On The Dynamic Origin Of The Crustal Dichotomy and Its Implications For Early Mars Evolution. Shijie Zhong, James H. Roberts and Allen McNamara, Department of Physics, University of Colorado, Boulder, Colorado 80309, USA (szhong@anquetil.colorado.edu).

Introduction: The crustal dichotomy and Tharsis Rise are the most important large-scale tectonic features on the Martian surface [1]. An understanding of their formation has important implications for understanding thermal evolution of Mars and the Martian gravity anomalies, tectonics, volcanism, and volatiles losing history [2,3]. Both endogenic and exogenic processes were proposed for the formation of the crustal dichotomy. In this study, we focus on endogenic processes. Two different endogenic processes were proposed: crustal erosion derived from degree-1 mantle convection [4] and plate tectonics [5], both proposed before the MGS missions.

With the MGS high resolution data, there are a number of studies on the nature of Martian crust, crustal dichotomy and Tharsis rise that should be considered in any attempts to unravel the formation of crustal dichotomy and the evolution of early Mars. 1) The discovery of abundant buried ancient impact craters in the northern plains indicates that the crust of the northern hemisphere is of the middle Noachian or as old as that of the southern hemisphere, if not older [6]. 2) The topography and gravity anomalies suggest a pole-to-pole gradual and smooth variation of crustal thickness [7]. 3) The topography and gravity anomalies suggest that Martian crust is on average >50 km thick and is thicker than the elastic plate (or the layer that is capable of supporting long-term geological loads) [7,8]. Not only the surface but also the bulk of the crust may have been produced quite early on (in the first 0.5 Ga), according to the thermal evolution modeling [9]. 4) Significant tectonic deformation occurred along the crustal dichotomy in late Noachian and early Hesperian [10]. 5) The surface tectonics suggest that the bulk of the Tharsis rise was formed by the late Noachian [11,4], similar to the formation time of crustal dichotomy. Modeling the Tharsis topography and gravity indicates that the Tharsis rise is mostly supported by surface loads on elastic plate with little or no dynamic contribution from a plume [12].

Among the two proposed endogenic processes (i.e., crustal erosion and plate tectonics) for crustal dichotomy formation, a necessary process is the degree-1 mantle convection in which hot upwellings preferentially occurs in one hemisphere while cold downwellings are in other hemisphere. Such a degree-1 mantle convection is also required for a plate tectonic process to explain the formation of crustal dichotomy, although this was never explicitly stated before (why does it occur only in the northern hemisphere?). However, the physical conditions under which mantle convection forms degree-1 structure are not well understood [13,14,15]. Furthermore, even if degree-1 mantle convection is achieved, it is unclear how degree-1 mantle convection could lead to crustal dichotomy and how crustal dichotomy could be preserved through the Martian geological history [15]. In addition to crustal dichotomy, the formation of the Tharsis rise also needs a largely degree-1 mantle convection or a one-plume convection that operated during late Noachian period, following the formation of crustal dichotomy [12]. Although the Tharsis rise is centered at the dichotomy boundary not below either of the hemispheres, the similarity in mantle dynamics is intriguing.

There are two goals of this study: 1) to critically review all the published mantle dynamic models for degree-1 mantle convection and to explore new and more realistic mantle parameter space for degree-1 mantle convection; 2) to synthesize surface observations and mantle dynamic models for a coherent picture for the early evolution of Mars.

Degree-1 mantle convection: Two different mechanisms have been proposed for degree-1 or one-plume mantle convection for Mars: 1) one-plume convection derived from exothermic or endothermic phase changes that was initially proposed for a dynamic support for the Tharsis rise [13,14], and 2) degree-1 convection caused by layered viscosity proposed to explain the formation of crustal dichotomy [15].

The effects of exothermic phase change on one-plume convection [14] were questioned in [16] that showed that the actual effects seen in [14] are caused by the moderately high viscosity lithosphere. There are two potential problems with the endothermic phase change models: 1) existence of such an endothermic phase change given the recent estimate of core size [17], and 2) the published models with phase changes were done with only moderate depth-dependent viscosity and no temperature-dependence. Our calculations with the endothermic phase change, while reproducing one-plume structure with no temperature-dependent viscosity, fail to produce one-plume structure with more realistic temperature-dependent viscosity [18]. The models with layered viscosity structure that produced degree-1 convection used a temperature- and pressure-dependent viscosity, but the models were done in 2-D axisymmetric models [15]. It is important to examine the effects of 3-D geometry on the flow.

We have recently explored the layered viscosity models in 3D spherical geometry with temperature- and pressure-dependent viscosity and pressure-dependent thermal expansion coefficient and thermal diffusivity [18]. Our calculations showed that degree-1 convection remains with 3D layered viscosity models. However, it appears that a smoothly varying viscosity with depth is not as effective as a step function like increase of viscosity in producing degree-1 convection. This suggests that either non-Newtonian viscosity or viscosity change caused by the olivine-spinel phase change may be essential.
Two end-member models for Martian mantle convection are the stagnant-lid convection and plate-tectonic style convection [5,19]. However, while the evidence for early plate tectonic process on Mars is still elusive, the application of stagnant-lid convection may also be problematic. It is well known that stagnant-lid convection in its original form often leads to small-wavelength structures [20], which is in sharp contrast with crustal dichotomy and Tharsis rise that are both of very long wavelength. We propose that for early Mars the crust may play an active role in controlling heat transfer and mantle structure, if the crust was indeed >50 km thick. The key components of our proposal are that the lower crust for early Mars may be sufficiently weak to serve effectively as free-slip boundary condition for the mantle and that the thickened crust increases the mantle lithospheric temperature so that the mantle lithosphere may be able to deform. The net effect for mantle convection is that mantle lithosphere may be mobile with only moderate viscosity contrast with respect to the underlying asthenosphere. In this scenario, the crust may be the limiting factor for heat transfer. If the lower crust is sufficiently weak that convection can take place there (i.e., crust convection), then crust may transfer heat efficiently out of the mantle. If crust convection cannot happen, then heat has to transfer conductively through the crust.

We have computed 3D spherical models with free-slip top boundary and moderate temperature-dependent viscosity that approximate the effects of the crust. We found that degree-1 convection may be produced within certain model parameter space. In particular, when large internal heating is included, the lithospheric viscosity becomes sufficiently large compared with the interior viscosity and degree-1 convection is achieved.

Degree-1 mantle convection and crustal dichotomy and Tharsis rise: Two possible scenarios were proposed in [15] to link degree-1 mantle convection and crustal dichotomy. 1) The southern hemisphere with thickened crust was formed above the upwellings of degree-1 convection due to melting and the significant fraction of the crust was created during the formation of the dichotomy. 2) The southern hemisphere was formed above the downwellings of degree-1 convection due to shear coupling between the mantle and crust that produces crustal convergence towards the southern hemisphere, and the bulk of the crust may be produced uniformly before degree-1 mantle convection occurs. The first scenario may imply that the southern hemisphere with newly produced crust is younger than the northern hemisphere. That this scenario permits an old northern hemisphere is consistent with the old crust age as suggested in [6]. The second scenario implies that the northern hemisphere is younger (but not much younger) than the southern hemisphere, as the crustal thinning there would lead to some amount of volcanisms in the northern hemisphere. Therefore, it seems that the relative ages of the two hemispheres are important in distinguishing these two scenarios.

With either scenario, as long as the degree-1 mantle convection is active for sufficiently long time, to maintain crustal dichotomy does not seem to be a problem. This is because mantle convection can have significant effects on crustal relaxation.

Finally, given the relatively short time span between the formation of crustal dichotomy and Tharsis rise and the fact that they both should be related to degree-1 mantle convection, it is interesting to consider how degree-1 mantle convection may shift its centers. We will speculate the role of melting in degree-1 mantle convection.