Formation of martian volcanic provinces by flushing of the deep mantle?

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Introduction

The two main volcanic centres on Mars, Tharsis and Elysium, are often interpreted in terms of mantle plume hotspots. Plumes are generally thought to originate at a thermal boundary layer at the core mantle boundary. Though it is possible that Mars had an initially superheated core, the absence of a magnetic field during most of the planet's history suggests the core was not much hotter than the mantle.

We present results of numerical experiments (see Box 1) which were designed to determine whether plume-like features can be produced in the martian mantle without a 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 (*EPSL*, 2000).

We consider the effects of a thick southern hemisphere crust (“raft”), viscosity stratification, and core size.

Results

Figure 1 shows two snapshots for each of four numerical experiments with isoviscous mantles. The first case (a,b), with no phase transitions and no southern hemisphere raft, shows the formation of four more or less equally spaced upwellings of about equal strength, counterflow to cold downwellings in between. Adding a southern hemisphere raft (c,d) results in the generation of a single unfocussed upwelling under the raft, balancing focussed cold downwellings in the northern mantle. Figure 1e,f (including phase transitions, no southern hemisphere raft) shows a focussing of upwellings from the deepest mantle. Their size is reduced relative to the previous case (a,b).Contrary to the model of frames c,d (raft, no phase transitions), the last case with both a raft and phase transitions shows continued focussed upwelling in the southern mantle (g,h).

Figure 2 shows the effects of viscosity stratification on the formation of a focussed upwelling. Two snapshots of each of three models (isoviscous mantle: a,b; strong transition zone: c,d; strong lower mantle: e,f) demonstrate that viscosity stratification somewhat modulates the convective pattern, but is not a very important factor.

The effects of core size are shown in Figure 3. a-d show two sets of snapshots for a models (Ra=5.10^6) with a 1497 km core and a 1297 km core. Similarly, results for models with Ra=5.10^5 are shown in frames e,f (R_{core} = 1497 km) and g,h (R_{core} = 1497 km). Comparison shows that the resulting dynamics are qualitatively identical.

Figure 4 shows the long-term evolution of a Mars convection model with a southern hemisphere raft, phase transitions, and a strong lower mantle. After an initial period of 500 Myr of active lid regime on the northern hemisphere, a strong crust was added here, resulting in a reduction of the thermal amplitude of the cold downwellings generated here. Nevertheless, the short initial active phase results in a convection pattern which shows downwellings predominant in the northern mantle and a single focussed upwelling underneath the southern hemisphere raft, stable for billions of years.

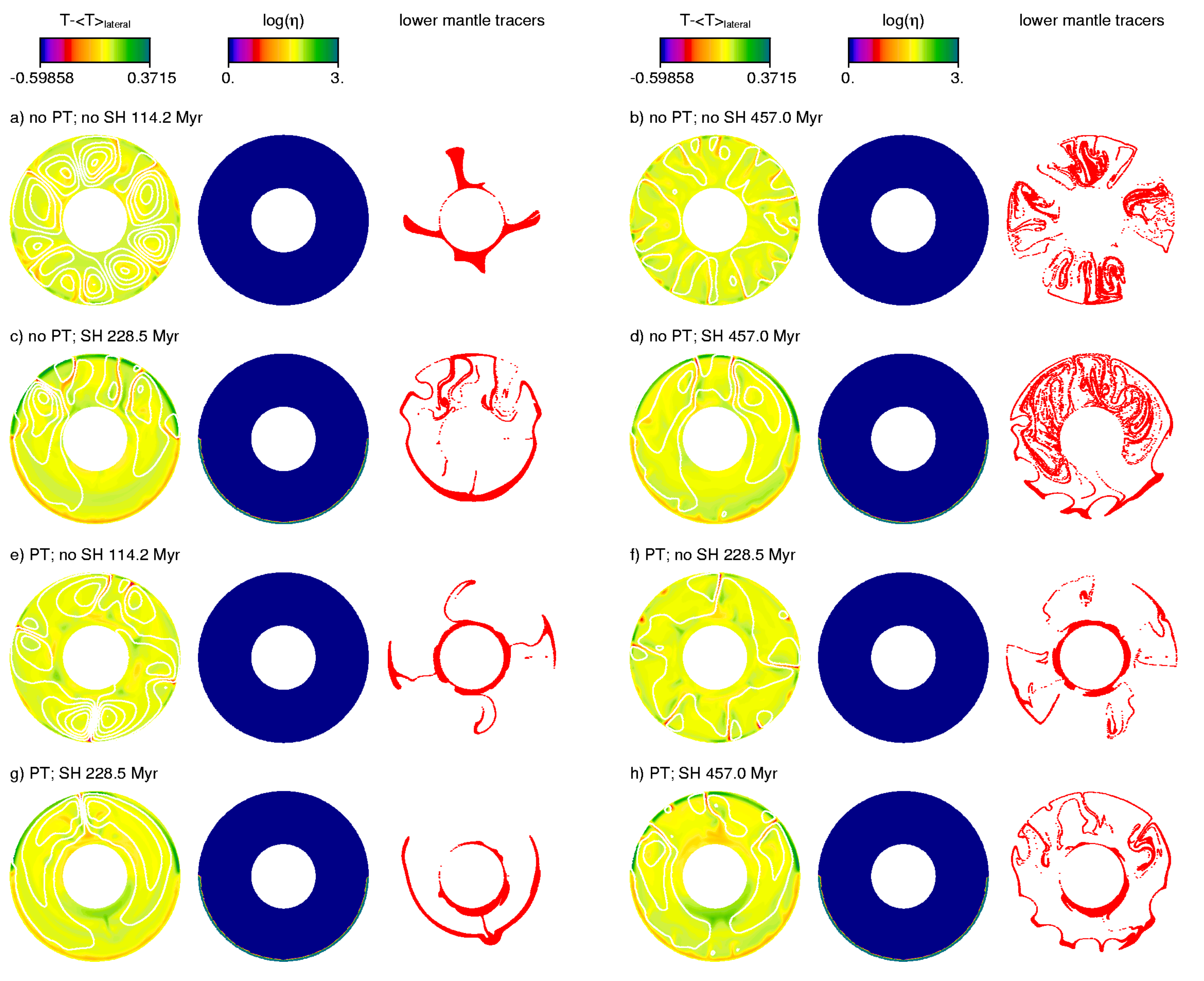

Figure 1: Effects of phase transitions and a southern hemisphere raft on the convective pattern. Left frames show the deviation of the local temperature from the laterally averaged temperature. Middle frames show the viscosity (in this figure only showing the raft if present), and the right hand side frames show the location of tracers which were initially in the lower mantle. The initial Rayleigh number is 5.10^6 in each case, and the core radius is 1297 km. PT: phase transitions; SH: southern hemisphere raft.

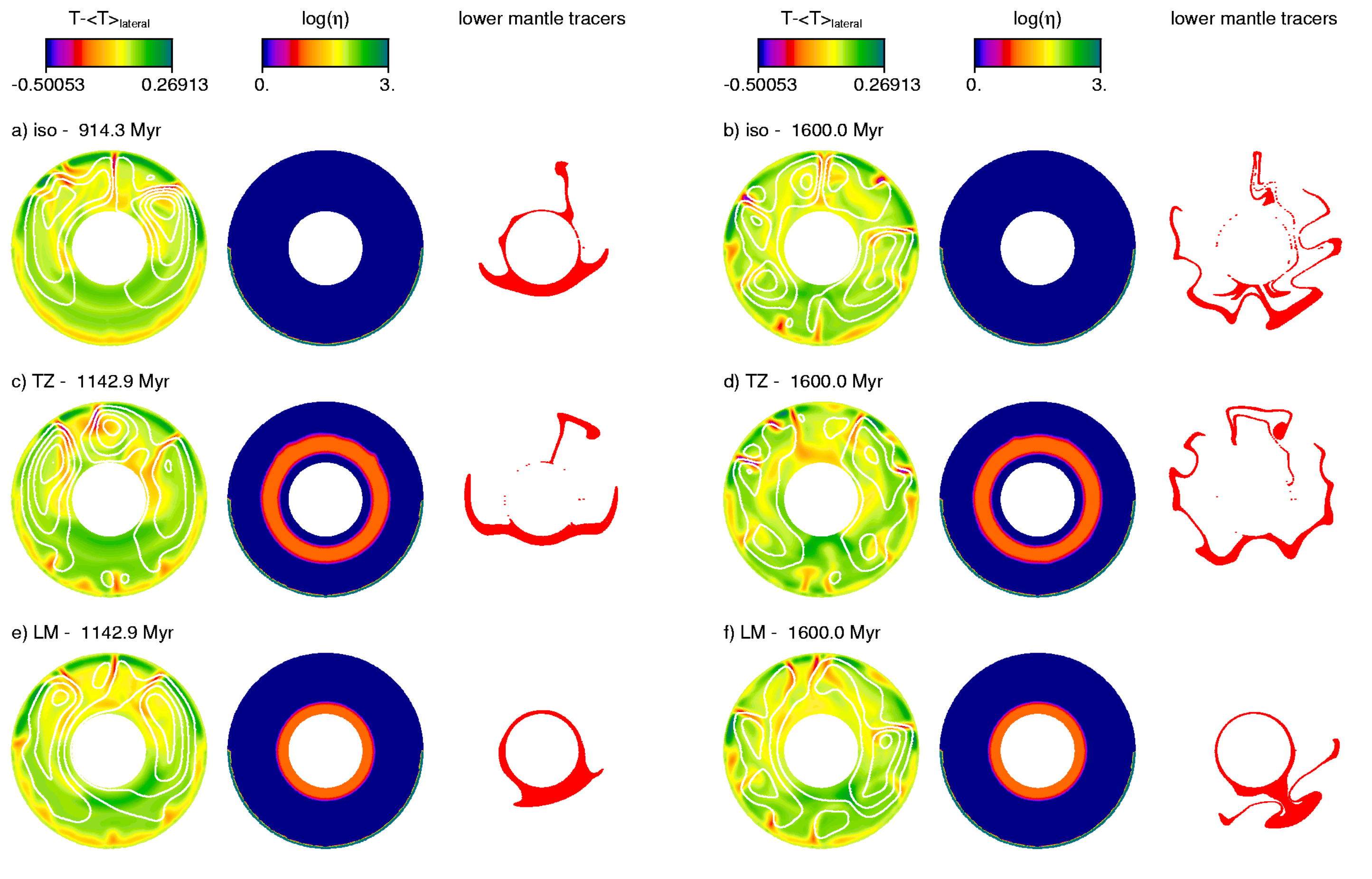

Figure 2: Effects of viscosity stratification on the formation of a focussed upwelling. Two snapshots of each of three models (isoviscous mantle: a,b; strong transition zone: c,d; strong lower mantle: e,f). The initial Rayleigh number is 5.10^5 in each case, and the core radius is 1297 km.

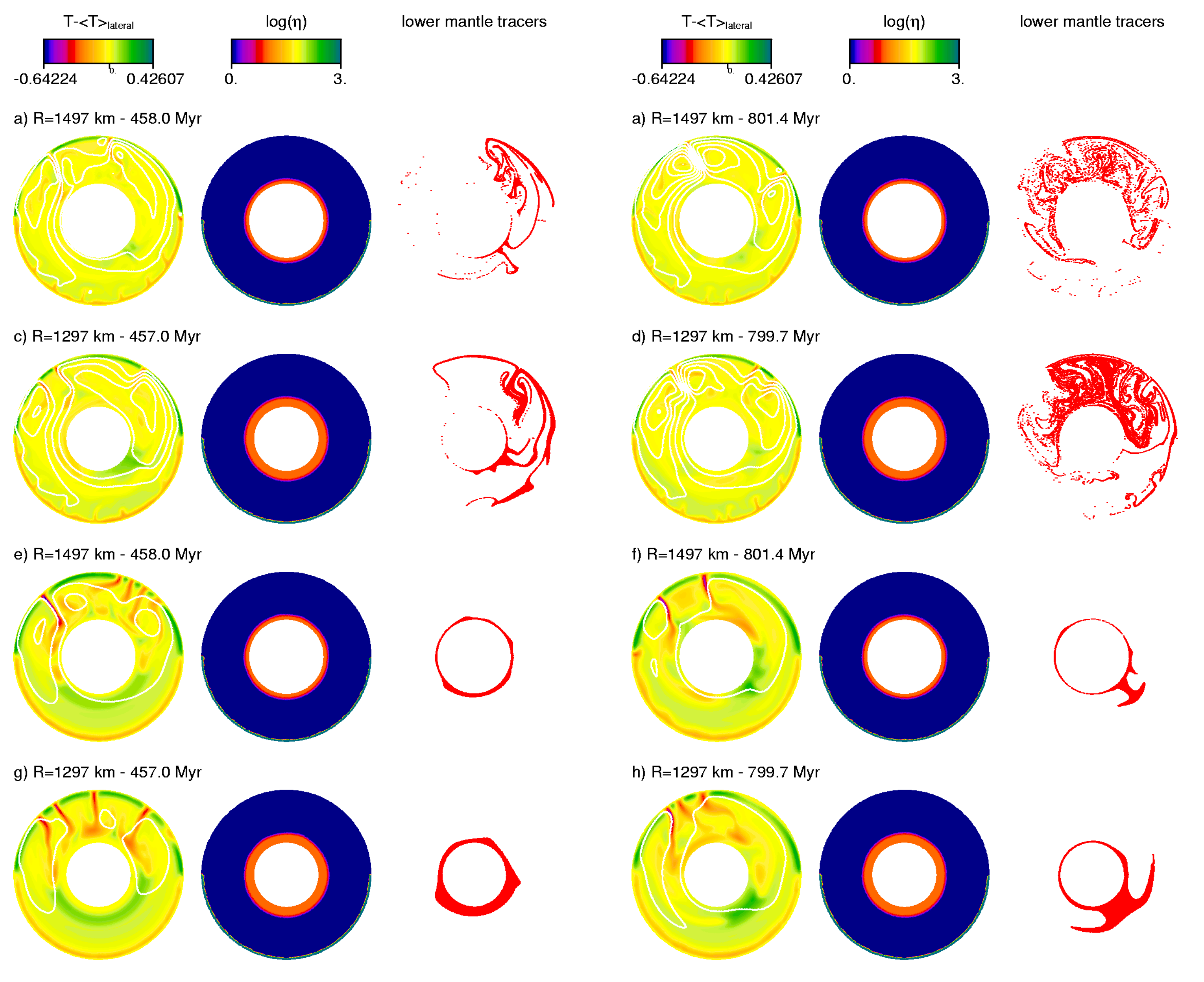

Figure 3: Effects of core size on upwelling dynamics. Two snapshots are shown for a model with a 1497 km core (a,b) and a 1297 km core (c,d) in models which are the same apart from the core size with Ra = 5.10^6, and also with Ra = 5.10^5 in frames e,f (R_{core}=1497 km) and g,h (R_{core}=1497 km).

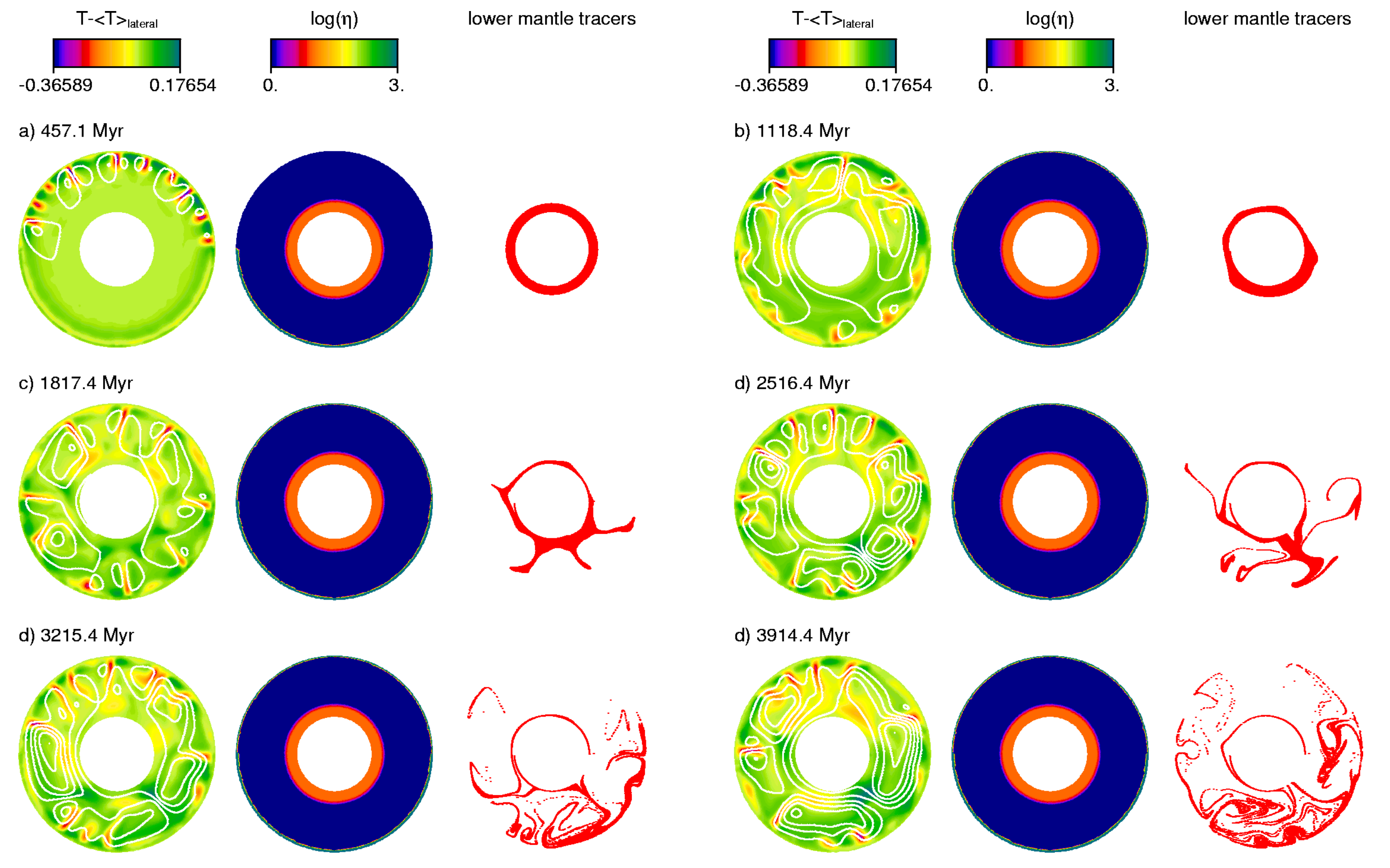

Figure 4: Long term stability of focussed upwelling. After an initial period of active lid activity in the northern hemisphere during the first 500 Myr, a stiff crust was added (b-f). The initial Rayleigh number is 5.10^5, and the core radius is 1297 km.

BOX 1: Numerical convection model

We present results of 2D cylindrical shell numerical mantle convection experiments with internal heating only (decaying heat sources). 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. 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:

$$\frac{\partial T}{\partial t} + u_j \partial_j T - Di(T+T_0)w =$$

$$\partial_j \partial_j T + \frac{Di}{Ra}\Phi \; + \; \sum_k \gamma_k \frac{Rc_k}{Ra} Di(T+T_0)\frac{d\Gamma_k}{dt} + RH$$

$$\partial_j u_j = 0$$

$$\partial_j \tau_{ij} - \partial_i \Delta p - \left(RaT - RbF - \sum_k Rc_k \Gamma_k\right) = 0$$

Different stratified and non-stratified viscosity models are applied. 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, *GJI*, 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. (*Tectonophysics*, 2004). Because of the low surface viscosity in these experiments, they result in an active lid regime.

More realistic rheologies

Application of a purely temperature and pressure dependent rheology results, not surprisingly, in a stagnant lid regime where strong cold downwellings, and thus the driving force for the mechanism under investigation, is absent. However, introduction of a yielding mechanism may overcome this problem, and allow strong cold downwellings nonetheless. This is confirmed by numerical experiments, initial experiments showing dynamics similar to that of Figures 2 and 4.

Conclusions

A combination of mantle phase transitions and a thick southern hemisphere crust with an active lid regime operating on the northern hemisphere during the initial phase of the planet's early history 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 until the present day, and thus provide an explanation for long lived volcanism in the Tharsis and Elysium regions.

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