Are Both the Tharsis Rise and the Crustal Dichotomy the Result of Dynamic Mantle Processes?

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Introduction: While there have been several attempts to model Martian mantle convection in a 3D geometry, producing both a hemispherical overturn that leads to the development of a crustal dichotomy followed by a single, stationary mantle plume that gives rise to the Tharsis volcanic province remains elusive. If Mars evolved in such a scenario, two degree 1 (i.e., hemispherical) patterns would be required to develop at 90 degrees to each other in the span of a few 100 million years. This has not been accomplished although several attempts have been made.

Harder and Christensen show that if a phase transition near the core-mantle boundary is incorporated in a constant viscosity convection calculation, a Mars-like mantle with 1 main plume and 1 minor plume will develop after about 8 Byr [1]. Zhong et al. [2] and Roberts and Zhong [3] show that in a temperature-dependent viscosity fluid, a single degree-1 overturn occurs if an early 50+ km thick crust exists (within 0.5 By) and is decoupled from the mantle. However, although the degree-1 upwelling persists after the overturn, its location is not adjacent to the dichotomy boundary as we see it today (i.e. the Tharsis Rise). Through a series of analogue laboratory experiments, Wenzel et al. [4] show that if an insulating plate overlies part of a temperature-dependent fluid, a large upwelling develops under the middle of the plate and remains stationary over billions of years. Again, the location of the upwelling is not at the edge of the dichotomy boundary.

As alternative explanations, the Martian crustal dichotomy could have formed by multiple large impacts occurring after the planet formed a lithosphere thick enough to maintain the topographic relief [5], or incomplete mixing of an early magma ocean that resulted in an overturn of an unstable mantle – thickening crust over downwellings and thinning elsewhere [6] or Tharsis volcanism may be related to a lithospheric, edge-driven instability [7].

Modeling: We model Martian mantle convection using the 3D finite element code CitComS [8]. We confirm that with an olivine-spinel phase transition near the Martian core-mantle boundary in a constant viscosity fluid, a 'Mars-like' mantle with 1 main plume and 1 minor plume develops after about 10 Byr, similar to that of [1]. However, throughout the majority of the calculation (i.e. 0.5 – 5 By) multiple plumes exist (Figure 1). If a temperature-dependent, Newtonian rheology is used (e.g. E=300 kJ/mol with Ra=3×10^6 and a heating rate of 3.25×10^{-9} W/m^3), also incorporating a phase transition near the core-mantle boundary, we find that 2 large plumes begin to develop 180 degrees to each other after only 2.5 Byr and remain stationary for more than 5 By (Figure 2). We have yet to find a set of parameters that will allow two different degree-1 upwellings to occur within a few 100 million years and 90 degrees to each other, which would be necessary to explain both the crustal dichotomy and the volcanism at Tharsis by global dynamic mantle processes. If we assume a crustal dichotomy already in place within the first 0.5 By of Mars' evolution, we may be able to generate small-scale convection at the boundary edge resulting in a Tharsis-like structure.

We simulate a dichotomy boundary by integrating a high viscosity lid over the "southern hemisphere" of our model and a free-slip boundary condition over the "northern hemisphere". Our goal is to create and modify a large enough viscosity "step" between the two hemispheres generating edge-driven convection (EDC) that results in long time-scale volcanism to one area.

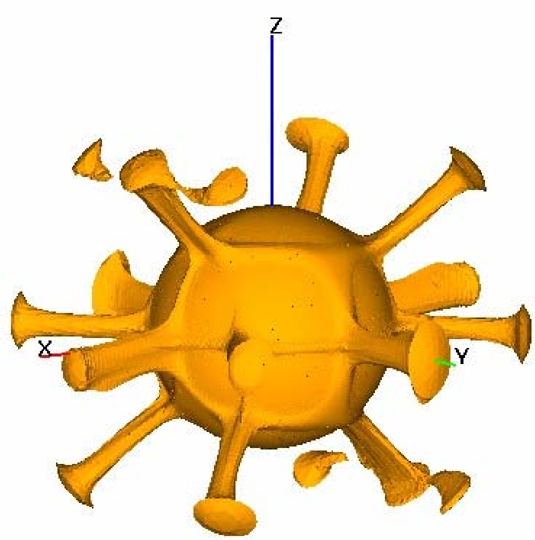

Figure 1: 3D numerical simulation of Martian mantle convection in an isoviscous rheology with a phase transition near the core-mantle boundary. Multiple plumes exist throughout most of the calculation reducing only to two main plumes after ~10 Byr.

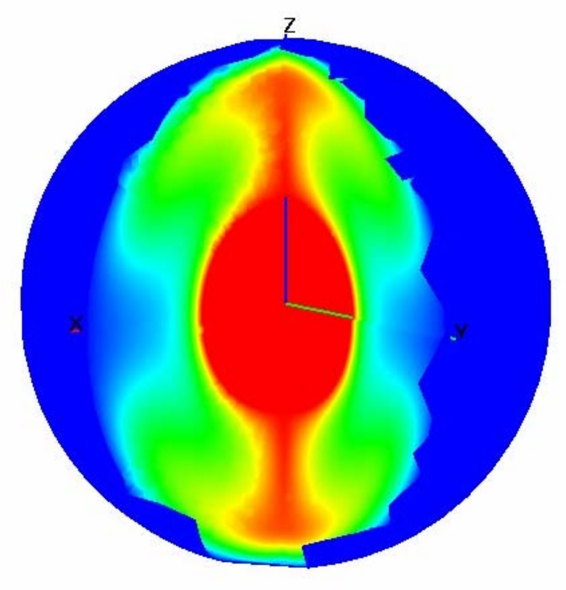

Figure 2: 3D numerical simulation of mantle convection on Mars after 5 By. This model uses a temperature-dependent Newtonian rheology and a phase transition near the core-mantle boundary.

Some Thoughts: Previous numerical experiments of small-scale convection by King and Anderson [7] show that an EDC instability can last for 50-100 million years depending on the erosion rate of the step in the boundary. Therefore, if EDC generated the volcanism comprising the Tharsis Rise in the Late-Noachian to Early-Hesperian period, then the same instability would not remain today. However, this does not rule out a series of instabilities, forming simultaneously and/or at various times along the edge, that together may have produced vast amounts of magmatism. In fact, it is interesting to note that the Tharsis swell formed in a concave section of the dichotomy boundary. This would make it easy (and maybe even coincidental) for magma producing upwellings to form in one circular area as a result of small-scale instabilities developing along the nearly 5,000 km arc of the boundary.

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