

DEGREE-1 MANTLE CONVECTION AS A PROCESS FOR GENERATING THE MARTIAN HEMISPHERIC DICHOTOMY. James H. Roberts, *Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder CO 80309-0391, USA, (jhr@anquetil.colorado.edu)*, Shijie Zhong, *Department of Physics, University of Colorado, Boulder CO 80309-0390, USA, (szhong@spice.colorado.edu)*.

Introduction

The crustal dichotomy is one of the most significant topographic and tectonic features on Mars [1]. The gradual pole-to-pole crustal thickness variations inferred from MGS topography and gravity data do not seem to support an exogenic origin, such as giant impacts [2]. We therefore seek to explain this as an endogenic feature, resulting from a degree-1 convection pattern in the mantle [3, 4].

We propose and test two hypotheses for how degree-1 mantle convection may lead to the crustal dichotomy [4]. In the first scenario, the planet starts with no crust at all. Partial melt occurs in a degree-1 plume, where upwelling material is above the solidus. This melt is then extracted to form crust above the plume. In the second scenario, a uniform crust overlies a mantle containing a single convection cell. The Martian crust is thought to be at least 50 km thick [3]. Early in Martian history, the base of such a thick crust may have been so warm as to be ductile. An upwelling mantle plume would erode the lower crust above it and move it laterally to be deposited at the base of the crust above the downwelling. As the interior cools, the crust would lose its mobility and this degree-1 pattern would be frozen in.

For either hypothesis to be tested, it is first necessary to have degree-1 convection in the mantle. We modeled stagnant lid convection in a primitive mantle to test the first hypothesis. In the second scenario, the warm, ductile lower crust may be decoupled from the mantle. The mantle is thus warm enough to be in the mobile-lid regime and we model it as such, overlain by a uniform crustal layer. We used finite-element convection code to solve the equations of mass, momentum, and energy in 2D axisymmetric and 3D spherical geometry [5,6]. The mantle was heated both from below and within and cooled from above. The viscosity was both temperature and pressure-dependent, following an Arrhenius Law. We used non-Newtonian activation parameters appropriate for a wet mantle [7] scaled to Newtonian rheology. We used depth-dependent thermal expansivity and diffusivity and considered the effects of adiabatic and frictional heating [8].

Stagnant-lid Convection in a Primitive Mantle

Many studies have been done to generate degree-1 convection in a stagnant-lid mantle [4,9-11], but all of them rely upon certain assumptions which may not be reasonable for a general Mars model. We sought to test these mechanisms while relaxing the assumptions to develop a more robust model of degree-1 convection.

Zhong and Zuber [4] achieved degree-1 convection using a layered-viscosity model, with an upper mantle 500 times less viscous than the lower mantle, capped by a high viscosity lid. The viscosity jump is a proxy for various possible mechanisms

including melting, phase change, pressure-dependent viscosity and non-Newtonian rheology. They did not attempt to seek minimum required viscosity jump for degree-1 convection. We wanted to relax the assumption that the mantle was layered, so we attempted to run their model using temperature and pressure-dependent viscosity in place of the layering, while preserving the overall viscosity contrast across the mantle. We were able to maintain a degree-1 pattern when we substituted pressure-dependence for much of the layering, but a jump in viscosity between the upper and lower mantle was still necessary. We were able to reduce the jump to a factor of 25 from a factor of 500 (Fig. 1), but could not eliminate it entirely and still maintain the convective pattern.

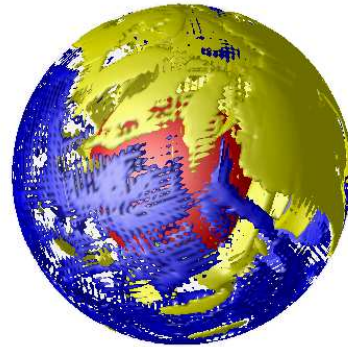


Figure 1: Degree-1 thermal convection pattern from a case with temperature- and depth-dependent rheology and a factor of 25 viscosity jump between the upper and lower mantle. Shown are 5% isosurfaces of residual temperature (yellow: relatively hot, blue: relatively cold)

Several studies [9-11] have utilized phase changes in the mantle as a mechanism for generating a degree-1 convective pattern. Harder and Christensen [9] and Harder [10] considered the endothermic spinel-perovskite phase change in an isoviscous mantle with a high viscosity lid. We successfully reproduced their results in 2D axisymmetric geometry, however, the inclusion of temperature-dependent viscosity destroys the single plume structure (Fig. 2). We have computed models with different phase change parameters, Rayleigh numbers and rheological parameters. We find that only when activation energy is unreasonably low (≤ 60 kJ/mol) we could produce degree-1 convection with the endothermic phase change. Furthermore, recent studies on the size of the Martian core [12] cast doubt as to whether the required pressure for this phase change is ever reached in the Martian mantle. Breuer *et al.* [11] considered the exothermic olivine-spinel transition, including the latent heat effects and obtained a single plume structure. Our experiments with this phase change failed to

produce a degree-1 pattern, indicating the limited role of the latent heating from the exothermic phase change. However, as Harder [10] pointed out, the calculations in [11] are in the mobile-lid regime. This, more than the physics of the exothermic phase change controls the convective pattern. Therefore, it is not surprising that we failed to achieve degree-1 in the stagnant lid regime.

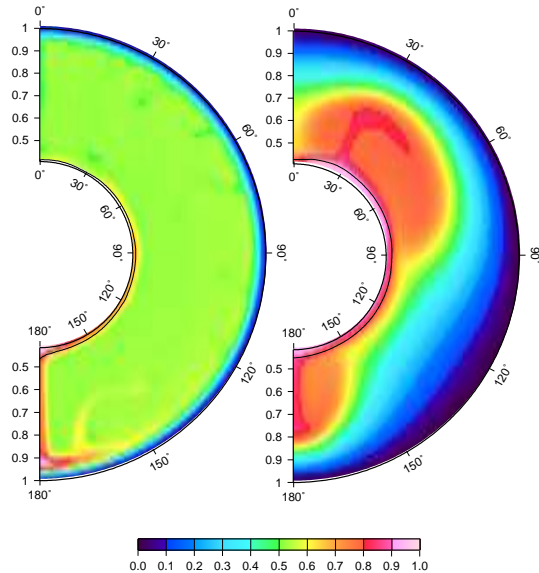


Figure 2: Comparison of two thermal convection cases including endothermic phase change. Location of phase transition indicated by the black curve near the CMB. Left: iso-viscous interior with high viscosity lid. Right: Temperature-dependent viscosity, activation energy of 180 kJ/mol.

Mobile-lid Convection

Mobile-lid convection, however, may be an appropriate choice for the second scenario. At the time of formation of the hemispheric dichotomy, the lower crust may have been so warm as to be decoupled from the mantle. We ran a series of calculations using the Moho temperature as the upper boundary

condition. The entire mantle was sufficiently warm that the mantle was in the mobile lid regime. However, we have not yet incorporated crust into these models. This produced degree-1 convection in some of the preliminary 2D models. With 3D spherical models, we achieve degree-1 structure with moderate temperature-dependent viscosity.

Discussions and Future Work

We find that although there are many ways of generating a degree-1 convective pattern in a stagnant-lid mantle, they rely upon certain assumptions that may not be reasonable for a realistic Mars. A layered viscosity structure is one way to get the desired convective pattern, but the actual mantle viscosity depends on temperature and pressure. If a viscosity jump is employed, there must be a physical reason for such a discontinuity. However a number of mechanisms may lead to a jump in viscosity. The exothermic phase change from olivine to spinel may lead to viscosity layering as often suggested for the Earth's mantle. Non-Newtonian mantle rheology may also be able to produce sharp viscosity transitions because of change in deformation mechanisms. We are currently exploring the roles of non-Newtonian rheology in producing sharp viscosity changes.

The mobile lid regime may be appropriate if the crust and mantle are sufficiently warm as to decouple the crust and the mantle, as one may expect for the early Mars. However, care must be taken to couple the convection models to the crustal conduction profile in a physically realistic way. We are currently working on a way to resolve this issue.

References

- [1] Smith et al. (1999) *Science* 284, 1495. [2] Zuber et al. (2000) *Science* 287, 1788. [3] Wise et al. (1979) *J. Geophys. Res.* 84, 7934. [4] Zhong and Zuber (2001) *Earth Planet. Sci. Lett.* 189, 75. [5] Zhong et al. (2000) *JGR* 105 11063. [6] Moresi and Solomatov (1995) *Phys. Fluids* 7, 2154. [7] Karato and Jung (2003) *Phil. Mag.* 83, 401. [8] Christensen and Yuen (1985) *J. Geophys. Res.* 90, 10,291. [9] Harder and Christensen (1996) *Nature* 380, 507. [10] Harder (2000) *Geophys. Res. Lett.* 27, 301. [11] Breuer et al. (1998) *GRL* 25 229-232. [12] Yoder et al. (2003) *Science* 300, 299.