Numerical Simulation of Planetary Interiors: Viscosity Variations due to the Influence of Partial Melt: Implications for the Thermal Evolution of Dry and Wet Planets

Ana-Catalina Plesa[1] and Doris Breuer[2]

[1]Dept. of Planetary Physics, Joint Planetary Interior Physics Research Group of the University Münster and IfP DLR Berlin,
[2]Institut for Planetary Research, DLR, Berlin, Germany

Contact: `http://dlr.de/pf` [ana.plesa@dle.de]

Helmholtz Alliance Planetary Evolution and Life

Westfälische Wilhelms-Universität Münster

Introduction

Partial melting is a common process in terrestrial planets and in fact difficult to avoid during some period of planetary evolution [1]. In earlier thermal evolution and convection models, melt production has been considered by the consumption and release of latent heat, the associated formation of a crust and the redistribution of radioactive heat sources [2, 3, 4]. Melt, however, is a most important element influencing also the viscosity of the mantle material. First, melt in suspension with the silicate matrix reduces the viscosity. Depending on the melt fraction the viscosity can be decreased by several magntiudes [5]. Second, melt can indirectly impact the viscosity of partially molten rocks through its influence on water content [6]. Mantle material will be dried out due to partioning of water from the minerals into the melt during melting process. As a consequence, the viscosity of water-depleted regions increases and will finally be a factor of > 100 larger than the water-saturated rocks.

In this preliminary study, we investigate the effects of both processes separately on the mantle dynamics and the efficiency of heat transport, i.e., the decrease of the viscosity with partial melt assuming a dry planetary interior and the increase of viscosity with depletion of water due to partial melt assuming a wet planetary interior (a decrease of viscosity with partial melt is negelected assuming that melt at degrees lower than a few percent will be separated from the solid matrix [6]).

Method

We use a 3D spherical convection model that can handle radial and lateral variations in the viscosity [7, 8]. The non-dimensional equations of a Boussinesq fluid with Newtonian rheology and including latent heat consumption by partial melting are:

$$\nabla \vec{u} = 0 \qquad \text{Continuity equation(mass conservation)}$$

$$\nabla \left[\eta(\nabla \vec{u} + (\nabla \vec{u})^T)\right] + RaT\,\vec{e_r} - \nabla p = 0 \qquad \text{Momentum equation(momentum conservation)}$$

$$\frac{dT}{dt} - \nabla^2 T - \frac{Ra_Q}{Ra} + (T + T_{surf})\frac{\Delta S}{cp}\frac{dF}{dt} = 0 \qquad \text{Heat transport equation(energy conservation)}$$

The viscosity law is modified in order to express the dependency on the degree of melt for a dry mantle:

$$\eta = \eta_0 \exp\left(\frac{E + Vp}{RT}\right)\exp(-\alpha F) \text{ with } F \leq F_{crit}$$

where η_0 is the reference viscosity, E is the activation energy, V is the activation volume, R is the gas constant, T is the temperature, α is a coefficient which value is 26 for diffusion creep and F_{crit} is the critical partial melt fraction [12]. In the second case we assume a wet mantle and

$$\eta = \eta_0 \exp\left(\frac{E + Vp}{RT}\right)\frac{1}{C_{OH}}$$

with C_{OH} as the concentration of OH in the solid material. See Figure 1 for the viscosity profiles of both cases.

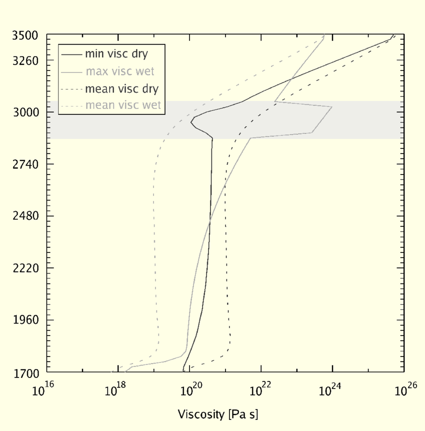

Figure 1: Viscosity profiles. The shaded region is where partial melt process locally takes place. This process is marked by a decrease in the min viscosity profile for dry mantle and by an increase in the max viscosity profile for wet mantle respectively

For simplicity, here we take $\frac{1}{C_{OH}}$ to be equal to $\exp(\alpha F)$. We further assume constant temperatures at the surface and at the core-mantle boundary, a constant heat production rate and free slip boundary conditions. Pressure dependence of the viscosity is neglected ($V = 0$) and E is 150 - 250 kJ/mol.

In the case of a dry mantle we assume that either up to 5% or 30% of melt can remain in suspension and reduces the viscosity accordingly. Melt fractions beyond these critical values are assuemd to rise instantaneously toward the surface and do not influence the viscosity. For the wet mantle case, we assume that the solid residual will be continuosly depleted of volatiles with increasing melt fraction but independent whether the melt remains in suspenison or is removed. This process results in a decrease of the viscosity.

Results

First, we present a comparison of the results obtained for a dry mantle with a critical melt fraction of 5% and a wet mantle for quasi steady state solutions. For these cases we have a mixed heating mode (heating from the core and radioactive heat sources). The Rayleigh numbers are set to $Ra_1 = 1e7$ and $RaQ = 3e7$.

Quasi steady state

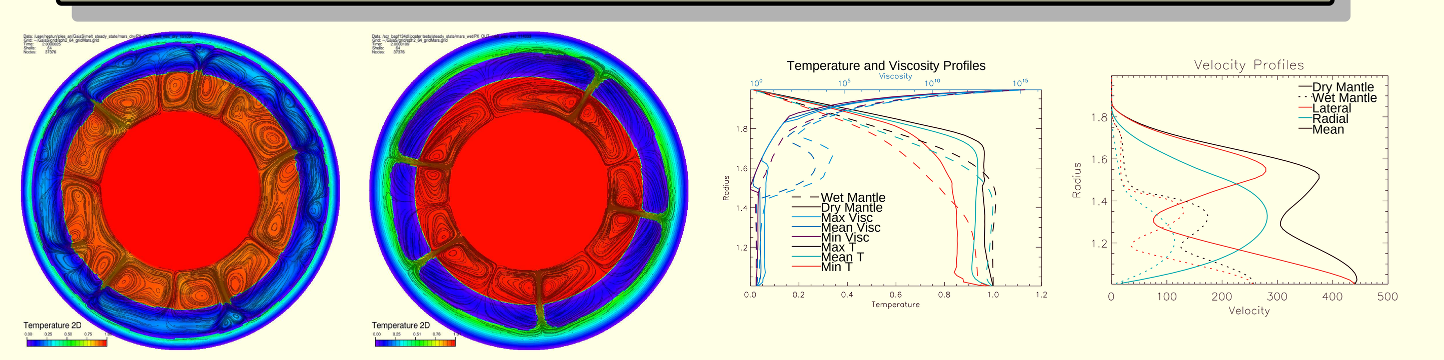

Figure 2: Comparison between dry and wet mantle. From left to right: temperature fields for dry and wet mantle, respectively, and temperature, viscosity and velocity profiles. Bluish regions mark the zones of partial melt.

Rheology	Nu_t	Nu_b	*Surface Heat Flow*	*CMB Heat Flow*	*Lid Thickness*
dry	5.12	1.88	46.44	17.08	0.197
wet	3.69	0.67	33.46	6.08	0.287

Table 1: dry vs. wet mantle results at non-dimensional simulation time = 2.0

In the second part, we further assume that the radioactive heat sources decay with time and that the core is cooling. The thermal evolution is calculated for a dry mantle with $F_{crit} = 5\%$, a wet mantle, a case where the viscosity in the partial melt zone is left unchanged and a dry mantle with $F_{crit} = 30\%$. For all four cases we assume the same initial conditions. The Rayleigh numbers are set to $Ra_1 = 1e7$ and $RaQ = 5e7$.

Evolution

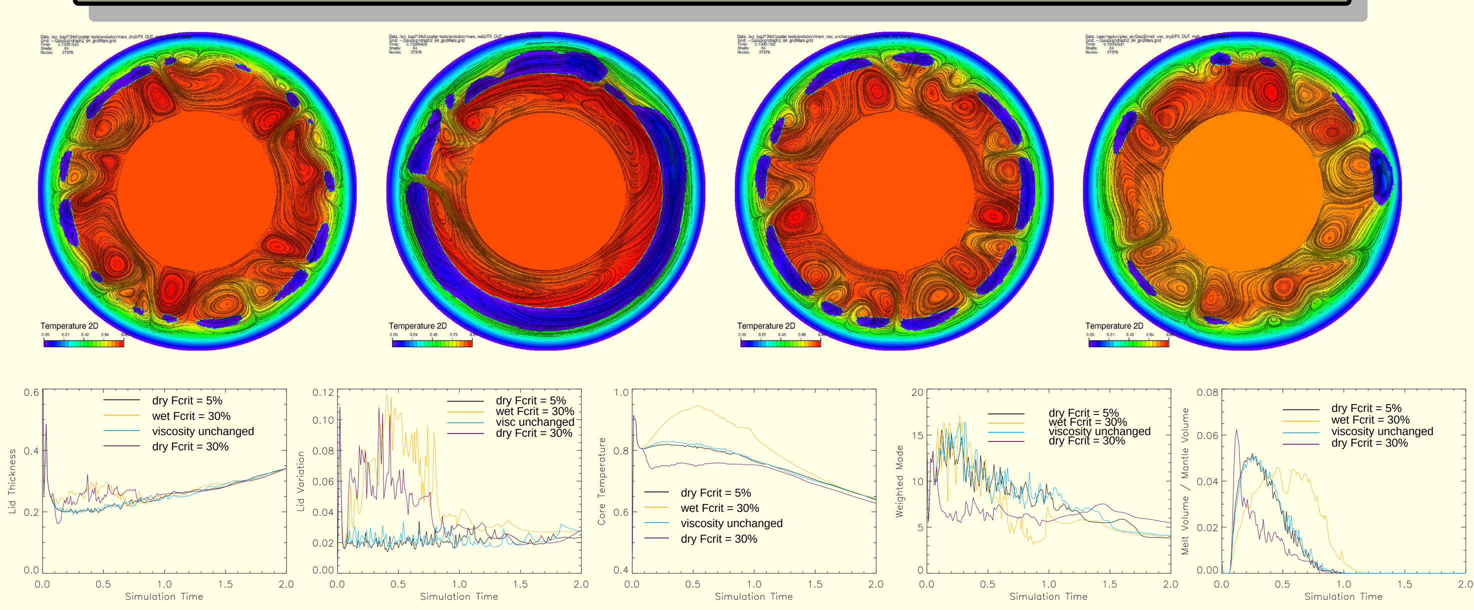

Figure 3: Top from left to right: Temperature field of a dry mantle 5% melt, wet mantle, viscosity unchanged, dry mantle 30% melt at non-dimensional simulation time 0.73. Bluish regions mark the zones of partial melt.
Bottom from left to right: Lid thickness, lid variation, core temperature, weighted mode and melt volume over the mantle volume as a function of time

Discussion

The effect of partial melt upon viscosity in the dry mantle case with Fcrit = 5% will only have an local impact and only small changes can be observed in the velocity and temperature profiles. However if more melt can remain in suspension or for the wet mantle case, the influence becomes stronger and more global. For instance, the cooling rates differ significantly from the model with unchanged viscosity (increased cooling for dry mantle case and lower cooling for the wet mantle case). Furthermore, the convection structure becomes more large-scale in both cases.

In our models we have studied the effects of partial melt on the viscosity for both dry and wet mantle cases. Note, however, that for a better comparison our models start with the same initial mantle viscosity (before partial melt occurs). Future studies will consider that at the same temperature the dry mantle has a higher viscosity than the wet mantle case.

Future steps are to extend our model by investigating the effects of partial melt upon compositional changes and mantle differentiation. For this another equation for the composition conservation will be added to the gorverning equations presented in the method section. Also tracer particles will be used to monitor the evolution of single material points along their flow-characteristics.

References

[1] V. S. Solomatov and L.-N. Moresi. Scaling of time-dependent stagnant lid convection: Application to small-scale convection on the earth and other terrestrial planets. *J. Geophys. Res.*, 2000, 105, 21795-21818.

[2] S.A. Hauck and R.J. Phillips. Thermal and crustal evolution of mars. *J. Geophys. Res.*, 2002, 107, NO. E7, 10.1029/2001JE001801.

[3] D. Breuer and T. Spohn. Early plate tectonics versus single plate tectonics: Evidence from the magnetic fieldhistory and crust evolution. *J. Geophys. Res. - Planets*, 2003, 108, 5072, doi:10.1029/20002JE001999.

[4] S. Schumacher and D. Breuer. Influence of a variable thermal conductivity on the thermochemical evolution of mars. *J. Geophys. Res.*, 2006, 111(E2), CiteID E02006.

[5] T. Hiraga D.L. Kohlstedt S. Mei, W. Bai. Influence of melt on the creep behavior of olivine-basalt aggregates under hydrous conditions. *Earth and Planetary Science Letters*, 2002, 201 (2002) 491-507.

[6] G. Hirth and D. L. Kohlstedt. Water in the oceanic upper mantle: Implication for rheology, melt extraction and the evolution of the lithosphere. *Earth and Planetary Science Letters*, 1996, 144, 93-108.

[7] C. Hüttig and K. Stemmer. The spiral grid: A new approach for the mantle convection in spherical geometry. *Geochem. Geophys. Geosyst.*, 2008, doi: 10.1029/2007 GC001581.

[8] C. Hüttig and K. Stemmer. Finite volume discretization for dynamic viscosities on voronoi grids. *Phys. Earth Planet Interiors*, 2008, doi: 10.1016/j.pepi.2008.07.007.