Formation of Martian volcanic provinces by lower mantle flushing?

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Introduction

The two main volcanic centres on Mars, Tharsis and Elysium, are often interpreted in terms of mantle plume hotspots. Several workers have tried to explain why there seem to be only two and not more plumes, invoking exothermic (Breuer et al., 1997) and endothermic (Harder, 1998) phase transitions. Alternative explanations for their formation presented in the literature include an impact genesis (Reese et al., 2004), the reduced thermal conductivity of the thick southern lithospere (Stegman et al., 2003), the combined effect of the dichotomy and a layered mantle (Wenzel et al. 2004), and the memory effect of a temperature dependent thermal conductivity (Schott et al., 2001).

In two classes of thermal evolution models, the early martian magnetic field is thermally driven by either an active lid regime which brings cold material to the core mantle boundary (Nimmo and Stevenson, 2000), or by an initially superheated core (Breuer and Spohn, 2003; Williams and Nimmo, 2004). A superheated core is also a prerequisite for the generation of thermal plumes from the core-mantle boundary.

Though it is possible that Mars had an initially superheated core (see box 1), we present results of numerical experiments which were designed to determine whether plume-like features can be produced in the martian mantle without an initially superheated core. The envisioned mechanism to produce these is the flushing of the deep mantle by cold downwellings in an active lid regime, similar to the 'second kind of mantle plume' of Cserepes and Yuen (2000).

Numerical models

We present results of 2D cylindrical shell numerical mantle convection experiments (see Box 2) with internal heating only. We investigate the effects of solid-state phase transitions, viscosity stratification in the mantle (related to solid-state phase transitions), and the presence of a thick southern hemisphere crust. Since the martian core size is not well constrained, the presence of the perovskite phase transition in the deepest martian mantle is uncertain. We apply two values for the core size within the range of uncertainty which are sufficiently small to allow this phase transition to be present.

Different stratified and non-stratified viscosity models are applied (see Box 3). The first has a lower mantle which is a factor 10 stronger than the upper mantle, similar to the viscosity contrast inferred in the Earth's mantle from glacial rebound studies (Lambeck et al, 1998). The second model has a transition zone which is a factor 10 stronger than the upper and lower mantle, based on recent work by Walzer et al. (2004). Because of the low surface viscosity in these experiments, they result in an active lid regime.

We also do some numerical experiments with a more realistic pressure and temperature dependent rheology (diffusion creep) following Karato and Wu (1993). This results in a stagnant lid regime in which cold downwellings from the bottom of the lid are small in size and magnitude. To be consistent with the hypothesis of an active lid regime in the northern hemisphere during the early evoltion of Mars, we include a yielding mechanism in the final experiment.

Results

Box 4 shows snapshots of the temperature, viscosity and lower mantle material for a series of numerical experiments. Starting from an isoviscous base model without dichotomy or phase transitions (a), we first include just the dichotomy (b), just phase transitions and viscosity stratification (c: strong transition zone; d: strong lower mantle), and then both the dichotomy and viscosity stratification (e: strong transition zone; f: strong lower mantle). In two final numerical experiments, we include a temperature and pressure dependent viscosity and in the last also lithosphere yielding (g).

The results show that the dichotomy effectively shields the southern mantle from cold downwellings, generating a quiet zone where passive hot upwellings driven by cold downwellings from the northern mantle can be formed. The presence of mantle phase transitions clearly has a focussing effect on these upwellings. The type of viscosity stratification modulates the dynamics and characteristic time scales.

Tests have shown these results to be qualitatively similar for varying Rayleigh numbers (5E5 and 5E6) and clapeyron slopes of the endothermic phase transition (-1 MPa/K and -3 MPa/K).

Box 5 shows a series of snapshots for a model with a strong lower mantle and a dichotomy. These results demonstrate that hot upwellings formed by the mechanism treated on this poster may be stable for billions of years. This long-term behaviour is reproduced in other long-running experiments with different parameter values.

Conclusions

A combination of mantle phase transitions and a thick southern hemisphere crust with an active lid regime operating on the northern hemisphere may provide conditions suitable for the generation of a small number (1-2) of large, hot, focussed upwellings in a purely internally heated mantle. Our results show that these may be stable for billions of years.

BOX 1: Was the Martian core initially superheated?

Due to the release of enormous amounts of potential energy during core segregation in terrestrial planetary bodies, the average temperature of a body may be raised by several hundred degrees for a Mars-sized body up to several thousand degrees for an Earth-sized body (Solomon, 1979). A recent isotope study has indicated that the time scales of core segregation (e.g. 4 Myr for Vesta, Kleine et al., 2002) may be similar to or even smaller than those of planetary accretion from 0.01 to 0.1 Earth mass planetary embryos in a Wetherill-type accretion model (5-100 Myr, Chambers, 2004). So the processes of accretion and core segregation appear to have taken place simultaneously. This makes it difficult to estimate whether the energy released by core segregation will primarily be present in the core or more evenly distributed throughout the planetary body. Additionally, there is the question to what extent thermal equilibration between core material and mantle silicates during the segregation process is established.

Therefore, an initially significantly superheated core relative to the surrounding mantle seems to be a potential but not necessary outcome of core segregation.

BOX 2: Numerical convection model

The numerical convection model is described by the non-dimensional equations for the conservation of energy, mass, and momentum, respectively, in the extended Boussinesq approximation:

$$\frac{\partial T}{\partial t} + u_j \partial_j T - Di(T+T_0)w =$$
$$\partial_j \partial_j T + \frac{Di}{Ra}\Phi + \sum_k \gamma_k \frac{Rc_k}{Ra} Di(T+T_0)\frac{d\Gamma_k}{dt} + RH$$
$$\partial_j u_j = 0$$
$$\partial_j \tau_{ij} - \partial_i \Delta p - (RaT - RbF - \sum_k Rc_k \Gamma_k) = 0$$

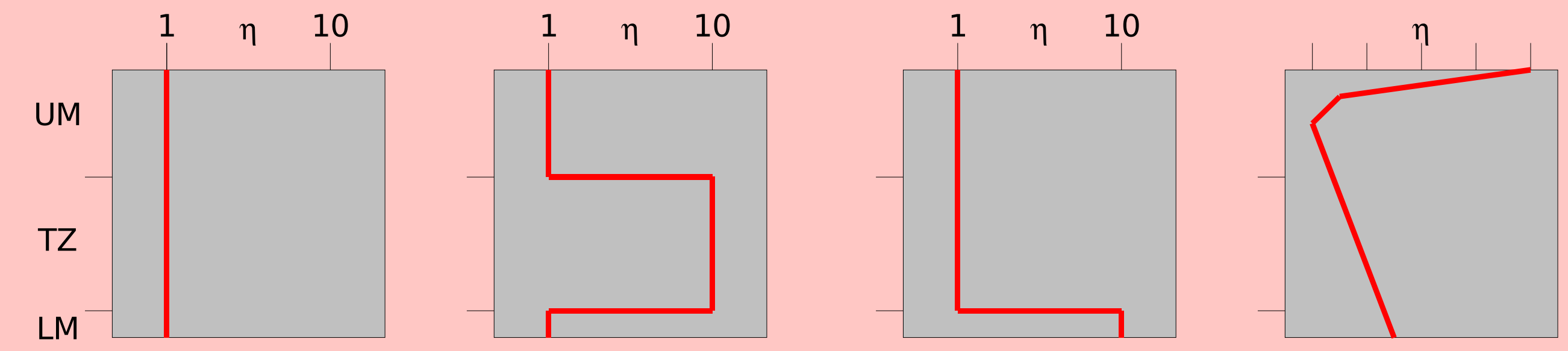
In most experiments, a layered viscosity model is applied, connected to the mantle phases (see Box 3). In the last two numerical experiments, a temperature and pressure dependent viscosity (Karato and Wu, 1993), is used, described by:

$$\eta_i = f(F) B_i \exp\left[\frac{E_i + PV_i}{RT}\right]$$

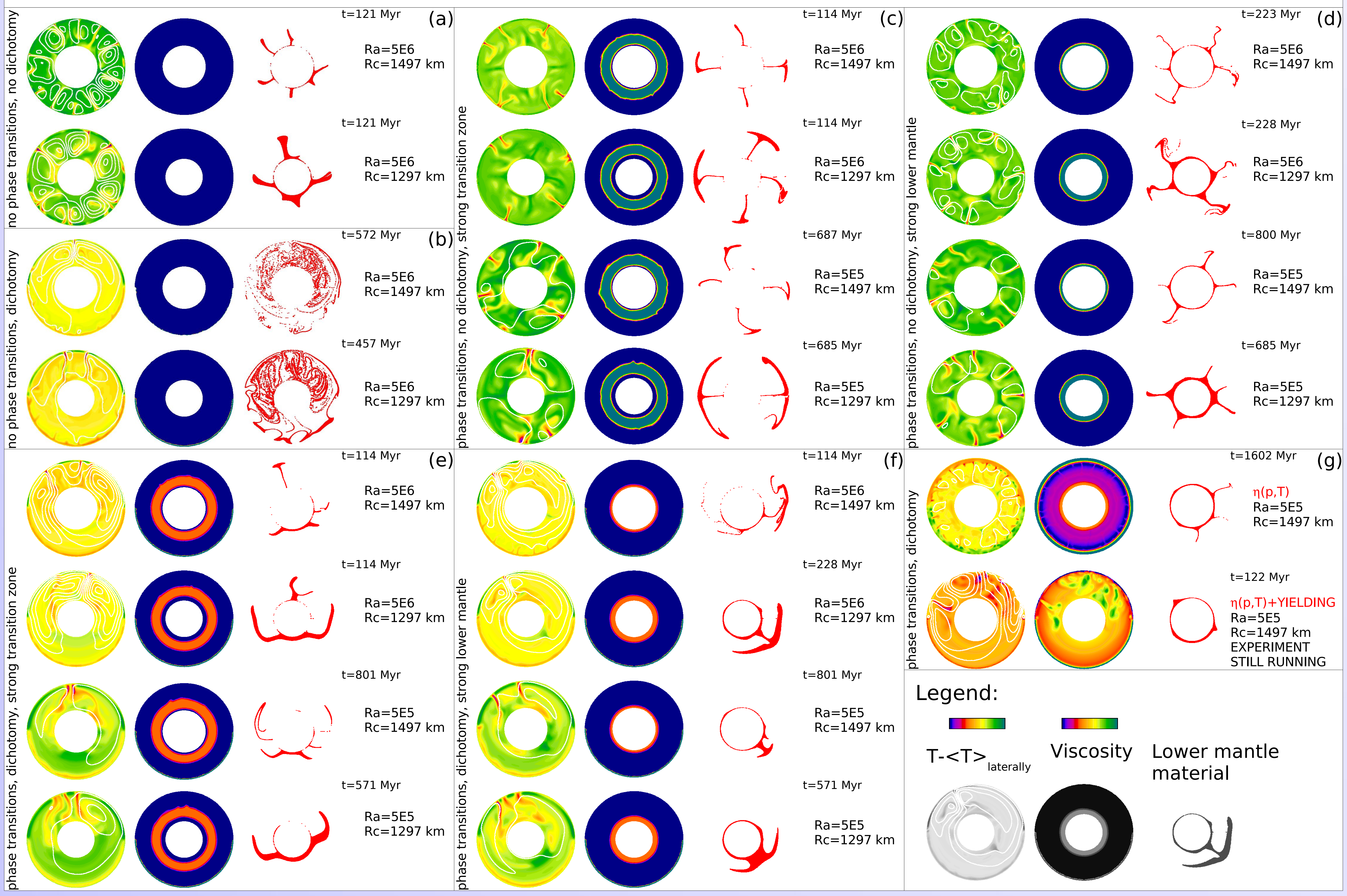
The last numerical experiment also includes yielding of the lithosphere, which is applied through the following expression (Van Hunen, 2001):

$$\eta_y = \tau_y \dot{\varepsilon}_y^{-1/n_y} \dot{\varepsilon}^{(1/n_y)-1}$$

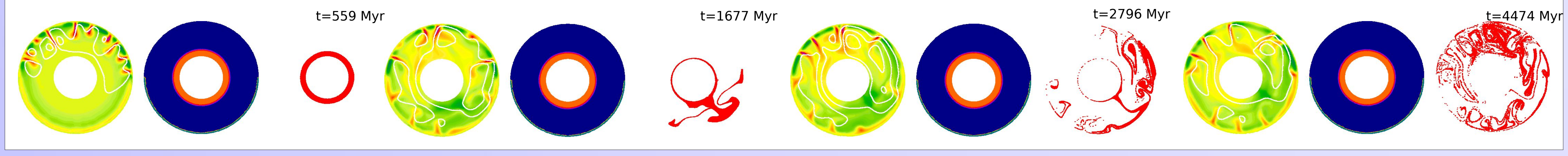
BOX 3: Viscosity models



BOX 4: Results of the numerical experiments.



BOX 5: Long-term stability of upwellings



References

Breuer D. et al. (1997) *EPSL* 148:457-469. Breuer D. and Spohn T. (2003) JGR 108(E7). Cserepes L. and Yuen D. (2000) *EPSL,* 183:61-71. Harder H. (1998) *JGR* 103(E7):16,775-16,797. Karato S. and Wu P. (1993) Science, 260(5109):771-778. Lambeck K. et al. (1998) *GJI* 134, 102-144. Nimmo F. and Stevenson D. (2000) *JGR* 105(E5): 19,969-19,979. Reese C. et al. (2004) *JGR*, 109. Schott B. et al. (2001) *GRL* 28(22):4271-4274. Stegman D. et al. (2003) AGU fall meeting. Van Hunen (2001) PhD thesis, Utrecht University Walzer. U. et al. (2004) *Tectonophysics* 384:55-90. Wenzel M. (2004) *GRL*, 31. Williams J.-P. and Nimmo F. (2004) *Geology,* 32(2):97-100.

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