MARTIAN DICHOTOMY FORMATION BY PARTIAL MELTING COUPLED TO EARLY THARSIS MIGRATION. Ondřej Šrámek[1] and Shijie Zhong[1], [1]University of Colorado at Boulder, Department of Physics, 390 UCB, Boulder, CO 80309-0390; ondrej.sramek@colorado.edu, shijie.zhong@colorado.edu

Introduction: Major global physiographic features on Mars include the hemispheric crustal dichotomy and the Tharsis volcanic province. The formation mechanism of the more ancient dichotomy (~4.1 Ga) remains unclear; different hypotheses invoke both external causes (a giant impact) and mechanisms of internal dynamics (e.g., long-wavelength mantle convection, or a large-scale overturn of unstable post-magma ocean cumulates). The bulk of Tharsis was probably in place one to few 100 My after dichotomy formation. Analyses of tectonic and volcanic features suggest a timed sequence of tectonic centers and an early migration of Tharsis volcanism from southern latitudes towards the equator over few 100 My [1–3].

A link between the preexisting dichotomy, and the formation and early evolution of Tharsis was proposed in a recent model [4]. In this model, it is assumed that the dichotomy was generated by partial melting with a strong hemispheric asymmetry, as would be the case of melting above a single upwelling in mantle convection with a spherical harmonic degree 1 planform. Consequently, the thicker crust below the southern highlands is considered underlain by a thick lithospheric keel that represents a devolatilized residue after melting. The lateral viscosity variations due to the keel could then excite a strong toroidal velocity flow field, including a degree-1 toroidal motion, i.e., a relative motion between the one-plate lithosphere and the underlying mantle.

This hypothesis was tested using convection models with a prescribed lithospheric keel spanning one hemisphere. The thermal upwelling of one-plume convection first forms below the thickest lithosphere at the center of the keel. Subsequently, a rotation between the lithosphere and the upwelling is observed, such that the upwelling migrates toward regions of smaller lithospheric thickness. This model is capable of explaining the apparent early migration of the Tharsis volcanic centers and their stabilization near the dichotomy boundary [4,5].

However, our previous dynamic models did not include melting, which prevented us from addressing the question of whether the large lithospheric thickness variation can be self-consistently produced. Another recent study [6] investigated the dichotomy formation by partial melting; however, devolatilization effects of partial melting were not considered, and therefore the modulation of the flow by the stiff melt residue was not captured. Here, we newly include a consistent description of partial melting in our model. We consider the effect of partial melt residue stiffening on the plume–lithosphere dynamics to address the following questions: Can the lithospheric thickness variation with a strong hemispheric pattern be generated as a result of partial melting? Will such a lithospheric root be sufficient to excite the relative motion between the lithosphere and the mantle, as was the case with a prescribed lithospheric keel?

Model: The setup – convection under the extended Boussinesq approximation in a spherical shell (CitcomS), heated both internally and form below – follows our previous studies [4,5,7]. Viscosity is temperature- and pressure-dependent and includes a 25-fold increase at 1020 km depth. The main new aspect is inclusion of partial melting, using the parametrization from [8]. At each time step, we calculate the equilibrium degree of melting in each finite element from the local (P,T) condition and compare it to the actual degree of melting advected by the tracers to determine whether new melt is generated. If so, the degree of melting, carried by the tracers, is updated; latent heat is accounted for. We assume that the newly produced melt is extracted to the surface where it increases the local crustal thickness. Non-zero surface horizontal velocity also requires advection of the surface melt field.

The residual material left behind after melting has increased viscosity due to devolatilization (dehydration), compared to mantle that has not been subject to partial melting. Here, we use a simple step-function viscosity pre-factor, equal to 1 below and 200 above a 5%-degree of melting threshold. In the present models, the internal heating rate corresponds to one-half of the chondritic heating rate at 4.5 Ga, assuming previous fractionation of heat producing elements into a primordial crust of uniform thickness, not contributing to the dichotomy. The models are started from a developed degree-1 temperature field.

Results: We show results from one particular series of calculations. The amount of melting depends strongly on the mantle temperature (Fig. 1). For high T_{CMB} (2200 K), large volume of melt is quickly produced which exceeds the melt volume needed to form the dichotomy. Even though the thickest crust is produced above the plume, significant melt production occurs globally, including the hemisphere antipodal to the plume. For low T_{CMB} (2000 K), the melt production is restricted to a small region above the upwelling. The volume of new crust is relatively small and not enough to explain the dichotomy. At intermediate T_{CMB} (2100 K), the volume of generated melt is comparable to what is required to form the dichotomy (Fig. 1). Significant crustal production occurs over a broad region above the upwelling (Fig. 2, bottom).

Relative motion between the lithosphere and the upwelling is observed in all the three cases discussed. It is most prominent in the case with T_{CMB}=2100 K (Fig. 2,

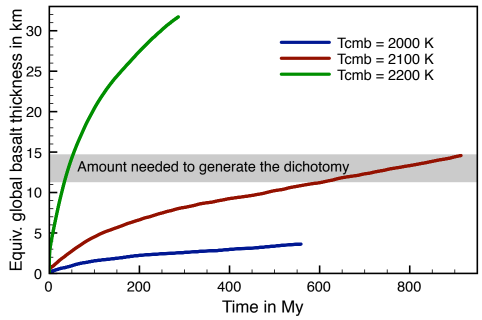

Figure 1. The amount of generated melt as a function of time. Plotted as the thickness of an equivalent global uniform surface layer of melt.

top). At earlier times (first ~400 My) when the new melt residue keel increases in volume, the lithosphere–plume motion is rather inconsistent, characterized by wobbling in various directions. After ~400 My, a clear relative rotation between the lithosphere and the upwelling is seen at an approximate rate of 20 deg/100 My. This rotation also results in broadening of the region with significant thickness of new crust to a roughly hemispheric extent (Fig. 2, bottom).

Discussion: The present model contains several simplifying assumptions. First, fractionation of heat-producing elements into the crust is not modeled. This effect would feed back to the long-term thermal evolution of the mantle and limit the crustal production at later times. Moreover, we keep the internal heating rate constant with time, rather than exponentially decaying. This also overestimates the mantle temperatures at later stages.

Second, we assume for simplicity that all the melt is instantaneously extracted to the surface. The complexities of melt extraction, such as extrusion at surface vs. subsurface intrusion in the crust, or possible trapping of melt at large depth or refreezing, are not considered. Nor does the model include lateral transport of melt at or below the surface; such crustal flow may result in modification of the crustal thickness distribution.

Third, the degree of melting–viscosity dependence for the melt residue is likely more complicated that a simple step-function, and may even vary regionally, esp. if isolated pockets of melt remain trapped at melting depths.

Fourth, we chose to start the models from a thermal structure with a developed single upwelling. This was motivated by the main goal of this study to investigate the possibility of a hemispheric distribution of crustal and lithospheric thickness generated from a degree-1 mantle. The dynamic effect of the viscous melt residue does introduce a strong coupling between the flow and the melting; it will be interesting to explore to what extent this feedback might retard the development of the preferred convective planform.

Considering the aforementioned effects would modify, to various degrees, the modeled melt production curves and crustal distribution patterns, but would not change our main conclusions summarized below.

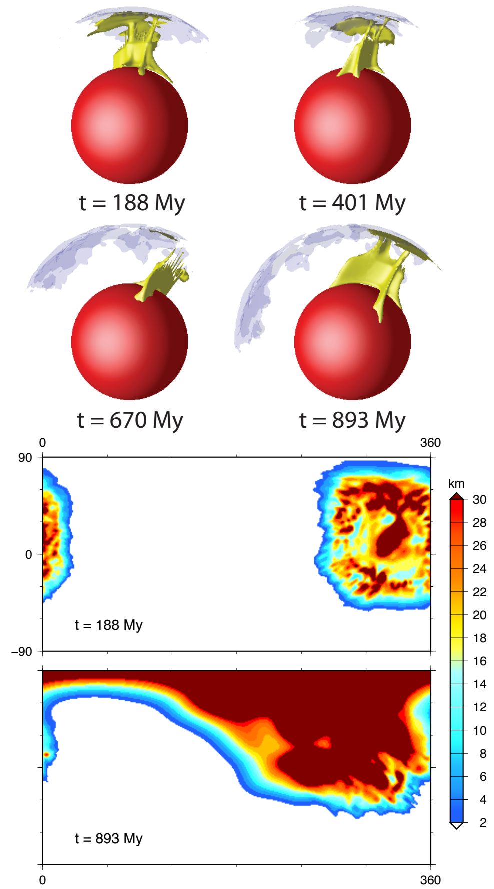

Figure 2. (top) Snapshots of temperature field (positive thermal anomaly in yellow) and high-viscosity melt residue (5% degree of melting as a blue contour), core-mantle boundary in red. **(bottom)** Map view of extracted melt thickness.

Conclusions: Lithospheric thickness and a corresponding crustal thickness variation with a hemispheric extent can be generated by partial melting in Martian mantle with a spherical harmonic degree 1 convection pattern (i.e., single thermal upwelling). Rotation of a one-plate lithosphere with respect to the upwelling and the underlying mantle can then be excited. This may offer an endogenic mechanism for generation of the Martian crustal dichotomy and subsequent evolution of the Tharsis volcanic province.

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