The evolution of planetary geodynamics modulated by water

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Introduction

It has been known for more than 20 years that the rheology of olivine depends on its water content (e.g. Karato, 1986). More recently, lab experiments have shown that the presence or absence of crystal water may change the viscosity by two orders of magnitude (Hirth and Kohlstedt, 1996). A number of parametric mantle convection models including the effects of water on the viscosity and water exchange with the hydrosphere have been published in the literature (e.g. McGovern and Schubert, 1989, Franck and Bounama, 1995?). In this work, we study the feedback between rheology and mantle water content using 2D cylindrical shell full convection models.

Numerical model

We use a finite element model including 400.000 particle tracers. These tracers are used to monitor water content. The rheology model which is applied is relatively simple: a layered model, with a lower mantle viscosity 30 times that of the upper mantle to mimic the stratification interpreted from glacial rebound data, and with a local prefactor f which varies linearly with the local water content, from 1 (wet) to 100 (dry). For comparison, numerical experiments without a water dependence of the viscosity are conducted as well.

We consider two classes of models. In the first, which represents an active lid scenario, the mechanical boundary condition at the top boundary is free slip. The uppermost part of the mantle (150 km in these experiments) is assumed to be hydrated by hydrothermal circulation. This rather deep hydration zone represents high water concentrations in the hydrothermally altered oceanic crust, distributed over a larger depth interval.

In the second scenario, corresponding to a stagnant lid regime, there is a no-slip top boundary condition, and no rehydration of mantle material takes place.

Dehydration takes place through partial melting of the mantle. This is implemented by removing any water in places where the local temperature is higher than the solidus temperature.

The models are heated both internally (decaying) and from below (fixed temperature). The Rayleigh number is $1.2{*}10^7$, based on a wet lower mantle viscosity.

Preliminary results

Figure 1 shows snapshots of the temperature, water content and viscosity for six different numerical experiments. In frame a), which has an active lid, and a rheology which does not depend on water content, the initially dry condition is rapidly destroyed by hydration of the convecting upper mantle and mixing of upper and lower mantle material. In Figure 1b, where the viscosity does depend on water content, the lower mantle is not gradually hydrated by admixture of wet upper mantle material, but suddenly and dramatically by a mantle flushing event around 800 Myr.

As both models evolve and cool down, their upper mantles become too cold to allow partial melting and dehydration no longer takes place.

Figure 1c,d shows similar models as the previous, however with an initially wet mantle. Partial melting in the upper mantle locally reduces the water content, and dehydrated upper mantle material is mixed troughout the mantle.

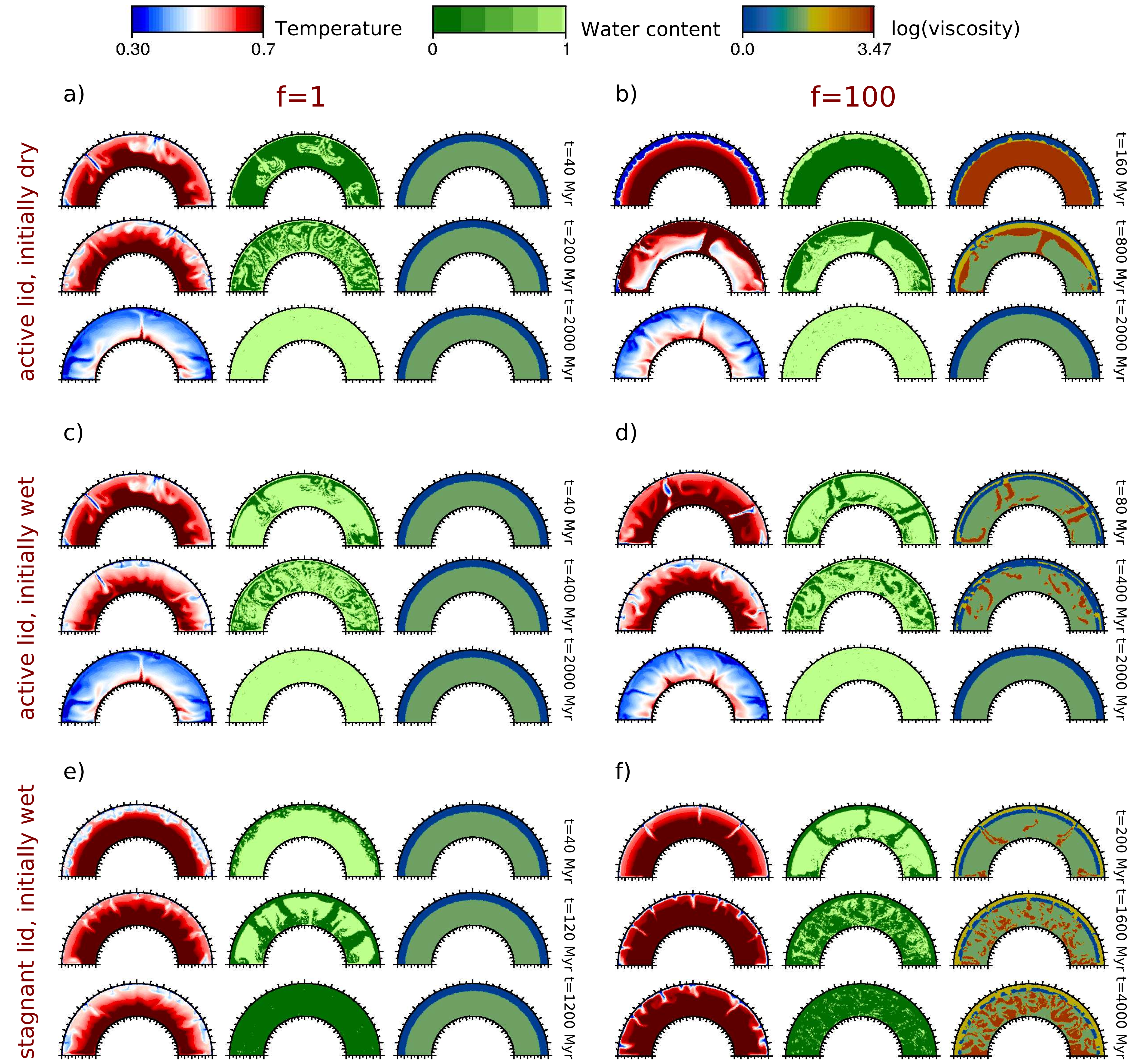

Figure 1: Selected snapshots of the evolution of the temperature (left), water (middle) and viscosity fields of six different numerical experiments. The left column (a,c,e) shows experiments without a dependence of the viscosity on water content. The right column (b,d,f), on the other hand, shows experiments with a strong water dependence of the rheology (factor 100 in the viscosity). The top row has an active lid and an initially dry interior. The middle row has an initially wet interior and an active lid. The bottom row shows stagnant lid models with an initially wet interior.

Rehydration keeps up reasonably well, and as melting ceases due to decreased temperatures, the mantle is completely rehydrated.

In the stagnant lid models of Figure 1e,f, dehydration of the mantle by local partial melting results in a globally dehydrated reservoir after some billions of years. As the higher viscosity of the water dependent rheology in frame f results in slower flow, dehydration is slower here as well. This is also illustrated in Figure 2, where nearly complete dehydration in a stagnant lid setting takes about 500 Myr or over 4 Gyr for the water independent and water dependent rheology models, respectively.

The active lid models all show re-equilibration times of about 1 to 2 Gyr in Figure 2.

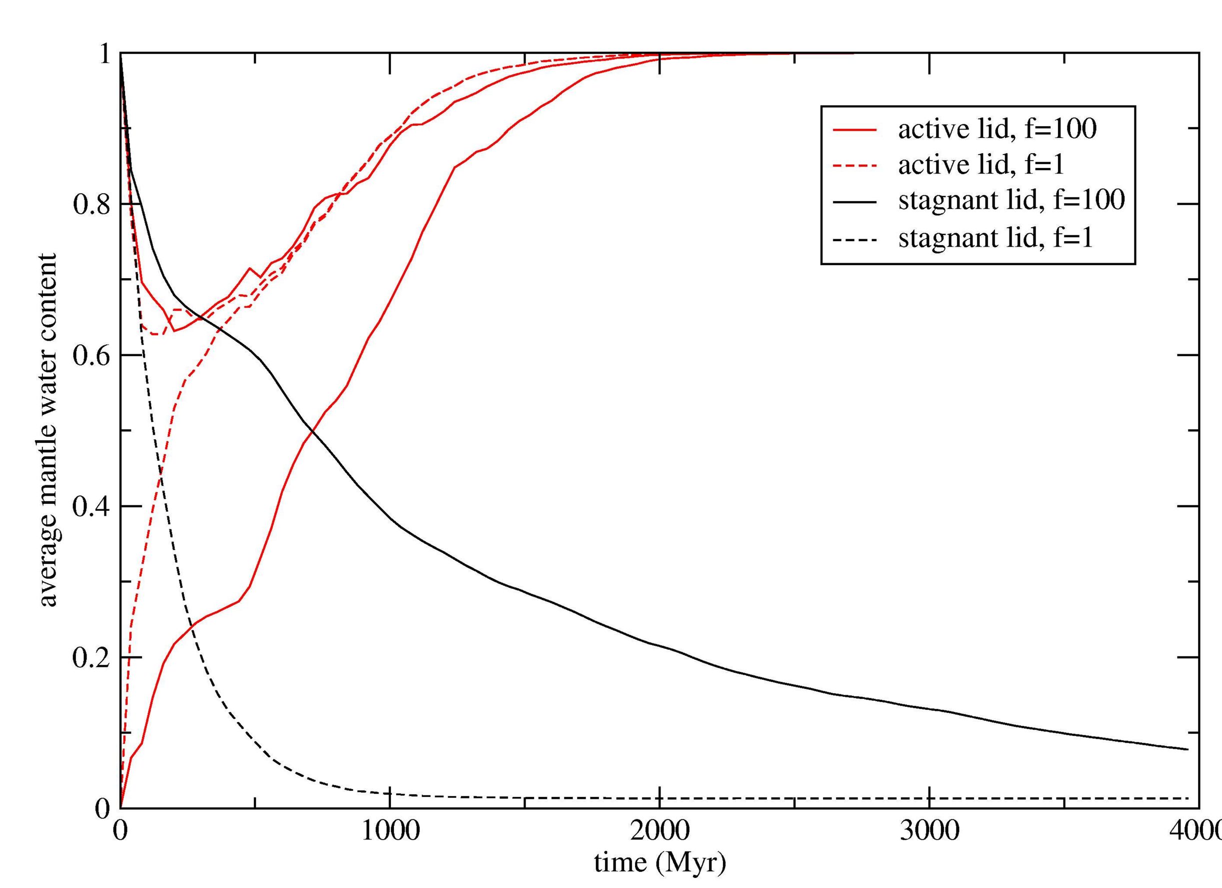

Figure 2: Volume averaged temperature (a) and water content (b) as a function of time.

Conclusions & Outlook

In the present set of models, viscosity increase by dehydration stretches the times scales of both dehydration and rehydration processes. Thus it may have a significant influence on the evolution of planetary mantle dynamics. However, further work is required. The inclusion of temperature-dependent viscosity is expected to reduce the cooling rate and extend time scales of processes. A more realistic parameterization of melt extraction will reduce the degassing rate. A continuous evaluation of the water content rather than the presently used binary (wet/dry) will be included. The sensitivity of the results to input parameters needs to be further examined to understand the relevance of the results for Earth, Mars and Venus, and terrestrial planets in general.

References

Franck, S. and Ch. Bounama (1995) *Adv. Space Res.*, 15(10): 79-86. Karato, S. (1986) *Nature*, 319: 309-310. Hirth, G. and Kohlstedt, D.L. (1996) *Earth Plan. Sci. Let.*, 144:93-108. McGovern, P.J. and G. Schubert (1989) *Earth Plan. Sci. Let.*, 96: 27-37.

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