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Numerical Modelling of the Internal Dynamics and Surface Tectonics of the Terrestrial Planets

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1 Introduction

The terrestrial planets can be separated roughly into two classes with respect to their interior dynamics. Mercury and the silicate-moons (e.g. of Jupiter) are in a so-called single plate regime, which is characterised by an immobile and rigid lithosphere. The lithosphere on Earth, however, is divided into several mobile but individually rigid plates. Oceanic crust is created and destroyed at mid-ocean ridges and subduction zones, respectively. The Earth's surface is therefore characterised by a process of constant renewal, at least partially.

Venus and Mars have a special position in this classification, as both planets do not show any evidence for recently active plate tectonics as observed on Earth. However, statistics on impact crater counts for Venus indicate a global resurfacing event approximately 100 million years ago[1]. This suggests an episodic behaviour of surface tectonics with alternating periods of surface mobility and stagnation. Mars also appears as a one-plate planet. However recent findings by the MAG/ER magnetometer experiment on board of the Mars Global Surveyor spacecraft have revealed the existence of magnetic anomalies within the Martian crust that resemble the magnetic line patterns found at the mid-ocean ridges on Earth[2,3]. This suggests the presence of an episode of active plate tectonics on Mars, limited to the first 500 million years after the formation of the planet[4,5].

Within the scope of the DFG priority program "Mars and the terrestrial planets" we investigate these different convective styles and focus especially on a self-consistent description of a temporal transition between two regimes and its consequences on the subsequent thermal evolution of the planet.

The thermal evolution of terrestrial planets is widely investigated[6–11]. This is commonly done by applying a scaling relationship which comprises a parameterisation of the heat flux in terms of the Rayleigh number. Seperate parameterisations have been discussed for different convective regimes by[12]. A transition from one convective style to another is thus achieved by prescribing scaling laws appropriate for each regime[13]. Our fluid dynamical approach allows us to investigate the interior dynamics and the surface tectonics as a coupled system. We are therefore able to address the question whether the proposed transition from a tectonically active plate to a nowadays stagnant surface is indeed plausible.

2 The Model

In order to study the convective processes that govern the dynamics of the Earth's mantle and that of other terrestrial planets we follow a fluid dynamical approach. This allows us

to investigate mantle convection and the dynamics of the planetary surface as a coupled system.

2.1 The Mathematical Model

We consider thermally driven convection of an incompressible Boussinesq medium with infinite Prandtl number. The governing equations describing the conservation of mass, momentum and energy, respectively, are as follows:

$$\boldsymbol{\nabla} \cdot \mathbf{u} = 0 \tag{1}$$

$$-\boldsymbol{\nabla} p + \boldsymbol{\nabla} \boldsymbol{\sigma} + Ra\, T \hat{z} = 0 \tag{2}$$

$$\frac{\partial T}{\partial t} + \boldsymbol{\nabla} \left(\mathbf{u} T \right) - \boldsymbol{\nabla}^2 T = Q \tag{3}$$

Here, $\mathbf{u}$ is the velocity vector, p the dynamic pressure (i.e. the pressure without the hydrostatic component) and $\boldsymbol{\sigma}$ the stress tensor with $\boldsymbol{\sigma} = \eta \left[(\nabla \mathbf{u}) + (\nabla \mathbf{u})^t \right]$. T is the temperature and $\hat{z}$ the vertical unit vector. The rate of internal heat production Q is assumed to be constant in space and time. All variables have been non-dimensionalised by using a common scaling based on thermal diffusion time and vertical temperature difference. The Rayleigh number resulting from this scaling reads:

$$Ra = \frac{\alpha \rho g \Delta T d^3}{\kappa \eta_0} \tag{4}$$

where α denotes the (constant) thermal expansivity, ρ the density, g the gravitational acceleration, ΔT the vertical temperature difference, d the height of the model volume and κ the (constant) coefficient of thermal conductivity. η_0 is the reference viscosity defined at the surface of the domain.

The experiments were carried out in a Cartesian box with stress-free, impermeable boundaries. The box was heated from below and cooled from above with constant temperatures of $T_{top} = 0$ and $T_{bot} = 1$. Reflecting conditions were employed at the sides.

2.2 The Rheological Model

The key parameter for the investigation of the convective processes taking place within planetary mantles is the viscosity η, which directly controls the ability of the material to flow and thus influences the dynamics of the system. Laboratory experiments with mantle material analogs have shown that the viscosity within the mantle is not constant but varies with pressure, strain-rate and, most important, with temperature. In fact, the viscosity variations induced by temperature alone may span more than six orders of magnitude making the numerical solution of the governing equations extremely delicate.

We employ the following rheology, which has proven to be suitable to describe the dynamics of planetary mantles[14–16]

$$\eta(T, z, E) = 2 \cdot \left[\frac{1}{\eta_{Tz}} + \frac{1}{\eta_E} \right]^{-1} \tag{5}$$

with

$$\eta_{Tz} = \exp\left(-r \cdot T + r_d \cdot (1-z)/d\right) \quad \text{and} \quad \eta_E = \eta^* + \frac{\sigma_0}{E} \tag{6}$$

being the temperature/depth- and strain-rate-dependent part of the viscosity, respectively. r determines the strength of the temperature dependency, with $R = \exp(r)$ being the viscosity contrast between the material with maximum (i.e. $T = 1$) and minimum temperature ($T = 0$). r_d describes the dependency of viscosity on depth (pressure), which is neglected in the investigations presented here. All calculations shown in this work have been carried out with $R = 10^5$. $\eta^* = 10^{-5}$ is the plastic viscosity, σ_0 the yield stress and E the second invariant of the strain-rate tensor.

2.3 Numerical Technique

The set of non-linear equations 1-3 is solved numerically using a technique presented by Trompert and Hansen[17]: A finite volume approach is applied for spatial discretisation and an implicit Crank-Nicholson scheme for discretisation in the time domain. The algebraic equations are solved iteratively employing a multigrid technique with SIMPLER as smoother.

Due to the large viscosity variations that have to be accounted for, the calculations are extremely demanding in terms of computation power and time. A single model run easily takes several months on a Pentium IV–class workstation, limiting the possibilities to carry out investigations at high resolution and extensive parameter studies. We therefore developed a modified version of the original program code that can benefit from parallel computer architectures. We applied a domain decomposition technique and used MPI for explicit message passing. This allows us to use the Intel-based cluster system located in our university's computer center and, even more important, high performance computer systems like the JUMP-system of the John-von-Neumann Institute for Computing, Jülich, Germany.

3 Results

3.1 Styles of Mantle Convection

Investigations of mantle convection considering a temperature- and strain-rate dependent viscosity have revealed the existence of three different styles of convection[12,14].

- Stagnant Lid regime: A rigid and immobile layer develops at the surface of the mantle. Vigorous convection takes place underneath this stagnant lid. This mode of convection is associated with the present state of Mars, which currently shows a plate-tectonically inactive surface.

- Mobile Lid regime: The surface layer is mobile and is constantly subducted by the convective cycle. The system behaviour in this regime resembles that observed for constant viscosity convection. By further assuming a depth-dependency of the yield stress σ_0, a plate-like surface behaviour is obtained, similar to what is observed on Earth.

- Episodic regime: An initially stagnant lid develops at the surface. The thickening lid gets mobilised by increasing strain rates and is subducted into the interior. The now hot surface cools and a new lid develops which is again mobilised. This mode of convection is often proposed to be relevant for Venus.

Figure 1 gives a visual impression of the episodic and the stagnant lid regime by showing snapshots of the colour-coded temperature field. In the episodic case (left picture) the surface is repeatedly mobilised at least partially, as indicated by the velocity vectors (white arrows). In the stagnant lid regime, a relatively thick cold surface layer develops, which does not take part in the convection process that dominates the interior of the system.

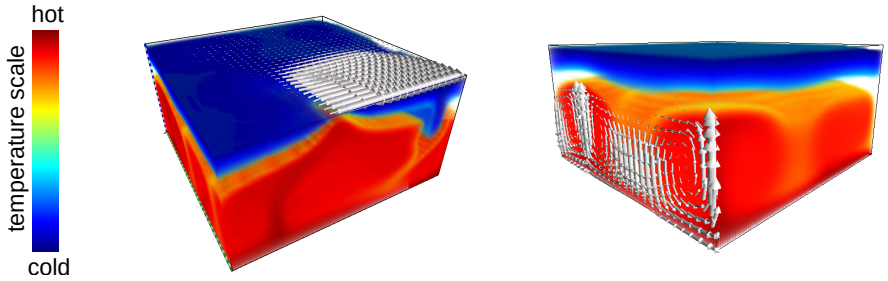


Figure 1. Two snapshots of model calculations showing the episodic regime (left picture) and the stagnant lid regime (right picture). In both cases the temperature field is visualised according to the colour scale shown. White arrows indicate the velocity field at the surface and at the left side of the box, respectively. For the episodic regime an event of surface mobilisation is shown with about a quarter of the surface being mobilised.

The actual choice of thermal and rheological parameters determines the state of convection finally emerging. A variation of the yield stress for example changes the system behaviour from the mobile lid regime, which is found for small values of σ_0 to the episodic regime for intermediate yield stresses. Finally, for large values of the yield stress the system exhibits the stagnant lid mode of convection. We carried out a systematic investigation of the dependency of the convective style on the various system parameters[14] and mapped the location of the different regimes in the parameter space, as shown in figure 2

3.2 Temporal Variations Between Convective Styles

Our investigations indicate that a change in the convective style is not only possible by means of a variation of parameters but can also appear temporally, for fixed parameters. For a critical set of parameters, that mark the border between the episodic and the stagnant lid regime (cf. figure 2) we observed the system behaviour illustrated in figure 3 by means of the non-dimensional surface heat flux. The system initially shows stagnant lid convection for more than one thermal diffusion time but eventually changes to an episodic behaviour.

Apart from this prominent example for a transitional behaviour, we also observed systems that show stagnant lid convection being interrupted by isolated events of surface mobilisation, as also shown in figure 3, again, by means of the surface Nusselt number, i.e.

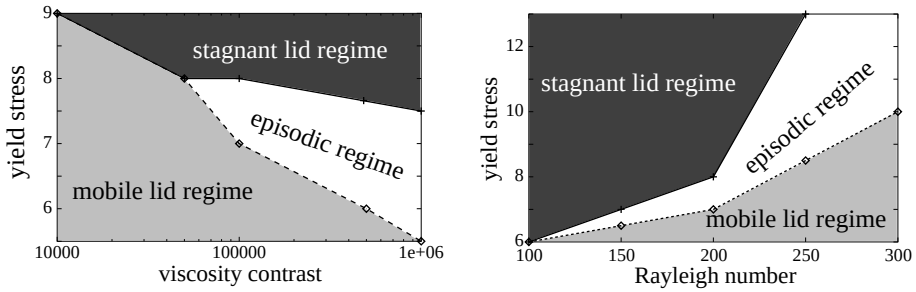


Figure 2. Two snapshots of the parameter space spanned by the Rayleigh number, the viscosity contrast and the yield stress indicating the location of the three different convective regimes. Taken from ref.[14].

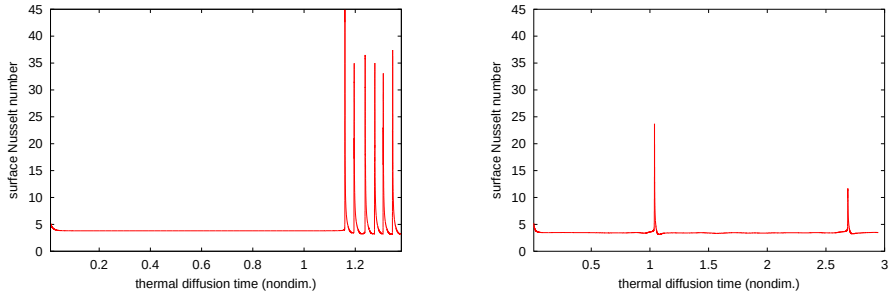


Figure 3. The surface Nusselt number as a function of time for two different model runs showing a temporal variation in the surface behaviour: A transition from stagnant lid convection to an episodic behaviour (left figure) and stagnant lid convection being interrupted by two sporadic events of sporadic surface mobilisation (right figure)

the non-dimensional surface heat flux. In both cases shown, the transition occurs out of an quasi-steady state with a thermally equilibrated heat budget.

Such a transition in the convective style is not only a fluid dynamical curiosity but is of major interest for planetological considerations. A transition of from a plate tectonically active, i.e. mobile surface to a nowadays stagnant surface has often been postulated for Mars in order to explain the remanent magnetisations of the Martian crust found by the MGS MAG/ER experiment and the presence of the crustal dichotomy[5,4,3].

Based on the rheological law (eq. 6), we were able to deduce a mobilisation criterion, that quantifies the stability of the stagnant surface layer:

$$\epsilon_M > 1 \qquad \text{with} \qquad \epsilon_M = \left.\frac{E}{\sigma_0}\right|_{surface} \tag{7}$$

Where E denotes the effective strain-rate as calculated from the velocity field and σ_0 is the yield stress parameter. The criterion serves as a necessary condition for a sporadic event of surface mobilisation. It is therefore possible to predict the occurrence of these events using our criterion as shown in figure 4.

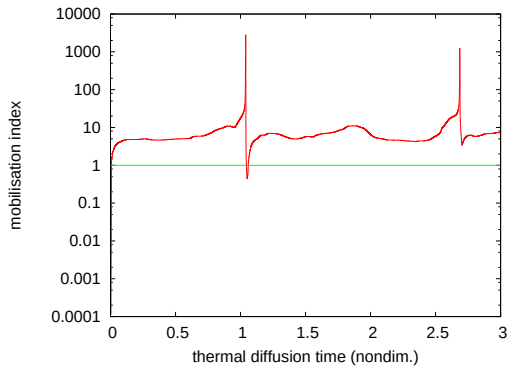


Figure 4. Value of our mobilisation index as a function of time for the model run shown in figure 3(right). Mobilisation of the otherwise stagnant surface occurs at $t = 1.0$ and $t = 2.7$. As clearly seen, the mobilisation criterion is fulfilled even during the periods of vanishing surface mobility, thus allowing a prediction of the occurrence of further mobilisation events

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