THE CAUSES AND CONSEQUENCES OF THE CRUSTAL DICHOTOMY AND THEIR IMPLICATIONS FOR THE EARLY EVOLUTION OF MARS.

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Introduction: The two most striking surface features on Mars are the crustal dichotomy and the Tharsis Rise [1]. While it is generally accepted that the Tharsis Rise is formed as a result of plume related volcanism [2], the formation mechanism for the crustal dichotomy is controversial with two main competing proposals: endogenic (mantle convection and flow) [3-5] and exogenic (mega-impact) mechanisms [6]. Recent studies on modeling mega-impact and reconstructing dichotomy boundary revive the mega-impact mechanism for the crustal dichotomy [7-9]. However, because the crustal dichotomy, as the oldest feature on Mars (i.e., the pre-Noachian or >4.1 Ga) [10], has been significantly modified by later processes such as the Tharsis formation, it is difficult to constrain the formation mechanism for the crustal dichotomy.

The Tharsis Rise is a younger feature and is formed during the Noachian (4.1-3.8 Ga) [11]. Both the crustal dichotomy and Tharsis Rise represent hemispheric asymmetric structrures (i.e., degree-1 feature) in that the crustal dichotomy marks the difference between the northern and southern hemispheres, while the Tharsis Rise repressents the difference between the western and eastern hemispheres. Although the center of Tharsis is near the dichotomy boundary at the equator, geophysical and geological observations suggest that Tharsis volcanisms may have initiated in the southern highlands (e.g., the Thaumasia region at ~40°S) and subsequently migrated to the current positions [12,13].

Recently, Zhong [14] suggested that the crustal dichotomy has an important effect on formation and evolution of the Tharsis Rise and volcanism. The key to Zhong's proposal is that the crustal dichotomy represents lateral variations in lithospheric shell thickness which interacts with one-plume convection to give rise to the differential rotation between the lithospheric shell and the underlying mantle with one-plume convection, thus explaining the migration of Tharsis volcanisms. This indicates that the Tharsis volcanism and tectonism may provide important constraints on the formation mechanism of the crustal dichotomy.

The goal of this study is to critically examine both endogenic and exogenic formation mechanisms for the crustal dichotomy. In particular, we seek constraints on the formation mechanism, by further exploring the consequences of the crustal dichotomy from these two different mechanisms on volcanisms and tectonisms and their relation to the Tharsis Rise.

Different Properties of the Crustal Dichotomy from Endogenic and Exogenic Origins: Endogenic and exogenic processes may lead to the crustal dichotomy with very different characteristics in crustal and lithospheric structures. As indicated in Zhong [14], in endogenic processes, the thickened crust is caused by extra melting in the underlying mantle, and below the thickened crust, a layer of melt residue with possibly 200-300 km thickness and high viscosity (due to loss of volatiles to melting) is expected. This thick melt residue may prevent further melting from happening under the thickened crust, because it limits the plume upwellings to a relatively large depth. In fact, the high viscosity melt residue below the thickened crust is the key to induce differential rotation of lithospheric shell relative to the mantle in Zhong's model.

Modeling gravity and topography data suggests that the elastic thickness for the early Mars in the thickened crust regions is 10-15 km or less, suggesting that the crust and mantle are hot at the time when these topography features were formed [15]. Lithospheric and crustal structures for the early Mars, as the crustal dichotomy is formed, are therefore expected to evolve dynamically to reduce heterogeneities and variabilities with gravitationally driven crustal channel-flow. Consequently, the bimodal distribution of present-day Martian crustal thickness is expected [16].

In exogenic or mega-impact formation mechanism for the crustal dichotomy, the thickened crust in the southern highlands is believed to result from redistribution or piling-up of impact ejecta that is removed from the northern lowlands with the thin crust. The effects of such a mega-impact on the lithosphere and mantle are poorly understood, but any such effects are likely transient based on the energy consideration.

Recent modeling of mega-impacts [8,9] suggests that the distribution of ejecta is rather non-uniform with significantly more ejecta piling up in the vicinity of the impact that doubles local crustal thickness to more than 100 km. This post-impact crustal structure must evolve dynamically via crustal flows to the present-day bimodal distribution in crustal thickness. However, it is unclear how such crustal flows could homogenize crustal thickness in the highlands with thickened crust but preserve the original impact boundary, as required in the mega-impact model. If the ejecta is uniformly distributed to form the thickened crust in the highlands, the addition of ~25 km thick crust onto the original surface would raise the temperature in the underlying original crust to well above the Curie temperature to demagnetize the original crust. Given that the present-day crustal magnetism is largely concentrated in the highlands, this would require that this crustal magnetism be acquired after the proposed mega-impact.

Effects of the Crustal Dichotomy on the Mantle Dynamics and Volcanisms: It is well known from studies of the Earth's mantle and lithospheric dynamics that the thickened crust tends to insulate the mantle below. This idea has been applied to Mars to examine the role of the crustal dichotomy in the dynamics of mantle plumes and melting [17,18]. More recently, Zhong [14] showed that the immediate effect of the crustal dichotomy is to place one-plume structure below the thickened crust, assuming that the crustal dichotomy is formed from endogenic processes with a high viscosity melt residue layer under the thickened crust (Fig. 1a). Subsequently, dynamic interaction of the high viscosity melt residue layer with one-plume convection causes a differential rotation of the lithospheric shell relative to the one-plume structure, leading to the melting and volcanisms that form the Tharsis Rise near the boundary of the crustal dichotomy (Fig. 1b).

We have calculated new models of mantle convection to examine the effects of the crustal dichotomy with characteristics expected from a mega-impact. The models are similar to what is in Zhong [14], but the thickened crust is modeled as an insulating layer with reduced thermal diffusivity but with no underlying high viscosity melt residue layer. We found that due to the insulating effects from the thickened crust, one-plume structure is generated below the thickened crust (Fig. 1c), similar to the first stage from the model in [14] with high viscosity melt residue (Fig. 1a). However, with no high viscosity melt residue, differential rotation of lithospheric shell becomes impossible, and the plume stays near the center of the thickened crust region (Fig. 1d). With no high viscosity melt residue, the plume can also reach shallow depths and cause melting and volcanism near the central region of the thickened crust (Fig. 1c). This melting and volcanism patterns can not account for the Tharsis volcanism, and more importantly, it implies that substantial amount of new crust would have been added to the already thickened crust, thus questioning the necessity of invoking the mega-impact for creating the crustal dichotomy.

Summary: We explored the possible crustal and lithosphere structures for the crustal dichotomy that may be produced from endogenic and exogenic formation mechanisms. We examined the consequences of the corresponding crustal and lithospheric structures on mantle dynamics and plume related melting. Our studies suggest that the endogenic process of one-plume convection and melting for the crustal dichotomy explains well the subsequent volcanism in the Tharsis region that otherwise would be difficult to be accounted for with the exogenic formation mechanism.

References: [1] Solomon, S.C. et al. (2005) *Science*, 307, 1214-1220. [2] Kiefer W.S. (2003) *Meteoritics and Planet. Sci., 38*, 1815-1832. [3] Wise et al., (1979) J. G.. R., 84, 7934-7939. [4] Zhong, S. & Zuber, M., (2001) *E. P.. Sci. Lett*., 189, 75-84. [5] Elkins-Tanton et al., (2005) E. P.. S. L., 236, 1 –12. [6] Frey, H. V. & Schultz, R.A (1988), G. R. L., 15, 229-232. [7] Andrews-Hanna, J. C. et al., (2008) *Nature* 453, 1212-1215. [8] Nimmo, F. (2008) *Nature* 453, 1220-1224. [9] Marinova, M.M. et al. (2008) *Nature* 453, 1216-1219. [10] Frey, H. (2006) *J. Geophys. Res.* 111, E08S91. [11] Phillips, R. J. *et al.* (2001) *Science* 291, 2587– 2591. [12] Frey, H. V. (1979) *J. Geophys. Res*. 84, 1009-1023. [13] Johnson, C. L. & Phillips, R. J. (2005) *Earth Planet. Sci. Lett*. 230, 241-254. [14] Zhong, S.J. (2009) *Nature-Geoscience* 2, 19-23. [15] McGovern et al. (2002) *J. Geophys. Res.* 107, 5136, doi:10.1029/2002JE001854. [16] Watters, T. et al. (2007) Annu. Rev. Earth Planet. Sci. 35, 621–652. [17] Wenzel, M. J. et al. (2004) *Geophys. Res. Lett*. 31, L04702. [18] Wullner, U. & Harder, H. (1998) *Phys. Earth Planet. Inter*. 109, 129-150.

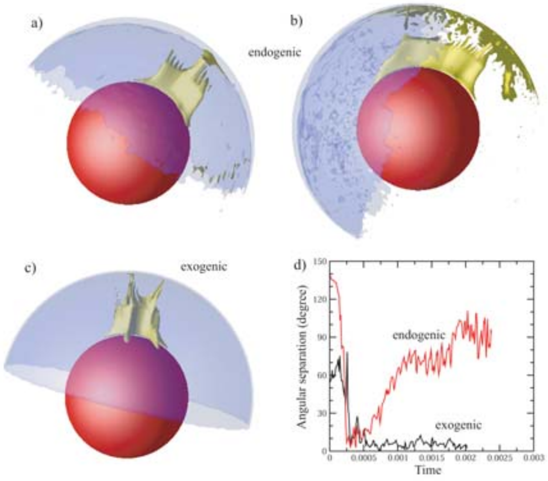

Figure 1. Thermal structure and melt residue representing the thickened crust (light blue iso-surface) at an initial stage (a) and later stage (b), thermal structure for a case with no melt residue long time after the one-plume structure is formed (c), and angular separation between the centers of plume and the thickened crust (d). Red and black curves are for the first and second models, respectively.