**3D MODELING OF MELTING HISTORY OF THE MARTIAN MANTLE.** Pavithra Sekhar¹ and Scott D. King², Virginia Polytechnic Institute and State University (4044 Derring hall (0420), Blacksburg, VA 24061; pav06@vt.edu; sdk@vt.edu²)

**Introduction:** Tharsis rise, where the shield volcanoes Olympus Mons, Arsia Mons, Pavonis Mons, Ascraeus Mons and Alba Patera are present, is one of the most prominent features of Mars, covering almost one quarter of the surface area of the planet. The Tharsis region consists of the shield volcanoes and two rises: the southern rise from 40°S to 20°N includes Arsia, Pavonis and Ascraeus Mons and, the northern rise consists of Alba Patera.

A number of researchers have suggested that one or more plumes are responsible for the volcanoes on Tharsis rise (Harder et al, 1996; Kiefer, 2003). The formation of Tharsis rise places a constraint on the timing of melt production and thus, the thermal history of Mars. There must be sufficient melt to create Tharsis rise by the end of the Noachian era but then melt production should taper off rapidly.

Studies have indicated that there has been recent volcanic activity on Mars, mainly Arsia Mons (Schumacher S et al, 2007; Wenzel et al, 2004). While most of Tharsis rise was in place by end of the Noachian period, at least one volcano on Tharsis swell (Arsia Mons) has been active within the last 10-30 Myr, indicating that upwelling convective flow remains active on Mars today.

**Thermal History:** Melting on Mars can be constrained by a number of factors through time, including: past melt generated, the amount of melt required to make Tharsis and also sufficient melt to explain the present day volcanism. Partitioning of radioactive elements between crust and mantle must have happened early in Mars history. If the heat producing elements are uniformly distributed throughout the mantle, there is widespread melting of the lower mantle. This provides a constraint on the melt production during the early stages of Mars’ formation.

A little later in the history of the planet, around 1.5 billion years after the formation, melt generated should be sufficient to create Tharsis region, providing another constraint on the melt production. Finally, studies have also indicated recent volcanism on Mars that suggests present day generation of melt as well. Existence of young volcanism implies that adiabatic decompression melting and hence, upwelling convective flow in the mantle remains important on Mars at present.

Previous work in 2D axisymmetric geometry has shown that present day melting would be restricted to the heads of hot mantle plumes that rise from core-mantle boundary, consistent with the spatially localized distribution of recent volcanism on Mars[1].

**Modeling:** Mantle convection models can be used to study the generation of melt on Mars through time. One important element of this is the inclusion of a radioactive heating term that decays with time. The main radioactive elements are uranium, thorium and potassium and we use the concentration and decay values from Turcotte and Schubert, 2002. Each element has a different half-life that decays at a different rate and contributes to the total radioactive heat generation. These elements decay with time producing internal heat that contributes to a convective or conductive mantle. Over 4.5 billion years, that rate of radioactive heating decreases by about 75%. This decay heat contributes to the production of melt and could also explain the recent volcanism.

The computational grid used for previous work was an axisymmetric, hemispherical shell rather than a full, 3D spherical shell. In this work, mantle convection simulations were performed using finite element code CitcomS in a 3D spherical shell. Temperature and radius are non-dimensional values varying between 0 and 1, where 0.4 defines the core-mantle boundary and 1 defines the surface. Comparison between previous 2D axisymmetric plume models by Kiefer[1] and 3D spherical shell convection were conducted.

**Results:** Models with different Rayleigh numbers and internal heating values were considered. The total amount of melt versus time and temperature as a function of radius for the various models, with and without partitioning of radioactive decay, is given below.

![Figure 1: Log scale of melt (km³) versus time (Myr). The straight black line is the amount of melt required to create Olympus Mons.](image-url)
Figure 1 is the total amount of melt versus time for four different models, with a uniform distribution of heat producing elements in the crust and mantle and constant internal heating with time. In addition to the Rayleigh number, the internal heating number is also an important component that contributes to the heating of a planet. The non-dimensional internal heating rate equation is given by
\[ H_{\text{int}} = \frac{Q R_o^2}{\rho_o C \Delta T \kappa_o} \]
Here Q is the default internal heating rate, R_o is the radius of the planet, \( \rho_o \) is the mantle density, C is the specific heat, \( \Delta T \) is the super-adiabatic temperature difference across the mantle, and \( \kappa_o \) is the thermal diffusivity.

The dark blue line is Kiefer’s model (Ra=4.08x10^8, H_{int}=17.25), orange line is Roberts and Zhong’s model (Ra=1.25x10^8, H_{int}=49.66), green line is our first model (Ra=1.0x10^8, H_{int}=49.66) and purple line is our second model (Ra=1.00x10^8, H_{int}=17.25). Kiefer’s model portrays a steady drop in melt, whereas Roberts and Zhong’s and our first model shows a peak at around 450 million years and then drops to very small values in melt. In our second model, the melting goes to zero around half way through Mars history.

**Figure 2: Non-dimensional temperature versus radius**

Figure 2 shows the temperature (averaged over colatitudes and longitude) as a function of radius for the four different models as described in Figure 1. The color scheme is the same as Figure 1.

Partitioning of radioactive heat sources between the mantle and the crust has been modeled as well. Varying ratios of partitioning of radioactive decay heat sources between the crust and mantle have been simulated. We observed that when more than 20% of the radioactive material was partitioned in the mantle, the model produced high temperatures in the lower mantle and a molten lower mantle. With less than 20% of the heat producing elements in the mantle, the lower mantle remains below the melting point for most of Mars history.

**Discussion:** Kiefer’s axisymmetry model with constant viscosity produces a single strong plume. The temperature anomaly in the plume head is large and produces significant melt at the plume head. Using the parameters from Kiefer’s model in a 3D constant viscosity spherical shell produces a number of smaller plumes with smaller temperature anomalies and very little melt. In Roberts and Zhong’s 3D temperature dependent model, there are fewer but much broader plumes than Kiefer’s 3D constant viscosity model. Because there are fewer plumes, the temperature anomalies in these plumes are larger and produce more melt. Thus the temperature-dependent, stagnant lid models in 3D produce similar plume structures to Kiefer’s axisymmetric model. In our model, there are few broad plumes with concentrated temperature but lesser melt. Both Roberts and Zhong’s model and our model are temperature dependent models. Our second model shuts off the melt production half way through Mars evolution.

During the early evolution of Mars, uniform distribution of heat producing element would lead to a very high temperature in the lower mantle early in Martian history, which results in a molten mantle. Thus segregation of radioactive elements into the crust must have occurred early in Martian history. In one of our radioactive decay models (Ra=5x10^8), where 80% of the radioactivity was partitioned in the crust, the decay of heat with time led to a vigorously convective solution for present day Mars. Because of the high temperatures in the lower mantle, the heat flux from the core is within the constraint set by the absence of a magnetic field (Nimmo et al, 2004).

**Conclusion:** Kiefer’s 3D constant viscosity model is starved for melt due to the presence of many smaller plumes and less concentrated temperature. Roberts and Zhong’s model and our model do produce sufficient melt to create Tharsis, but they appear to produce similar amount of melt, even to the present day. These models require some additional mechanism such as crustal underplating beneath Tharsis to explain the rapid emplacement of Tharsis by the end of the Noachian, followed by a small amount of volcanism to the present day. Our second model explains the thermal evolution of Mars as it shuts off the melting but it does not explain the presence of recent volcanism of Mars.

When we consider the radioactive factor in our models, they provide a more idealistic view on the melting history of Mars. These models will provide a better insight to explain the present day melt production and recent volcanism on Mars.

**References:**
