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

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Introduction

The hemispheric dichotomy on Mars is largely an expression of varying crustal thickness [1]. Although there is some disagreement as to the timing of its formation, the dichotomy is very old, forming during or before the early Noachian [2]. Several formation mechanisms, including both exogenic (giant impacts) [3] and endogenic processes including mantle convection [4], plate tectonics [5], and overturn of magma ocean residue [6] have been proposed.

We have investigated the possibility for mantle convection to produce the hemispheric dichotomy. To be feasible, the pattern of convection must reflect the shape of the dichotomy, primarily spherical harmonic degree-1. This pattern must also emerge on a timescale consistent with the early age of the dichotomy (within the first couple hundred Ma). We considered viscosity layering in the mantle as a method of promoting long-wavelength convection [4] addressing several key issues not previously considered. We generalized our study to three dimensions, used a more realistic temperature- and pressure-dependent viscosity formulation [7] in addition to the layering, examined the extent to which internal heating controls the wavelength [8], examined the magnitude of the viscosity jump and total viscosity variation across the mantle, and noted the timescale required for the formation of degree-1. We also considered the possibility of generating degree-1 convection by means of an endothermic phase transition near the CMB [9].

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.

Viscosity Layering and Degree-1 convection

Zhong and Zuber [4] 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 to a 3D spherical geometry, and explored a more general rheology.

We first examined the necessity of having a viscosity jump in the mid-mantle, or whether a strong continuous variation in viscosity was sufficient to produce degree-1. We found that the convection is dominated by a degree-2 pattern when no jump is included. As in [4], we then imposed a step function in viscosity at about 1000 km depth. We reduced the activation volume in these cases in order to maintain approximately the same total viscosity variation across the sublithospheric mantle (Fig 1). We were able to generate a degree-1 convective pattern in a 3-D geometry with as little as a factor of 8 jump in viscosity. When the jump was increased to 25X, degree-1 convection developed within 175 Ma (Fig. 2a). By increasing the convective vigor, we achieved this pattern even faster, by 98 Ma (Fig 2b).

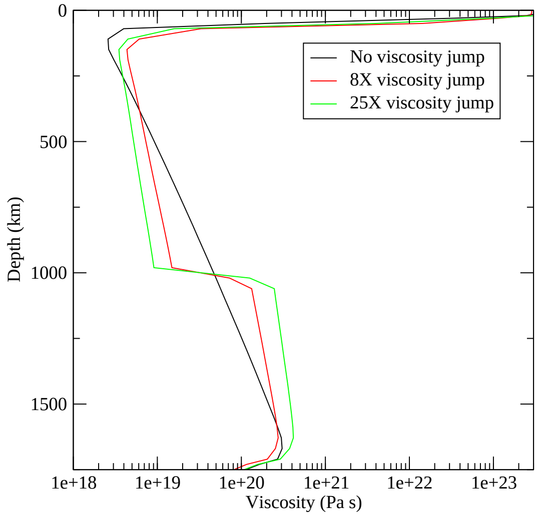

Figure 1: Radial viscosity profiles for three 3D convection cases

We tested the effect of heating mode on the planform of convection for our stagnant-lid models. We reduced the heating rate by half and found that degree-1 convection developed within 125 My. However, the upwellings are more linear than before. Reducing the heating to one-fourth its original value still resulted in a degree-1 pattern by 138 My. The degree-1 in this case is no longer a single upwelling, but rather a “forest” of plumes all localized in one hemisphere.

We considered an even stronger sublithospheric viscosity variation ($\approx$ 1000X) based on recent experiments [7]. We found that a model with no viscosity jump still evolves to a degree-2 structure, and that models with a factor of 8 or 25 jump develop degree-1 convection. However, in all cases, the single upwelling is a linear ridge rather than a classical plume shape (e.g. Fig. 3).

We also considered an endothermic phase transition near the CMB as a mechanism for producing degree-1 structures [9]. We found that degree-1 convection only developed if the viscosity was constant or very weakly temperature-dependent, and only at relatively low Ra. The timescale required to develop degree-1 even in these special cases was several Ga, inappropriate to the formation of the crustal dichotomy.

Finally, we examined the effects of geometry. Each model was run using both 2D axisymmetric and 3D spherical geometry. While the final convective planforms agreed in many cases, it was always easier to develop degree-1 structure in 3D.

Figure 2: Degree-1 plumes in two convection models with viscosity layering. E=157 kJ/mol, V=2.7 cm^3/mol, H_{int}=2.2*10^{-11} W/kg. The upper mantle viscosity has been reduced by a factor of 25. Ra=1.25*10^8 (a) and Ra=10^9 (b)

Figure 3: Degree-1 upwelling in convection model with high viscosity contrast. Model parameters same as in Fig. 2a, but V increased to 5.4 cm^3/mol)

Discussion

Pressure-dependent viscosity promotes the formation of long wavelengths. However, purely temperature- and depth-dependent viscosity models failed to produce a degree 1 structure. Including a factor of 8 or 25 viscosity jump while maintaining the same overall viscosity contrast promotes the formation of a degree-1 upwelling.

The required viscosity structure to generate degree-1 convection is consistent with the Earth's mantle rheology and viscosity [7,10]. This required viscosity jump is also significantly less than the factor of 500 from 2D models [4].

Several of our models develop a one-plume structure in less than 200 Ma, a timescale appropriate to the formation of the dichotomy [2]. We observe no significant dependence of the convective planform on the convective vigor. Increasing Ra helped the degree-1 pattern to emerge more quickly, in less than 100 Ma. Degree-1 convection from our models, once formed, can be maintained over hundreds of My, an essential property for maintaining the crustal dichotomy after its formation. The dichotomy formed when the crust and mantle were warm and weak. Without being maintained in some way, crustal thickness variations associated with the dichotomy may have relaxed long before the present.

A relatively high internal heating rate is consistent with an early primordial mantle. If degree-1 convection developed in this situation, a large amount of melt would be produced in the plume, forming a thicker crust over the upwelling in the present-day southern hemisphere. This crust would have cooled in the presence of the early magnetic field resulting in magnetic anomalies such as those seen in the southern highlands [11].

Conclusions

We can draw three main conclusions from our modeling:

1. A viscosity jump of a factor of 8-25 is sufficient to develop degree-1 convection in the martian mantle on a timescale appropriate to the formation of the hemispheric dichotomy, and can be maintained over geologic time. The timescale depends inversely on convective vigor, but the planform is insensitive to it.

2. A sublithospheric viscosity contrast of a factor of 100 produces classical plumes, where a factor of 1000 contrast leads to more ridge-like upwellings.

3. There is often good agreement between 2D and 3D models, but when they differ it is always easier to produce degree-1 convection in 3D.

References

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