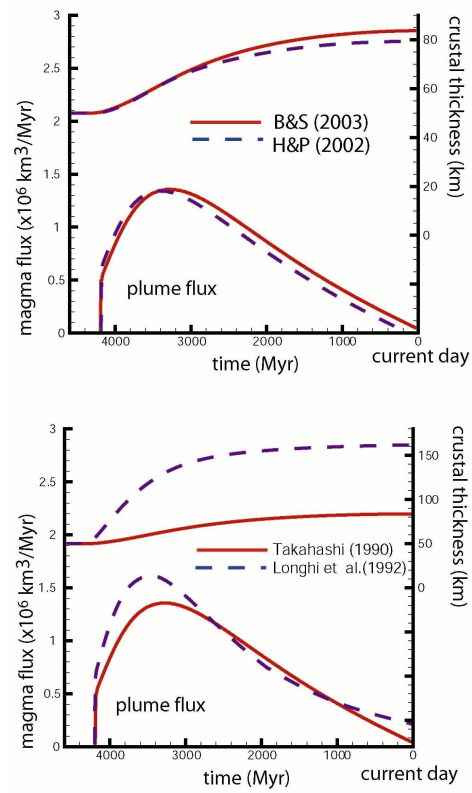

Figure 7: Magma fluxes and crustal thickness as a function of time. *(Upper)* We compare different models for melt generation. The overall effect on the rate and duration of melt generation is relatively minor. *(Lower)* We compare the influence of proposed solidus and liquidus. Although more melt is created, the duration of melt generation is not strongly affected..

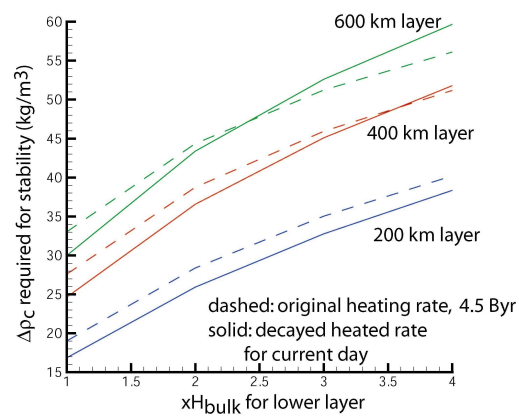

Figure 8: Estimated compositional density differences required to keep various layers stable as a function of dense layer radiogenic element enrichment. The density differences required are lower than those predicted by magma ocean crystallization and overturn models [8].