DEGREE-1 MANTLE CONVECTION AND THE ORIGIN OF THE MARTIAN HEMISPHERIC DICHOTOMY.

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Introduction

The hemispheric dichotomy on Mars is thought to have formed very early in the planet's history, possibly within the first 100 million years [1,2]. This feature has been attributed either to exogenic mechanisms (one or more giant impacts) [2-4] or to endogenic processes such as degree-1 mantle convection [5].

While endogenic processes such as degree-1 mantle convection may also be able to form the dichotomy, previous studies have required special conditions and long timescales to set up a degree-1 pattern [6-9]. We explore the range of parameters in which degree-1 convection develops and the timescale required for it to happen.

Phase changes have been suggested as one mechanism for producing long-wavelength mantle structures [6-8]. We investigated the effects of the endothermic spinel-perovskite and the exothermic olivine-spinel phase transitions on the convective pattern in the mantle under a variety of rheological conditions.

We also investigated the possibility viscosity layering in the mantle [9], since a sharp change in viscosity with depth will help to promote long-wavelength structures more easily than a continuous variation. We pay particular attention to the timescale required for a degree-1 pattern to appear.

We used finite-element convection codes to solve the continuity, momentum, and energy equations in 2-D axisymmetric and in 3-D (CitcomS) spherical geometry.

Phase Changes

Harder [8] successfully generated degree-1 convection by including both the exothermic and endothermic phase transitions in an isoviscous mantle, capped by a high viscosity lid. We tested the effectiveness of the phase changes to generate long wavelengths under a more general range of rheology and allowed the coefficient of thermal expansivity to vary with depth. We first reproduced Harder's model and indeed got a degree-1 pattern (Fig. 1). However, the convective structure is considerably different when temperature-dependent viscosity is used. Even with a relatively low activation energy of 50 kJ/mol, the structure is dominated by degree-4 (Fig. 2).

Recent studies suggest that the Martian core is relatively large (1650 km) [10], and the required pressure for the endothermic transition may never be reached. These items, combined with the inability of the phase changes to produce degree-1 convection with temperature-dependent viscosity suggests that phase transitions are not an effective method of producing the dichotomy.

Viscosity Layering

Zhong and Zuber [9] found that long-wavelength patterns are preferred in a layered mantle with a significant viscosity contrast between the layers. They generated a degree-1 mantle structure in 2-D axisymmetric geometry using an upper mantle viscosity 500 times less than that of the lower mantle. We expanded this model by running in a fully 3D spherical geometry, and explored a more general rheology. We included the adiabatic and frictional heating effects and allowed thermal expansivity and diffusivity to vary with depth.

By using a temperature- and pressure-dependent rheology, we remove the need to artificially impose a high viscosity lid. As in [9], we impose a step function in viscosity in the mid-mantle. Using this viscosity structure we are able to generate a degree-1 convective pattern in a 3-D geometry within 80 Myr with Ra=$2*10^7$ (Fig. 3). By increasing the convective vigor, we can achieve this pattern in even less time. A case with Ra=10^8 develops a degree-1 dominated pattern within 20 Myr.

We find we can achieve results with a more moderate viscosity contrast between the layers than that used in [9].

Figure 1: Isoviscous mantle with both phase changes and high-viscosity lid imposed at top. Degree-1 mantle plume forms eventually.

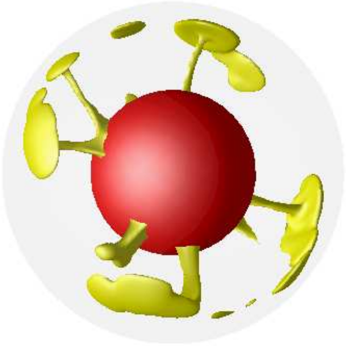

Figure 2: Mantle with E=50 kJ/mol and high viscosity lid. Convection is dominated by degree-4.

Figure 3: Temperature- and depth-dependent viscosity mantle. Ra=2*10^7, E=157 kJ/mol, V=6 cm^3/mol, H_{int}=1.54*10^{-12} W/kg. The upper mantle viscosity has been reduced by a factor of 50. Degree-1 forms very quickly.

A degree-1 pattern forms if the upper layer is only 50 times weaker than the upper layer. We cannot achieve degree 1 using a only a continuous viscosity gradient, such as that following an Arrhenius law, however. If we remove the rapid change in viscosity and increase the activation volume such as to preserve the overall viscosity contrast across the mantle (Fig. 4), a degree-1 pattern never develops. A rapid change in viscosity in the mid-mantle is required for a degree-1 pattern.

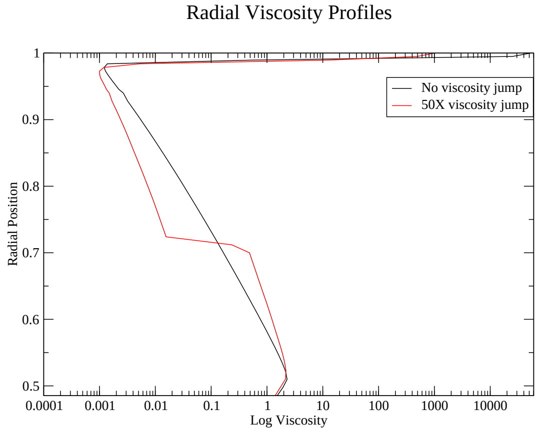

Figure 4: Radial viscosity profiles for two cases with temperature- and pressure-dependence. Both cases have Ra=2*10^7, E=157 kJ/mol, H_{int}=2.35*10^{-11} W/kg. Black curve: V=8 cm^3/mol. Red curve: V= 6 cm^3/mol.

One explanation for viscosity layering such as that required above is a change in visosity associated with the exothermic phase transition in the mid-mantle of Mars. A second possibility is that the rapid change is caused by a change in deformation mechanism to something other than diffusion creep. Further modeling with non-Newtonian rheology will tell us more about the validity of this possibility.

Discussions

There are two ways that degree-1 convection may lead to the formation of the crustal dichotomy. If a primordial crust is already in place on early Mars, the lower crust will be warm and weak. A convective upwelling can erode the crustal material above it. Shear coupling between crust and mantle will cause this material to flow away from the upwelling. It will adhere to the base of the crust above the downwelling, resulting in the thickest crust there. Alternately, the hot upwelling will be the region where most of the melting occurs. The thicker crust will therefore form over the upwelling in this scenario [9].

Degree-1 convection is necessary for the maintenance of the Martian hemispheric dichotomy. If the dichotomy had been produced by some exogenic mechanism, the topography would need to be supported by elastic stresses within the lithosphere. However, the Martian crust is at least 50 km thick [11] and was probably thicker than the early lithosphere. Therefore, crustal thickness variations would have relaxed within a few hundred Myr. Without some force to maintain the dichotomy, it could not have survived to the present. With viscosity layering, a degree-1 convective pattern can be generated in less than 100 Myr. Ongoing convection can support the dichotomy dynamically until the thickening lithosphere is strong enough to support it elastically.

While phase changes may produce degree-1 convection in an isoviscous mantle, they cannot do so with a more reasonable rheology. It is also not clear whether phase transitions can produce this pattern on an appropriate timescale. Furthermore, this phase transition is unlikely to exist due to the probable size of the core. Viscosity layering is a much more robust way of generating the degree-1 pattern. This inclusion of the rapid change in viscosity in the mid-mantle is the only remaining caveat for the success of this model. We plan to investigate non-Newtonian rheology as a mechanism for explaining this.

Conclusions

We can draw three main conclusions from our modeling:

1. Phase changes have difficulty promoting degree-1 structures when temperature-dependent viscosity is considered.

2. Degree-1 convection develops quickly in a temperature- and depth-dependent viscosity mantle, when a rapid change in viscosity is present in the mid-mantle.

3. If the viscosity layering is absent, a degree-1 pattern will not develop.

References

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