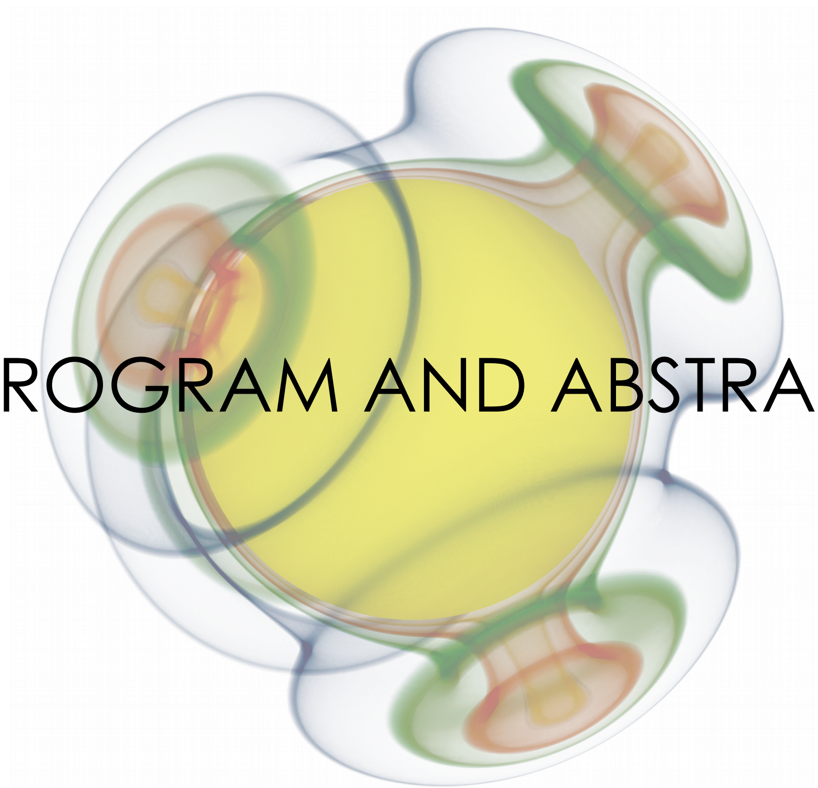
Geodynamics Workshop 2012

Wandlitz, 10 - 12 September



PROGRAM AND ABSTRACTS

Deutsche Geophysikalische Gesellschaft e.V.

Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

Helmholtz Alliance Planetary Evolution and Life

Local organizers

Doris Breuer (DLR Berlin)
Lena Noack (DLR Berlin)
Ana-Catalina Plesa (DLR Berlin)
Tina Rückriemen (DLR Berlin)
Nicola Tosi (TU Berlin / DLR Berlin)

PROGRAM

Sunday, 9th September

19:00 Social Event

Monday, 10th September

12:00 Lunch

13:45 – 14:00 D. Breuer, *Opening*

14:00 – 14:30 M. Tirone, *Why thermodynamics (and petrology) matter to geodynamic modelling*

14:30 – 15:00 H. Schmeling and G. Marquart, *The effect of hydrothermal cooling of the "square root t"- law for a cooling oceanic lithosphere using parameterized porous convection*

15:00 – 15:30 J. Dannberg and S.V. Sobolev, *Dynamics of low-buoyancy mantle plumes*

15:30 – 16:00 Coffee break

16:00 – 16:30 R. Agrusta, D. Arcay and A. Tommasi, *Lithosphere erosion and small-scale convection atop mantle plume*

16:30 – 17:00 J. Tympel, S. Schröder and S. Sobolev, *Effects of rheology, composition and surface erosion during collision of India and Eurasia*

17:00 – 17:30 J. Quinteros and S.V. Sobolev, *Why does the convergence rate between Nazca and South America decrease since the Neogene?*

17:30 – 18:00 Coffee break

18:00 – 19:00 R. Wagner, *Crater distributions and surface ages of icy satellites: comparison with the Moon, current status of impact chronologies, and problems of age dating*

19:00 Dinner

Tuesday, 11th September

09:00 – 09:30 W. Neumann, D. Breuer and T. Spohn, *Thermo-chemical evolution of asteroid 21 Lutetia*

09:30 – 09:45 T. Rückriemen, D. Breuer and T. Spohn, *Magnetic field generation in Ganymede's core in the context of the Fe-snow regime*

09:45 – 10:15 M. Laneuville, M. Wieczorek and D. Breuer, *Asymmetric thermal evolution of the Moon*

10:15 – 10:30 T. Steinke, M.Knapmeyer, F.W. Wagner and F. Sohl, *Interior structure of Mercury*

10:30 – 11:00 Coffee break

11:00 – 11:30 N. Tosi, D. Breuer, A.-C. Plesa and M. Laneuville, *Mercury's thermo-chemical evolution from numerical models constrained by MESSENGER observations*

11:30 – 12:00 B. Steinberger and S.C. Werner, *On the possible deep origin of large-scale gravity anomalies on Moon and Mercury*

12:00 – 12:30 A.-C. Plesa and D. Breuer, *The formation of stable geochemical reservoirs in the interior of Mars*

12:30 – 14:00 Lunch

14:00 – 14:30 A. Stuke, N. Tosi, A.-C. Plesa and D. Breuer, *The influence of a compositional stratification on the thermo-chemical convection in the interior of Mars*

14:30 – 15:00 R. Gassmöller and B. Steinberger, *Modelling the interaction between subducted slabs and thermo-chemical piles*

15:00 – 15:30 M.J. Beuchert and H. Schmeling, *A thermodynamically consistent model for melting of the convecting lowermost mantle: consequences for the thickness of Ultra Low Velocity Zones (ULVZs)*

15:30 – 16:00 R. Ziethe and T. Spohn, *Constraints for a solid lunar inner core*

16:00 – 16:30 Coffee break

16:30 – 17:15 Poster Presentations (3 - 5 minutes presentations of each poster)

17:15 – 19:00 Poster session

19:00 Dinner

Wednesday, 12th September

09:00 – 09:30 T. Spohn, *Planetary dynamics and habitability*

09:30 – 10:00 D. Höning, H. Hansen-Goos and T. Spohn, *A model of continental growth and mantle degassing comparing biotic and abiotic worlds*

10:00 – 10:30 S.V. Sobolev, *Origin and environmental impact of the Earth's largest intraplate magmatic events- Siberian Traps and Ontong Java Plateau*

10:30 – 11:00 Coffee Break

11:00 – 11:30 A. Davaille, S. Androvandi and A. Limare, *Thermal boundary layer instabilities in viscous fluids and planets*

11:30 – 12:00 L. Noack and D. Breuer, *Plate tectonics simulations using reduced viscosity contrasts – The simple approach?*

12:00 – 12:30 C. Hüttig, B. Moore and N. Tosi, *A novel formulation for the incompressible Navier-Stokes equations with variable viscosity, eliminating cross-derivatives*

12:30 Lunch

Departure

Poster Session

Tuesday, 10th September

C. Köstler, M.Müller, U. Walzer and J. Baumgardner, *An improved 3-D Spherical FEM formulation of Variable Viscosity*

C. Hüttig, B. Moore and N. Tosi, *A novel formulation for the incompressible Navier-Stokes equations with variable viscosity, eliminating cross-derivatives*

B. Futterer, A. Krebs, A.-C. Plesa, D. Breuer and C. Egbers, *Sheet-like and plume-like thermal flow in a spherical convection experiment performed under microgravity*

L. Noack and D. Breuer, *Scaling laws revised: employment of a rheology-dependent exponent*

H. Hansen-Goos, *A classical density functional theory for liquid Fe-FeS mixtures at high pressures*

A. Möller and U. Hansen, *Numerical parameter study of the 'metal rain scenario'*

H. Wallner and H. Schmeling, *Effect of density changes on convection flow pattern caused by enrichment in consequence of melting and emplacement*

P. Osinski and U. Hansen, *Double diffusive convection in the finger-regime – Applications to magmatic systems*

N. Tosi, D. Yuen, N. de Koker and R. Wentzcovitch, *Mantle dynamics from analytical parametrization of thermal expansivity and conductivity*

M. Mertens and U. Hansen, *Dynamically established structures at the Core-Mantle-Boundary*

E. Mulyukova, M. Dabrowski and B. Steinberger, *Numerical modelling of deep mantle convection*

T. Baumann, B. Kaus and A. Popov, *Data-driven geodynamic modeling: Constraining Stokes-rheology from surface observations*

C. Stein, J. Lowman and U. Hansen, *Mantle convection models featuring plates*

N. Müller, *Venus Express infrared surface imaging: New evidence for the mantle dynamics of Venus?*

ABSTRACTS

Lithosphere erosion and small-scale convection atop mantle plume

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2D petrological-thermo-mechanical numerical models [1] based on a finite-difference method on a staggered grid and marker in cell method is used to study the role of partial melting on the plume-lithosphere interaction. Mantle plumes are traditionally proposed to play an important role in lithosphere erosion. Seismic images beneath Hawaii show a lithosphere-asthenosphere-boundary (LAB) up to 50 km shallower than the surroundings [2]. However, numerical models show that unless the plate is stationary the thermo-mechanical erosion of the lithosphere does not exceed 30 km [3]. A homogeneous peridotite composition with a Newtonian temperature- and pressure-dependent viscosity is used to simulate both the plate and the convective mantle. A constant velocity, ranging from 5 to 12.5 cm/yr, is imposed at the top of the plate. Plumes are created by imposing a thermal anomaly of 150 to 350 K on a 50 km wide domain at the base of the model (700 km depth); the plate right above the thermal anomaly is 40 Myr old. Partial melting is estimated using batch-melting curves for anhydrous melting as a function of pressure [4]. We model the progressive depletion of peridotite and its effect on partial melting by assuming that the melting degree only strictly increases through time. Melt is accumulated until a porosity threshold is reached and the excess melt is extracted. The rheology of the partially molten peridotite is determined using viscous constitutive relationship based on a contiguity model, which enables to take into account the effects of grain-scale melt distribution [5]. Above a threshold of 1%, melt is instantaneously extracted. The density varies as a function of partial melting degree and extraction. We analyze the kinematics of the plume as it impacts a moving plate, the dynamics of time-dependent small-scale convection (SSC) instabilities developing in the low-viscosity layer formed by spreading of hot plume material at the lithosphere base, and the resulting thermal rejuvenation of the lithosphere. The onset time and the vigor of SSC and, hence, the new equilibrium thermal state of the lithosphere atop the plume wake depends on the Rayleigh number (Ra) in the unstable layer at the base of the lithosphere, which is controlled by the temperature anomaly and rheology in the plume-fed layer. For vigorous, hot plumes, SSC onset times do not depend on plate velocity. For more sluggish plumes, SSC onset times decrease with increasing plate velocity. This behavior is explained by differences in the thermal structure of the lithosphere, due to variations in the spreading behavior of the plume material at the lithosphere base. Reduction of the viscosity in partial molten domains and decrease in density of the depleted residuum enhance the vigor of small-scale convection in the plume-fed low-viscosity layer at the lithosphere base, leading to more effective erosion of the base of the lithosphere.

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Data-driven geodynamic modeling: Constraining Stokes-rheology from surface observations

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We follow the approach of combining geodynamical models with inverse modeling techniques to perform inversions of surface observations to better understand the rheology and dynamics of the lithosphere.

Since forward models are computationally intensive, parallelisation is important in this context. We use a massively parallel program-layout to perform the inversion, which consists of two parts: First, a parallel direct search technique (Neighbourhood algorithm, [1]), which preforms the inversion and controls several forward modeling jobs using different rheologies at the same time. The respective misfit between modeled data and observed data drives this process. Second, parallel forward modelling, which involves solving the Stokes problem and modelling of the gravity field. For solving the Stokes problem, we employ a 3D finite difference staggered grid mechanical Stokes code (FDSTAG) as part of the Lithospheric and Mantle Evolution Model (LaMEM).

In this work test the approach with synthetic setups (as fig. 1). We use gravity signals and surface (Stokes) velocities measured on top of the models as observations. Furthermore, we explicitly test how model resolution affects the inversion results.

Funding was provided by the European Research Council under the European Community's Seventh Framework Program (FP7/2007-2013) / ERC Grant agreement #258830.

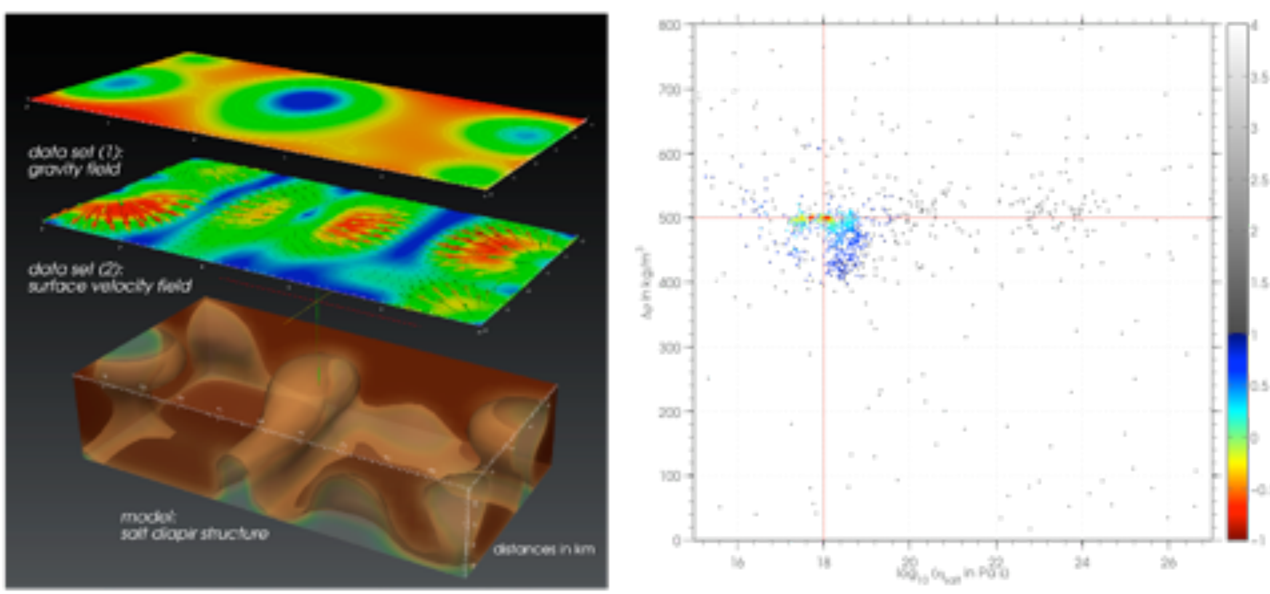

Figure 1. Left: Synthetic setup of salt diapirs together with its gravity field and surface Stokes-velocity field that is used to perform the inversion. Target parameters are viscosities and density contrasts. Right: Forward models vs. misfit - represented as a component view of the parameter space. The parameters, which represent the reference data, are illustrated as red lines.

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A thermodynamically consistent model for melting of the convecting lowermost mantle: consequences for the thickness of Ultra Low Velocity Zones (ULVZs)

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Ultra Low Velocity Zones (ULVZs) are relatively thin regions directly above the Core-Mantle Boundary (CMB) that exhibit marked seismic P- and S-velocity reductions. A viable explanation for the reduction is the presence of melt fractions within ULVZs. Since melt was found to be denser than solid in melting experiments at lowermost mantle pressures, partially molten ULVZs should exhibit negative buoyancy. Based on published experimental data, we present a thermodynamically consistent melting model for the formation of ULVZs as partially molten regions above the CMB and apply the resulting melting curves and latent heat effects in fully dynamic, regionally constant viscosity convection simulations of the lowermost mantle. We find that the height of the ULVZs depends only moderately on Rayleigh number but strongly decreases with increasing excess density of melt over solid. The models predict excess density of at least 1% to explain observed heights. The combined effect of topography and latent heat of melting reduces the vigor of mantle convection only very slightly, while if combined with a decrease of the ULVZ viscosity, mantle flow velocities are significantly enhanced near the CMB, and overall mantle temperatures are notably increased. ULVZ heights are found to be insensitive to ULVZ viscosity (for the range isoviscous to 1/100 the viscosity of the ambient mantle).

Dynamics of low-buoyancy mantle plumes

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According to widely recognized models, large igneous provinces (LIPs) are generated by the massive melting caused by a plume approaching the base of the lithosphere [1]. However, the details of this process are still under debate: Classical models of purely thermal plumes predict a kilometer-scale surface uplift above the rising plume head [e.g. 2]. On the contrary, several paleogeographic and paleotectonic field studies indicate significantly smaller surface uplift during the development of many LIPs, such as the Siberian Traps, Deccan Traps and Ontong Java Plateau.

Recently, it was shown [3] that a thermo-chemical plume, which contains a fraction of 10-20% of eclogitic material derived from recycled oceanic crust, explains the observations much better. Due to the high eclogite density, these thermo-chemical plumes have lower buoyancy and thus generate much smaller surface uplift than predicted by classical models. Nevertheless, recent studies are in two dimensions and include only the upper mantle [3], assume a constant density difference between peridotite and eclogite [4] or neglect phase transitions [5]. Therefore, the question remains if such a low-buoyancy plume with a realistic excess temperature containing 10-20% of eclogite can rise from the core-mantle boundary to the base of the lithosphere or not and which conditions are required for this ascent.

In this work we use a two-dimensional axisymmetric finite-element model that includes 410 km and 660 km phase boundaries as well as depth-dependent density difference between pyrolite and the MORB material. We employ a modified version of the Citcom code [6,7] that includes mantle compressibility, a tracer-ratio method to incorporate the two chemical components and strongly temperature- and depth-dependent viscosity.

We have determined the conditions for the ascent of a low-buoyancy plume through the whole mantle: They include an initial temperature contrast of 450 − 500 K between plume and adjacent mantle, a high plume volume, an adiabatic, or better subadiabatic, mantle temperature profile and a chemical boundary layer in the lowermost mantle. These conditions will allow for the ascent of a thermo-chemical plume with 15% of eclogite or more, causing a surface uplift on a scale of hundreds of meters as the plume approaches the base of the lithosphere. In addition, we show that a plume containing a too high fraction of recycled oceanic crust to rise to the lithosphere more likely ponds at a depth of 300 − 400 km than at the 660-km phase boundary. This barrier is caused by the high eclogite density in this region. Our results are consistent with some recent seismic tomography models, which do not show large plume heads, but wide plume tails in the lower mantle with radii of at least 300 − 400 km [8].

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Thermal boundary layer instabilities in viscous fluids and planets

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We study the development and local characteristics of thermal boundary layer (TBL) instabilities in newtonian fluids whose viscosity depends strongly on temperature, for Rayleigh numbers up to 10^8, Prandtl numbers up to 10^6, and viscosity ratios across the tank up to 4000 [1]. We use thermochromic liquid crystals (TLC) slurries in combination with PIV to obtain simultaneously the temperature and the velocity fields (fig.1).

The temperature-dependence of viscosity introduces a strong asymmetry in the TBLs. At high Rayleigh numbers, hot instabilities develop as mushroom-shaped plumes while cold instabilities develop as thin fingers. Howard's phenomenological model [2] describes well the hot instabilities formation: the TBL first grows by conduction until the local Rayleigh number calculated across it reaches a critical value Ra_c. Then a plume develops and drains the TBL. If the latter is completely drained, the plume detaches. Otherwise, plumes merge with their neighbours. Cold more viscous instabilites only disappear by merging. Plume lateral motions and merging occur along networks of ridges localized at the edges of the TBLs. Scaling laws are derived for the plume characteristics temperature and velocity structures. They are compared with those of plumes issued from a point heat source [3]. In particular, both types of plumes mainly sample the TBLs from which they are issued, and very little entrainment during their ascent is reported.

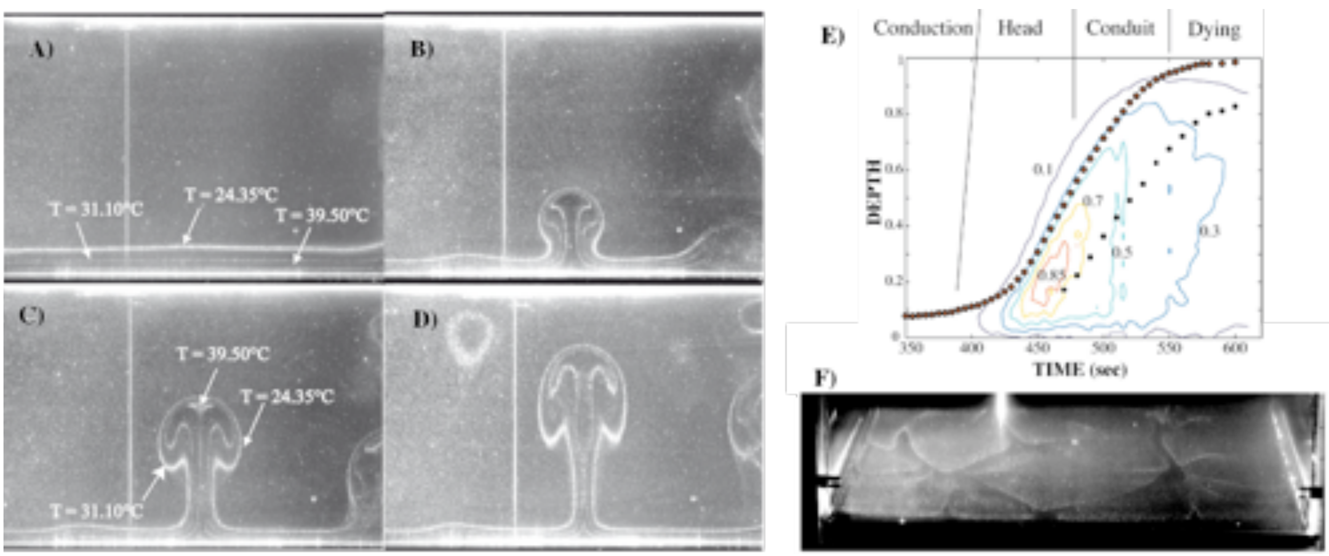

Figure 1: Evolution of the growth of hot instabilities in a layer of sugar syrup. The fluid, initially at 21.9∘C, is heated from below and cooled from above. Ra = 8.0 10^5. The horizontal bright lines at the bottom of the tank are 3 different isotherms. The vertical line is a thermocouple probe. A) t = 560s. Construction of the TBL where heat is transported by conduction. B) t = 730s. A mushroom-shaped hot plume rises from the TBL. C) t = 790s. The plume rises, taking hot material from the TBL which shrinks. The conduit width is about one-third of the head one. D) t = 830s. The plume continues to rise and cools. E) Vertical velocity along the plume axis as a function of depth and time for Ra = 6.0 10^6. The numbers give the isocontours as fraction of the maximum vertical velocity. The dots show the top, and the squares the bottom of the plume head given by the isotherm 24.35∘C. F) Horizontal cross section of the same tank just at the upper edge of the bottom hot TBL. Ridges are clearly seen, on which thermal plumes travel. They will cross the whole tank only when at the junction of those ridges

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Sheet-like and plume-like thermal flow in a spherical convection experiment performed under microgravity

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In mantle dynamics research, especially the laboratory experiments in rectangular geometries have the character of 'exploring new physics and testing theories' [1]. We introduce our *spherical* experiments on electro-hydrodynamical driven Rayleigh-Bénard convection that have been performed either with temperature-independent properties of the fluid, called 'GeoFlow I', or with temperature-dependent properties, called 'GeoFlow II'. To set up a self-gravitating force field with radial directed buoyancy, we use a high voltage potential between the inner and outer boundaries and a dielectric insulating liquid. Additionally, we perform the experiment in the microgravity conditions of the ISS [2, 3]. In comparison to the research mentioned above, it strongly simplifies the fluid dynamical aspects of the geophysical motivation (i. e. a weak temperature-dependent viscosity resulting in a viscosity contrast of at most 2). However, it delivers the possibility of including non-linear properties and related hydrodynamic instabilities in spherical geometry also in comparison to only numerically described fluid flow patterns.

An important finding is the difference in the flow pattern for our two experiments. We see a sheet-like thermal flow, if the physical properties of the fluid are not varying with temperature - a result from 'GeoFlow I'. If we use a liquid with varying (electro-hydrodynamic) volume expansion and temperature-dependent viscosity (GeoFlow II), we observe a plume-like dominated flow. As in [4], where the authors give an illustrated overview on relevant numerical and experimental contributions in 3D cartesian box to classify the convective patterns depending on the Rayleigh number at the top and bottom boundaries, we show a regime diagram of the various numerically assessed viscosity regimes in spherical geometry including our unique experimental data. We will discuss the similarities and the differences between the GeoFlow experiments and the numerical simulations in terms of convective patterns.

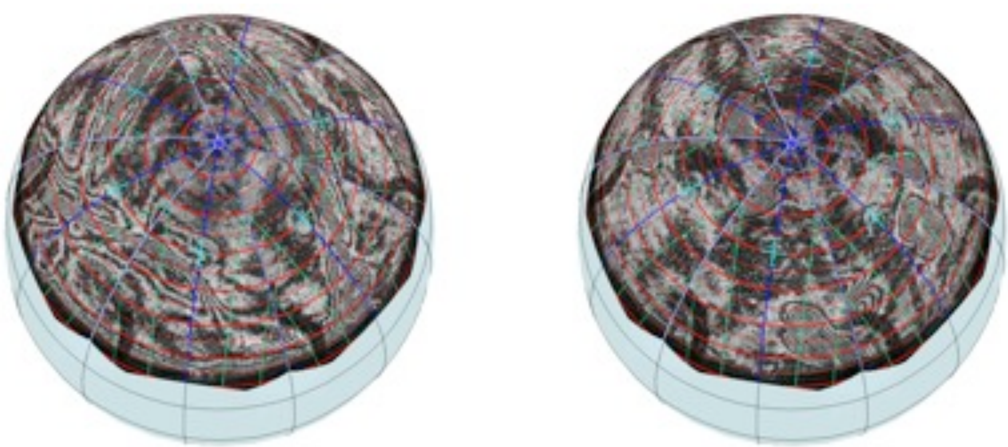

Figure 1. Sheet-like thermal flow in the GeoFlow I spherical experiment with silicone oil of temperature-stable properties (left, $Ra_E=1.17\cdot 10^6$) and plume-like flow in the GeoFlow II experiment using a fluid with temperature dependent viscosity and volume expansion (right, $Ra_E=1.87\cdot 10^6$).

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Modelling the interaction between subducted slabs and thermo-chemical piles

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Based on the reconstructed eruption locations of volcanic products (Large Igneous Provinces and kimberlites) it has recently been proposed that most plumes get generated at the steep edges of the large low shear-velocity provinces (LLSVPs) and that these edges have not discernibly moved over the past few hundred Myr [1]. Following this idea, it is of specific importance to investigate the influences on the movement of these edges, which would determine the surface plume positions. Independent of this argumentation, the position and shape of the LLSVPs are a main factor in mantle convection and should be reproduced by models which show an earth-like convection pattern. In current models this is done in a rather qualitative way, with a focus either only on position or only on shape [2,3].

In our 3D geodynamic numerical models of the global mantle we combine several of the improvements to mantle convection models made during the last few years: A complex plate reconstruction is used as a kinematic boundary condition [4]. A self-consistent thermodynamic material model for basalt and harzburgite is used to derive a temperature- and pressure-dependent database for parameters like density, thermal expansivity and specific heat [5]. Furthermore, we use a viscosity profile derived from surface observations and mineral physics constraints [6]. We use the model to clarify the influence of surface motions on processes at the CMB.

The results of our models show not only that it is possible to generate LLSVPs at the actual position and with a similar shape compared to what is observed through seismic tomography, but even to recreate plumes at positions that match many of today's hot spots. We will also show the influence of boundary and initial conditions. Furthermore, we will discuss the possibility to create a model matching seismic tomography and plume positions without a chemical boundary layer at the core-mantle boundary.

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A classical density functional theory for liquid Fe-FeS mixtures at high pressures

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Modeling the thermal evolution of a planet requires information about material properties under extreme conditions, such as high temperatures and pressures. Experimental data is necessary to inform our assumptions that enter evolution models and to validate theoretical results from first principles computations. The available data from shock experiments and high pressures cells are valuable in this respect. Here, we focus more closely on one particular aspect of planetary evolution, namely the properties of liquid iron cores. Understanding the thermal evolution of the core is crucial in order to describe dynamo action throughout a planet's history, which in turn is relevant for questions of habitability. We review the experimental data relevant for liquid iron cores with varying sulfur content. For the pressure range 2 GPa to 8 GPa, equations of state have been thoroughly measured. However, the data is spread over various publications and is sometimes contradictory.

In order to provide a useful tool for modelers of liquid iron cores, we condense the available data into a classical density functional theory (DFT), which is simple but reproduces the measurements very well. The covered range of sulfur content lies between 0 to 50 atomic percent and pressures are between 2 GPa to 8 GPa. The approach can be extended to higher pressures at the expense of accuracy in the intermediate pressure regime. We describe how the DFT can be used to calculate the radial profiles of density and sulfur content in core models and present some results. Considering that there is some contradiction in the published data, we devise two different free energy functionals, each applying to one of the measured sets. We assess how the differences between the two functionals affect the density profiles that result from our DFT.

A model of continental growth and mantle degassing comparing biotic and abiotic worlds

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While examples for interaction of the biosphere with the atmosphere can be easily cited (e.g., production and consumption of O_2), interaction between the biosphere and the solid planet and its interior is much less established. It has been argued (e.g., Rosing et al. 2006; Sleep et al, 2012) that the formation of continents could be a consequence of bioactivity harvesting solar energy through photosynthesis to help build the continents and that the mantle should carry a chemical biosignature. We present an interaction model that includes mantle convection, mantle water vapor degassing at mid-oceanic ridges and regassing through subduction zones, continental crust formation and erosion and water storage and transport in a porous oceanic crust that includes hydrous mineral phases. The mantle viscosity in this model depends on the water concentration in the mantle. We use boundary layer theory of mantle convection to parameterize the mantle convection flow rate and assume that the plate speed equals the mantle flow rate. The biosphere enters the calculation through the assumption that the continental erosion rate is enhanced through bioactivity, and through an assumed reduction of the kinetic barrier to diagenetic and metamorphic reactions (e.g., Kim et al. 2004) in the sedimentary basins in subduction zones that would lead to increased water storage capacities. We further include a stochastic model of continent-to-continent interactions that limits the effective total length of subduction zones. We use present day parameters of the Earth and explore a phase plane spanned by the percentage of surface coverage of the Earth by continents and the total water content of the mantle. We vary the ratio of the erosion rate in a postulated abiotic Earth to the present Earth, as well as the activation barrier to diagenetic and metamorphic reactions that affect the water storage capacity of the subducting crust. We find stable and unstable fixed points in the phase area where the net degassing and continental growth rates are zero. Many of the parameter combinations result in one stable fixed point with a completely dry mantle that lacks continents altogether and a second stable fixed point with a continent coverage and mantle water concentration close to that of the present Earth. In addition, there is an unstable fixed point situated between the two. In general, the abiotic world has a larger zone of attraction for the fixed point with a dry mantle and no continents than the biotic world. Thus a biotic world is found to be more likely to develop continents and a have wet mantle. Furthermore, the biotic model is generally found to have a wetter mantle than an abiotic model. Through the effect of water on the mantle rheology, the biotic world would thus tend to be tectonically more active and have a more rapid long-term carbon silicate cycle.

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A novel formulation for the incompressible Navier-Stokes equations with variable viscosity, eliminating cross-derivatives

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We present a reformulation of the incompressible Navier-Stokes equations with variable viscosity. By including explicitly the incompressibility constraint into the deviatoric stress tensor, we show that cross-derivatives of the velocity field vanish, making our approach useful for co-located discretization techniques on both structured- and unstructured grids. This simplification naturally leads to the elimination of the trace in the stress tensor, which is important when using sequential mass/momentum iterations to enforce incompressibility. A trace-free stress tensor also removes a typical source of net-rotation for simulations employing free-slip boundary conditions in spherical geometry. We implement the new scheme as a modification of an existing mantle-convection code, which we benchmark against analytical solutions of the Stokes problem in a spherical shell with constant and radially dependent viscosity, and time-dependent thermal convection, illustrated in figure 1, at infinite Prandtl number with large viscosity contrasts, following [1].

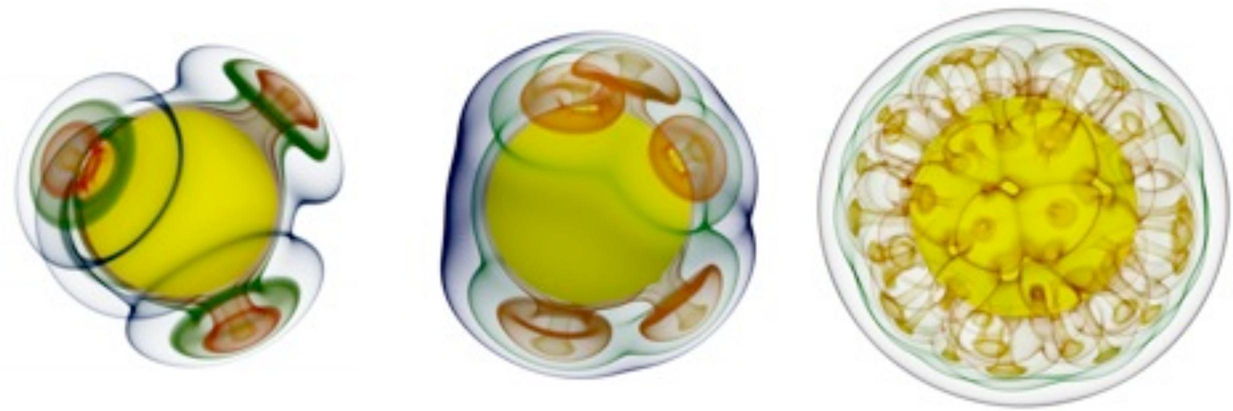

Figure 1: Three different benchmark cases, based on Ra@T=0.5 = 7000, with a viscosity contrast from left to right: 100 (case A4), 10^4 (A6) and 10^7 (A9).

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An improved 3-D spherical FEM formulation of variable viscosity

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The strong spatial variations in the rheology of the Earth's interior pose one of the main challenges to realistic numerical convection models. Apart from the lithosphere, most of the rheology is incorporated into the models by means of an effective viscosity. Despite our increasing knowledge of the detailed composition and structure of the mantle, estimates of local viscosities often differ by several orders of magnitude between various model assumptions. However, due to its exponential dependency on temperature, a lateral viscosity variation of four orders of magnitude is generally assumed. This variation is, apart from show case, rarely incorporated into complex thermal convection and evolution models of the Earth's mantle.

We improve the variable viscosity formulation in the 3-D spherical mantle convection code Terra [1] by changing its discretization in the FEM operators. We switch from a node-based to a cell-based formulation and apply a physically consistent momentum operator using cell-averaged viscosities. Because of its exponential dependence on the linearly varying temperature, we average viscosity cell-wise harmonically from the nodal values. With the previous formulation in Terra being optimized to get maximum computational efficiency, the most significant code change is the switch from nodal based to triangle based momentum operator parts on the sphere, which is nowadays done in most FEM codes. While the computational efficiency is retained as much as possible, the cost for applying the momentum operator increases by a factor of 3.5. However, a physically consistent formulation on all grid-levels could pay off for this, especially if we get a better convergence rate of the multigrid algorithm. We show first results of the new implementation regarding accuracy and convergence.

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Asymmetric thermal evolution of the Moon

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The Moon possesses a clear dichotomy in geological processes between the neaside and farside hemispheres [1]. The most pronounced expression of this dichotomy is the strong concentration of both radioactive heat sources [2,3] and mare basalts on the nearside hemisphere in a region known as the Procellarum KREEP Terrane (PKT). The very strong correlation between thorium concentration and mare basalts suggests a genetic link between the two (Fig. 1). However, Apollo samples and remote sensing data suggest that the volumetrically insignificant mare basalts are not the direct carrier of the heat producing elements in the PKT and that these elements are likely concentrated in the underlying crust [1]. If the entire crust below this region were enriched in heat producing elements, it could have influenced the complete lunar thermal history.

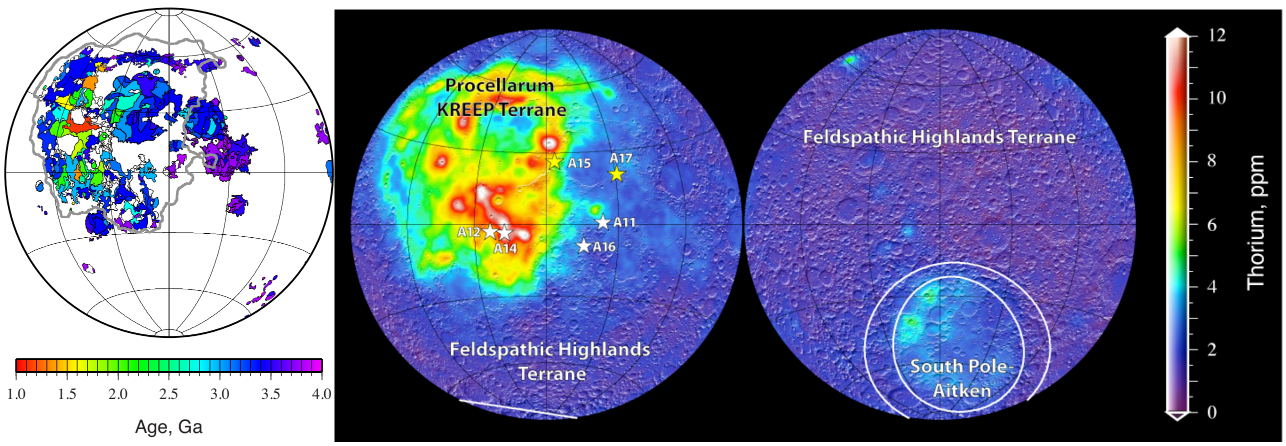

Figure 1. (Left) Maria ages map using data from [3]. (Right) Thorium concentration map.

The question of the influence of the PKT on the lunar evolution has already been asked [5,6]. Considering a thick KREEP layer directly below the PKT in a simple conduction model, [5] showed that partial melting of the underlying mantle is inevitable and that volcanism should be active for most of the lunar history. These results were confirmed by a similar study [6]. In this project, we compute 3D thermochemical evolution of the Moon including the PKT anomaly to test its consequences against observations and understand its implications.

Key results have been found. In addition to confirming that heat source localization leads to asymmetrical melt production, we predict that (1) a thermal anomaly is still present today below the PKT and (2) such a peculiar thermal evolution would have influenced the cooling history of the core. The first result will, when taken into account, change crustal thickness models. The unobserved gravity low in this region has to be compensated partly by dense basalts erupted at the surface and partly by a comparatively thinner crust in the region. The second point directly influences the magnetic history of the Moon. We find that warming up of the core can occur after 1 to 2 Ga and therefore stop any compositional dynamo active at that time and help match paleomagnetism observations.

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Dynamically established structures at the Core-Mantle-Boundary

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Mantle convection largely determines the structure and the dynamics of the Earth. Like other strongly nonlinear transport processes, convection in the Earth's mantle acts to establish structures of different scales, particularly in the boundary layers of the convecting systems. While the lithosphere forms the upper boundary layer of the mantle convection system, the Core-Mantle-Boundary (CMB) is usually identified as the lower boundary layer. Seismological studies have demonstrated that a whole spectrum of structures seems to exist at the CMB (for a summary see [1]).

In this study we focus on patterns, as created by convection, at the CMB. In particular we want to analyze line-like structures, which have been numerically and experimentally investigated by several authors in the context of turbulent convection (c.f. [2] and references in it).

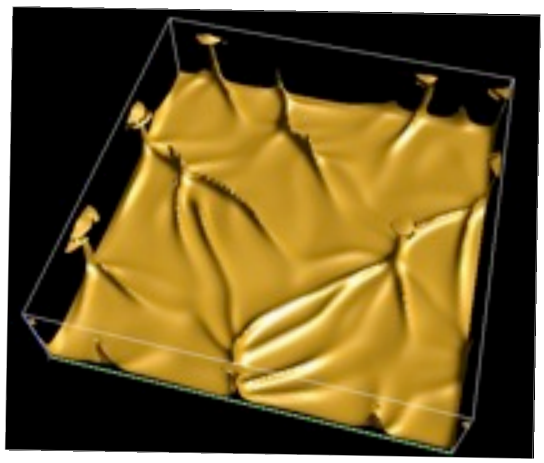

Figure 1. Isosurface of the temperature for a case with temperature- and depth-dependent viscosity showing line-like structures.

These structures are intrinsic features of convection. They have a finite height, show a strong increase in the temperature and the vertical velocity and form a kind of flow channels. In these channels hot material flows along the bottom boundary.

We want to explore these structures with respect to their geophysical significance. Especially we want to investigate, whether these features can account for structures at the CMB, as revealed in seismological studies.

A finite volume code is used in order to integrate the equations, describing thermally driven convection of an incompressible Boussinesq-Fluid with infinite Prandtl number. Realistic features of mantle convection, like strongly temperature- and depth-dependent viscosity, internal heating and a variable thermal expansion coefficient are considered in our model.

We present first results of our work which show that these structures can be observed over a wide range of parameters. We have analyzed the features of the structures and present their geometrical properties.

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Numerical parameter study of the 'metal rain scenario'

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Today it is widely accepted that the Earth experienced a period of extended mantle melting 4.5 billion years ago. The most likely explanation is the 'Giant Impact hypothesis'. A consequence of such a giant impact is the formation of a magma ocean covering the whole Earth with a depth of about 1000km. In this magma ocean the first steps of core formation can take place. Iron entrapped in the mantle will separate from the silicate magma and form small metal droplets that fall, due to their higher densities, to the bottom of the magma ocean like metal rain drops. This is the so called 'Metal Rain Scenario'. The behavior of the falling metal droplets is strongly dependent on the influence of the surrounding magma. Due to its low viscosity, this magma ocean was not only strongly convecting but also experienced the influence of strong rotation. The resulting fluid flows will have altered the settling of the iron particles and can prevent them from falling straight to the bottom of the magma ocean.

Because the exact parameters of the magma ocean are unknown and all assumptions lead to parameters that are far beyond anything that is computational and experimentally feasible today, it is important to develop general principles for the behavior of the iron droplets.

Previous studies show that especially at the equatorial region of the Earth the droplets can show different settling dynamics depending on the rotation rate of the system. At low rotation rates the droplets will fall with nearly Stokes' velocity through the magma and form a pond at the bottom. With increasing rotation rate the droplets at the equator can stay suspended, and other phenomena, like temperature layering, can occur in this scenarios. If the iron droplets stay suspended in a magma ocean over a longer time period, perhaps even during the freezing process this will have strong consequences for the later differentiation processes in the Earth's mantle. But it is not quite clear in which parameter ranges the different phenomena can develop and if it is possible to interpolate their occurrence to the much higher parameter values of the real magma ocean.

We use a 3D-Cartesian numerical model with finite Prandtl number, based on a finite volume discretisation. This is combined with a discrete element method for the simulation of granular material. With this combination the simulation of the iron droplets in a strongly convecting and rotating environment is possible. This numerical model gives us the possibility to study a wide range of possible scenarios and systematically explore the parameter space of the magma ocean. Here our numerical parameter study focuses on the effect of the rotation on the iron droplets to derive possible scenarios for the settling history of the metal rain.

Venus Express infrared surface imaging: New evidence for the mantle dynamics of Venus

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The combination of Magellan radar altimetry and infrared imaging of the Venus cloud cover on the nightside is indicative of surface emissivity at 1µm wavelength [1]. Surface emissivity constrains surface mineralogy and [1] propose based on a flyby Galileo NIMS image that the highlands of Venus have a felsic composition comparable to continental crust on Earth. The formation of felsic continents requires recycling of hydrated crust into the mantle. Any felsic crust on Venus must therefore have been formed before the atmosphere entered the present dry state, possibly in the first few 100 Ma [2]. Infrared mapping by VIRTIS on Venus Express supports this hypothesis [3]. Repeated imaging shows that the possibly felsic crust is limited to the tessera dominated plateau highlands. Tessera is tectonically deformed terrain that generally predates any volcanic terrain. In the context of mantle dynamics this hypothesis of tessera plateaus as continents requires the change from a mobile lid or plate tectonic regime in the very early history to the present stagnant lid regime. The tesserae (10% of the planet's surface) must have survived the volcanic resurfacing in the meantime. Whether this resurfacing was caused by episodic surface mobilization or continuing magmatism within the stagnant lid regime is still unclear. The tectonic structure of tesserae highlands is however consistent with the stresses exerted on a buoyant continental crust during episodic mobilization of the lithosphere [4].

Possibly relevant to present day mantle dynamics is the mapping of the broad topographic swells thought to be hotspots caused by deep mantle plumes. VIRTIS has imaged only 3 out the 10 hotspot regions but all of them appear to have less weathered and thus possibly recent lava flows [5]. The number of hotspots on Venus is similar to that of Earth and is used by [6] as a constraint on convection pattern. The ongoing magmatism constrains lithospheric thickness and mantle temperature.

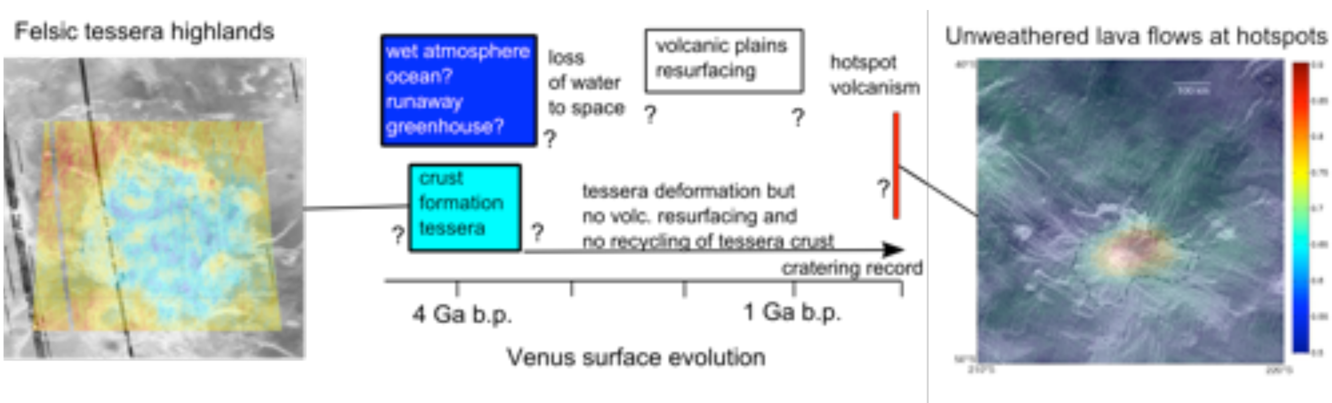

Figure 1. Hypothetical scenario of a surface evolution resulting in the emissivity anomalies observed by VIRTIS. This scenario implies crustal recycling in the early history, survival of at least 10% of crust over 4 Ga, a present mantle convection pattern with a similar number of major plumes as Earth and ongoing magmatism.

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Numerical modeling of deep mantle convection

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One of the most robust results from tomographic studies is the existence of two antipodally located Large Low Shear Velocity Provinces (LLSVPs) at the base of the mantle. Reconstructions of the eruption sites of large igneous provinces (LIPs), hotspot volcanoes, and kimberlites of the last 350 Ma have shown that these project radially downward to the margins of the LLSVPs [1]. This has led to inferences that plumes of arguably deep origin are generated from the margins of the LLSVPs, and that the LLSVPs are stable and long-lived. The negative correlation between the bulk sound velocity and the shear velocity within the LLSVPs, as well as the sharp boundaries between the LLSVPs and surrounding mantle, suggest that these anomalies are not of purely thermal origin.

Numerous numerical and experimental studies have investigated the influence of physical parameters of the heterogeneity in the lower mantle, e.g. density, on its stability and survival time. Initial distribution of temperature and the anomalous material varies between different models. The initial distribution of the chemical field depends on the assumption about the origin of the anomalous material, which is currently debated. It generally falls into two categories: primitive layer at the base of the mantle, which formed early in the Earth's history [2], and/or segregation of the subducted MORB over time [3]. Recent studies have also proposed 'leaking' of iron from the outer core into the lower mantle as a possible mechanism for generating an anomalously dense heterogeneity at the base of the mantle [4].

In the present study, we investigate the importance of the initial distribution of temperature and composition on the evolution of the thermochemical system. We have developed a two-dimensional FEM code to model thermal convection in the deep mantle with presence of chemical heterogeneities. Aspects of the numerical tools, e.g. the spatial resolution, that are necessary in order to make reliable predictions are the focus of the presented work.

The results of this study may potentially shed light on which thermal and compositional structures are most likely to survive over the long term history of the Earth.

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Thermo-chemical evolution of asteroid 21 Lutetia

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The early thermal evolution and differentiation of the asteroid 21 Lutetia has been studied using new data obtained by the Rosetta flyby in 2011. We have used the thermal evolution model by [1], which includes accretion [2], sintering due to hot pressing [3], associated changes of the material properties (such as density and thermal conductivity), melting, and the convective heat transport and differentiation by porous flow. Our work provides constraints on the macroporosity φ_m, the internal structure and the formation time of Lutetia.

To account for the location of formation and the outward migration of Lutetia, we have modified the thermal evolution and differentiation model by [1] with a radiation boundary condition and a ambient temperature in the protoplanetary nebula, which depends on the time t since the formation of the calcium-aluminum rich inclusions (CAIs) and on the distance $d(t)$ to the proto-sun. The initial material properties (such as intrinsic density, mass fractions of the components iron and silicates, abundances of the radiogenic heat sources ^{26}Al and ^{60}Fe) are calculated assuming enstatitic nature of the primordial material. The body accretes assuming late runaway material accumulation at the time t_0 relative to the CAI formation within t_{accr}=0-1 Ma at ≈1.4 AU and to migrate to 2.4 AU within 0.2 Ma due to the migration of Jupiter[4,5]. The initial radius 1 km and the theoretical final radius D=60 km (both corresponding to entirely compacted material) have been used. The latter is the radius of the smallest sphere Lutetia fits into. The above radius and the initial porosity 0.4 of the accreting material result in the potential radius R≈71 km at the end of accretion if no compaction takes place. The heat transport by melt segregation is modeled assuming melt flow in porous media and by supplementing the energy balance equation with additional advection terms. The advection terms for iron and silicate melts are calculated using the Darcy flow equation.

For different values of the macroporosity φ_m the initial material properties such as density, composition, abundances of the radiogenic heat sources are calculated assuming enstatitic origin of Lutetia's primordial material. We have varied the onset time of accretion and the accretion duration to study the compaction, partial differentiation and resulting internal structure of Lutetia. The final bulk density arising from our models have been compared to the observed bulk density in order to constrain the macroporosity, the onset time of accretion and accretion duration and the internal structure.

We obtain a number of possible compaction and differentiation scenarios consistent with the properties of the present-day Lutetia. The most probable macroporosities for a Lutetia-like body with the bulk density of 3400 kg m^{-3} are $\varphi_m \geq 0.04$. Small changes can be expected if the error of ±300 kg m^{-3} in the bulk density is considered. Depending on the adopted value of φ_m, the formation times range from the formation contemporarily with the formation of the CAIs for $\varphi_m = 0.04$ to 7 Ma after the formation of the CAIs for $\varphi_m = 0.25$. We find a differentiated interior, i.e. an iron-rich core and silicate mantle, only for a rather narrow interval between $0.04 \leq \varphi_m < 0.06$ with the formation times between 0 Ma and 1.8 Ma after the CAIs. In that case, the size of the core is at most 25 km and the thickness of the mantle amounts to approximately the same value. Regardless of melting and partial differentiation no melt extrusion through the porous layer is likely, which is consistent with the lack of basalt at the surface of Lutetia. For higher values of φ_m, e.g. $\varphi_m \geq 0.6$, an iron-silicate differentiation is not possible but the interior is sintered / compacted below a porous outer layer.

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Scaling laws revised: employment of a rheology-dependent exponent

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To assess the interior and surface dynamics of large terrestrial planets, often convection simulations are used in 2D or 3D geometry. These simulations typically use a reduced viscosity contrast, for example by employing either a reduced activation energy or an increased surface temperature in the viscosity law or by using the Frank-Kamenetskii approximation of the viscosity. Furthermore, parameterized model are often used to investigate large parameter spaces. However, these models are based on scaling laws, which are typically derived for small Rayleigh numbers and predefined viscosity contrasts (typically 10^5 to guarantee a stagnant lid convection).

In this study, we therefore concentrate on the dependence of the scaling laws on rheology parameters and resulting viscosity contrast (influenced either by a change in surface temperature, activation energy or viscosity approximation). First results of our parameter study show already that the scaling of lid thickness, convective stress below the lid, root-mean-square velocity and Nusselt number leads to different scaling parameters depending on the viscosity contrast. A formulation following

(1) $Nu \sim \vartheta^{\alpha} Ra^{\beta}$

for varying viscosity contrasts (with $\vartheta = \ln(\eta_{surf}/\eta_i)$ from surface to interior viscosity) and Rayleigh numbers but fixed exponents $\alpha\beta$ does not hold. Instead, we found that the exponent of the Rayleigh number itself depends on the viscosity contrast ($\beta(\vartheta)$). We determine a universal scaling that fits to all viscosity contrasts investigated.

Figure 1 shows the predicted scaling of the lid thickness compared to the actual lid thickness for a case with a constant exponent β compared to an exponent depending on activation energy (and analogously non-dimensional surface temperature) $\beta(E',T'_0)$. In the left panel, it can be observed that the predicted values differ from the actual lid thickness for larger viscosity contrasts. In the right panel, for all viscosity contrast above 10^5 the predicted values match the actual values; for the smallest viscosity contrast no perfect stagnant lid was obtained.

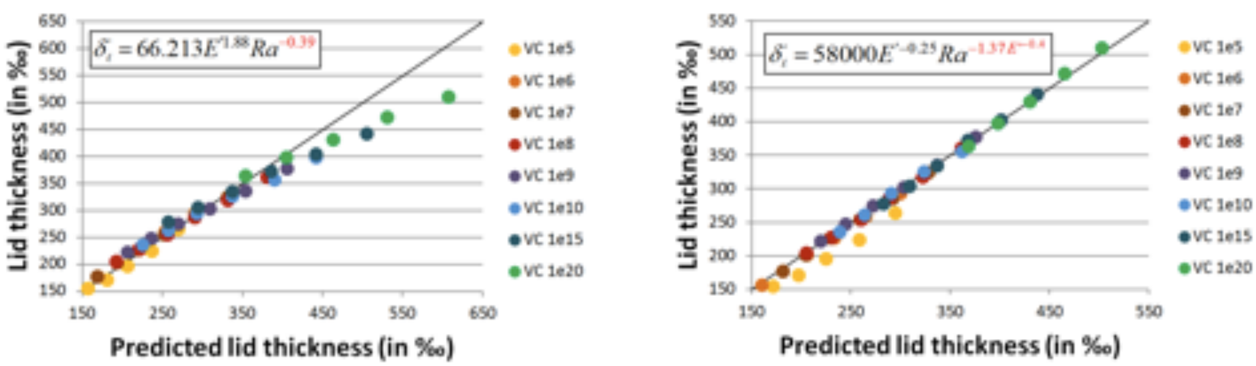

Figure 1. Standard (left) and new scaling law (right) for the lid thickness for variations in activation energy leading to different viscosity contrasts (VC). Taken from [1].

Our investigations show, that the scaling laws, which have been derived in past studies, have to be adapted accordingly to larger viscosity contrasts, to allow for realistic predictions of quantities like the Nusselt number, lid thickness, mantle velocity and convective stresses for Earth-like rheological parameters.

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Plate tectonics simulations using reduced viscosity contrasts – The simple approach?

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In the last decades, more and more studies focused on the simulation of plate tectonics for Earth and other terrestrial planets inside and outside the solar system. But only the recent development of new robust codes (e.g. GAIA [1] or RHEA [2]) and the usage of super-computers shifted the investigation of planetary mantles into more realistic regimes.

One of the problems that many codes still cannot handle is the large viscosity contrast (global or local cell-to-cell contrasts) expected for terrestrial planets and the viscosity is typically simplified [3]. On Earth, the expected contrast varies with 10 or more orders of magnitude. On planets with higher mantle temperatures (e.g. as can be expected for young super-Earths), this viscosity contrast may be even higher with steeper viscosity gradients at the lower boundary of the lithosphere.

To solve this problem one can either use a larger non-dimensional surface temperature in the Arrhenius viscosity law (or analogously a smaller activation energy) or linearize the exponent of the viscosity, leading to the so-called Frank-Kamenetskii approximation. Several codes use one of these two approximations to be able to simulate terrestrial planets and try to investigate the trend of the likeliness of processes like plate tectonics, depending on factors as surface temperature, internal heating, or mantle thickness.

However, our findings propose that the trends observed with these viscosity approximations differ from the ones obtained with the Newtonian Arrhenius law. The first observation is that the approximations lead more easily to plate tectonics than the Arrhenius law [4]. In addition, the dependence of the critical yield stress (i.e. where the transition from plate-tectonics regime to stagnant-lid regime takes place) on the Rayleigh number strongly differs, and the plate tectonics regime is much more easily obtained than for the Arrhenius viscosity. The difference increases with planetary radius.

Note that a more realistic rheology using a mixed Newtonian/non-Newtonian viscosity law including an elastic surface regime is expected to further differ from the Newtonian Arrhenius law.

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Double diffusive convection in the finger-regime – Applications to magmatic systems

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Flows in magmatic systems are often driven by thermally and compositionally induced buoyancy. Such type of flow is usually known as double diffusive convection. In this work we concentrate of the so called finger regime of double diffusive convection. This regime is characterized by the slowly diffusing component (usually composition) driving the flow, while the fast diffusing component (usually temperature) acts as a restoring force. A magma chamber in which a hot magma, enriched in a heavy component overlies a colder depleted magma is a typical example. This scenario can undergo subcritical instabilities, i.e. even if the net density is stably stratified, convection can take place. Employing a numerical model, based on a finite volume discretization, we investigate transport properties of this type of flow. We consider a Boussinesq-fluid in the limit of an infinite Prandtl number and have applied Dirichlet boundary conditions at the horizontal walls and insulating boundary conditions at the side walls for the temperature and composition as well as stress-free BC for the velocity.

Key parameters influencing the flow are the thermal and compositional Rayleigh number Ra and Ra_c and the Lewis number Le (ratio of compositional to thermal diffusivity). For the three different Lewis numbers Le=3, Le=10 and Le=100, the thermal Rayleigh number Ra and the chemical Rayleigh number Ra_c are varied systematically and the general features of the flow are explored. Especially the heat - and the chemical fluxes are computed in terms of the thermal and chemical Nusselt numbers, which represent the ratio between the overall fluxes and the fluxes under pure diffusive conditions. Simulations are performed with temperature-dependent viscosity and with constant viscosity and the results are compared.

We find two flow regimes: One regime dominated by finger instabilities and a regime dominated by large scale chemical convection. Traditionally it was believed that the first regime only occurs if $R_\rho = Ra/Ra_c > 1$ with an abrupt change to large scale convection around $R_\rho = 1$. Only recently Hage and Tilgner [1] performed experiments in which they showed that finger instabilities can be dominant if $R_\rho < 1$. Our simulations confirm these results. We investigate the transition between the two regimes and show that this transition is rather continuous than abrupt. It is shown that the developments of the thermal and chemical Nusselt numbers are similar as long as the flow is dominated by large scale convection but differ if fingers dominate.

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The formation of stable geochemical reservoirs in the interior of Mars

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Geochemical analysis of the so-called SNC meteorites suggests the existence of three to four separate isotopically distinct reservoirs in the mantle of Mars which have been preserved over the entire planetary evolution [1]. Until present, only a few scenarios involving a magma ocean have been proposed to explain chemical heterogeneities in the Martian mantle [2, 3]. They suggest that early in the evolution of Mars, the large amount of primordial heat due to accretion and core formation can give rise to a magma ocean as a consequence of significant or perhaps even complete melting of the mantle. Fractional crystallization of the mantle leads to a gravitationally unstable layering, which causes the mantle overturn. Previous works [2, 3] simulate only the magma ocean cumulate overturn and and find a stable chemical stratification of the mantle which is suggested to supress thermal convection. We use dynamical models [4] to investigate the influence of such a scenario on the thermo-chemical evolution of Mars and run our models for the entire planetary evolution. In our models we account for a density change upon the transition at 14GPa from pyroxene olivine and garnet to majorite and γ-olivine as suggested in [2]. We use two scenarios: a “plate-tectonic” scenario where the upper layer, in which the heat producing elements are enriched during the magma-ocean fractional crystallization, overturns and a “stagnant-lid” scenario with a strong temperature-dependent viscosity where the upper layer, since lies in the stagnant lid, does not overturn. We find that a stable chemical gradient is reached over the entire mantle or below the stagnant-lid and in both cases thermal convection ceases early in the planetary evolution. This is at odds with the inferred volcanic history of Mars, for which an active convecting interior up to the recent past is needed.

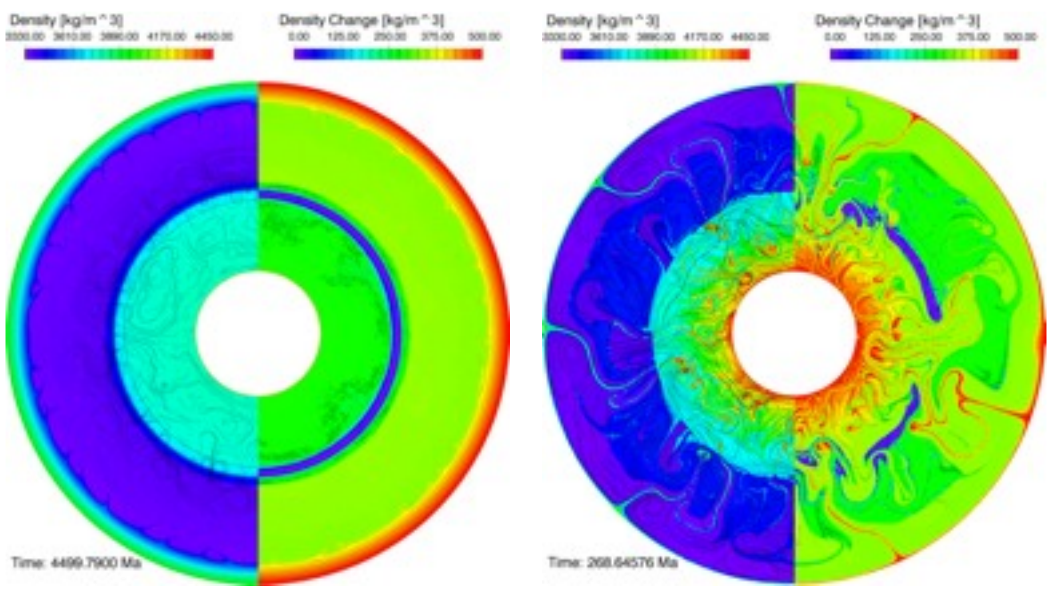

Figure 1. Left: density plot for the “plate-tectonic” case during the overturn. Right: density plot for the “stagnant-lid” case at 4.5 Gyr. While in the “plate-tectonic” case the entire mantle overturns and reaches a stable chemical stratification which then stops thermally driven convection in the “stagnant-lid” case a stable chemical stratifictaion is reached below the stagnant lid. However, also in this case, convection ceases due to the fact that heat-producing elements are enriched in the upper-most 50 km which lie in the stagnant-lid.

An alternatve scenario for the formation of stable chemical reservoirs is due to partial melting. We further present simulations where we account for partial melting and its associated density change of the residual material left behind when melt is extracted. Chemical reservoirs can be formed in this case where also an active convecting interior is maintained up to 4.5 Gyr.

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Why does the convergence rate between Nazca and South America decrease since the Neogene?

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The classic example of the poorly understood rapid change of tectonic plates motion is the increase and then decrease of the convergence rate between the Nazca and South America plates during the last 25 Myr that has coincided with the growth of the Andes Mountains [1]. Currently the decrease in convergence rate is explained either by the increasing load of the Andes or by the appearance of flat slab segments beneath South America. Here we present an alternative view derived from a thermomechanical self-consistent (gravity driven) model of Nazca plate subduction.

Reconstructions of global plate velocities [2] suggest that before some 25 Ma subduction of the Faralon/Nazca plate was almost perfectly parallel to the coastline of South America south of 20°S. After 22 Ma the direction of subduction became almost perpendicular to the trench. Based on these data as well as seismic tomographic images [3], we assume that the tip of the oceanic slab was still in the upper mantle under the central and southern parts of South America till 22 Ma. We run 2D thermomechanical models of the gravity driven subduction starting at 22 Ma in the 1200 km deep mantle domain considering the most important phase transformations. In all our numerical experiments we get large increment in convergence velocity related to the penetration of the tip of the slab into the mantle transition zone. The subduction velocity is later reduced when the slab interacts with the spinel/perovskite phase transition and underlying more viscous lower mantle. Our models fit quite well observed variations of the convergence rate and are consistent with seismic tomographic images of the Nazca plate beneath South America. In a number of experiments we also added thick crust and high topography of Andes. These experiments demonstrate that presence of the Andes does not affect much the convergence rate between Nazca and South America plates.

From our models we conclude that the variations in the convergence rate between Nazca and South America plates since 22 Ma are not related to the appearance of Andes. They are rather natural consequences of the first penetration of the Nazca plate into the transition zone and lower mantle beneath the southern part of South America after ending of the long-term oblique subduction.

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Magnetic field generation in Ganymede's core in the context of the Fe-snow regime

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The Fe-snow solidification regime has been suggested to operate in the low-pressure regime of Fe-FeS cores in small planetary bodies such as Ganymede [1,2]. In that regime, iron crystals form first at the core-mantle boundary (CMB) due to shallow or negative slopes of the melting temperature [3]. The iron crystals are heavier than the surrounding Fe-FeS fluid, which causes them to settle. In this way a stable chemical gradient arises within the solidification zone. Below this zone the local core temperature is higher than the melting temperature, which leads to remelting of the solid particles. The process of remelting forms a dense Fe-rich fluid on top of a lighter Fe-FeS fluid creating a Rayleigh-Taylor instability leading to chemical convection. In this way the lower fluid layer will be homogenously enriched in iron. Due to constant cooling of the core, the solidification zone grows until the lower fluid layer vanishes and iron droplets precipitate everywhere in the core. At this point an inner solid iron core will start to form.

Up to now it remains absolutely unclear whether the settling of iron droplets in the solidification zone can create any kind of fluid motion being relevant for magnetic field generation. We assume the Rayleigh-Taylor instability in the lower fluid core to be the potential starting point for large-scale fluid motions and associated magnetic field generation. In this case magnetic field generation would be confined to the timeframe, which starts when the first iron droplets form at the CMB and ends when the solidification zone extends across the entire core.

Since Ganymede is supposed to have an internally generated magnetic field [4], we investigate the described Fe-snow regime with a 1D thermal evolution model for Ganymede's core. The important output parameters of the model are the strength of the evolving chemical gradient as an opposing force to thermal buoyant motions as well as the time span needed to grow the solidification zone across the entire core as a temporal constraint for magnetic field generation regarding to our model. We model the thermal evolution of the core for two different heat transport regimes: one governed by convective heat transport (adiabatic temperature profile) and the other governed by conduction. To study the effect of latent heat we consider the latent heat of freezing and fusion for the conductive regime. As an important input parameter we vary the initial sulfur concentration of the core.

We find average chemical gradients from 0.26 $kg \cdot m^{-3}/km$ to 0.64 $kg \cdot m^{-3}/km$. These two values correspond to density contrasts between the CMB and the core center of $\Delta\rho=208\ kg \cdot m^{-3}$ and $\Delta\rho=512\ kg \cdot m^{-3}$. All investigated scenarios require strong superadiabatic core heat fluxes for thermal buoyant motions to overcome the stable chemical layering. The associated time spans allowing for magnetic field generation range from 475 Myr to 2112 Myr. Comparing our findings to the results of [1] we find considerably larger time spans to grow the solidification zone across the entire core. Latent heat tends to only slightly decrease the average chemical gradient and increase the time span.

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The effect of hydrothermal cooling on the "square root t" - law for a cooling oceanic lithosphere using parameterized porous convection

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The thickness of the oceanic lithosphere is generally associated with the cooling of the mantle when moving away from mid ocean ridges (MOR). While the surface topography is in good agreement with simple plate or halfspace cooling models for ages < 80 Ma, the observed surface heat flux is not in accordance with such models and cannot be explained by a square root t - law. The difference is mainly attributed to hydrothermal cooling in the oceanic crust and estimates of the fraction of hydrothermally removed heat range between 20 and 40% of the total heat flow of the earth.

Our aim is to consistently include this hydrothermal cooling mechanism in lithospheric cooling models. In our approach we mimic hydrothermal cooling by an increased effective heat conductivity based on parameterized hydrothermal convection (HC). First the temperature and pressure dependent permeability and porosity is derived using an elastic crack closure model. This will allow us to define the thickness of the HC-layer to evolve self-consistently. Given the temperature at the bottom of this layer the Rayleigh- and Nusselt number of HC can be determined and used to define an effective heat conductivity. Using this conductivity in the 1D conductive heat equation fully couples the parameterized HC to the thermal evolution of the cooling lithosphere.

Our models show that the strength of hydrothermal cooling is mainly controlled by the crack aspect ratio and the crack porosity at the surface. For realistic values HC strongly enhances the heat flow of young MOR's and leads to significant deviations from the square root t – law, possibly even up to high lithospheric ages.

Origin and environmental impact of the Earth's largest intraplate magmatic events - Siberian Traps and Ontong Java Plateau

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Large igneous provinces (LIPs) are known for their rapid production of enormous volumes of magma (up to several million km3 in less than a million years), for dramatic thinning of the lithosphere, often ending with a continental break-up and for their links to global environmental catastrophes. Despite their importance, controversy surrounds even the basic idea that LIPs form through melting in the heads of thermal mantle plumes. The Permo-Triassic (252 Ma) Siberian Traps (ST) – the type example and the largest continental LIP– is located on thick cratonic lithosphere and was synchronous with the largest known mass-extinction event. The Cretaceous (120 Ma) Ontong-Java Plateau (OJP) is the largest oceanic LIP and the largest LIP overall, that has generated up to 30 km thick oceanic crust and was synchronous with the global ocean anoxic event, but its environmental effect was not comparable to the effect of ST. These two major continental and oceanic LIPs shear common features that make their origin apparently controversial. Extreme volcanic production at large areas and high potential temperature of the magma sources of both LIPs support classical model of melting of a large starting plume head. However, contrary to the prediction of the classical plume-head model there was no pre-magmatic uplift associated with ST. Also, OJP remained at about 1 km depth below the sea level despite of exceptionally thick (30 km) oceanic crust produced during OJP event. Moreover, average seismic velocities of the OJP crust (< 7.3 km/s) are much lower than velocities expected for the high-Mg basalts derived from the hot mantle plume (> 7.5 km/s).

Here I present thermomechanical model that explains controversial observations for both ST and OJP . The model implies that both LIPs originate from decompression melting of a similar low-buoyancy mantle plumes with potential temperature of 1600°C (ST) and 1600-1650°C (OJP) that contained about 15-20 wt% (ST) and 20-25wt% (OJP) of the dense recycled oceanic crust. Differences in volume of melts and their composition were mainly caused by the difference in the initial thickness of the lithosphere that was thicker than 130 km in the case of ST and was thinner than 60 km in the case of OJP. In both cases similar amount of CO_2 was released resulting in comparable global warming events. Much more destructive effect of the gases released by ST on biota is explained by (1) stronger acidification effect of the released CO_2 on the Permian Ocean that was much less resistant to the acidification than the Cretaceous Ocean and by (2) large amount of halogens released to the atmosphere during ST event.

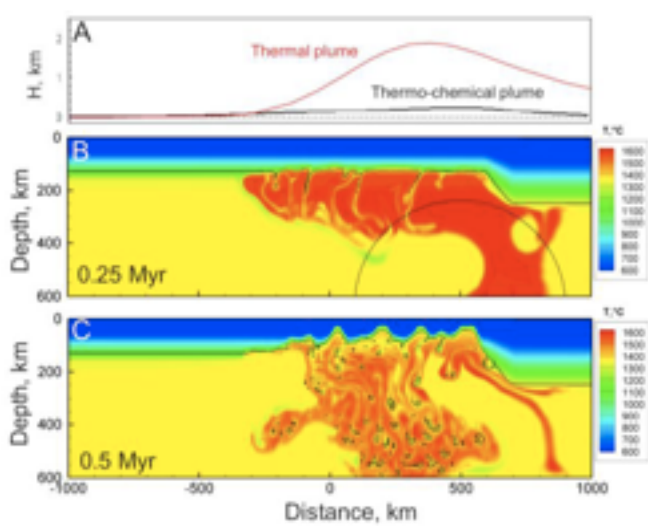

Figure 1. Model of rapid destruction of thick cratonic lithosphere (ST) by thermochemical plume without pre-magmatic surface uplift [1].

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Planetary dynamics and habitability

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The habitability of planets has received increasing interest in recent years, in particular in view of the increasing number of detected extrasolar planets. Planetary habitability (for life as we know it) is usually thought to require water on (or near) the surface, a magnetic field to protect life against radiation, and transport mechanisms for nutrients. Present theories of the origin of life and an early chemotrophic biosphere would also require volcanic activity and the associated large thermal gradients. A magnetic field is argued to serve to protect an existing atmosphere against erosion by the solar wind and thus to help stabilize the presence of water and habitability. Magnetic fields are generated in the cores of the terrestrial planets and thus habitability is linked to the evolution of the interior through magnetic field generation and volcanic activity. Moreover, the interior is a potential source and sink for water and may interact with the surface and atmosphere reservoirs through volcanic activity and recycling. The most efficient known mechanism for recycling is plate tectonics. Plate tectonics is known to operate, at present, only on the Earth, although Mars may have had a phase of plate tectonics as may have Venus. Plate tectonics also supports the generation of magnetic fields by effectively cooling the deep interior. (In addition, plate tectonics rejuvenates nutrients on the surface and generates granitic cratons.) On the Earth, surface water is stabilized by complex interactions between the atmosphere, the biosphere, the oceans, the crust, and the deep interior in the carbon-silicate cycle. As plate tectonics is widely believed to require water in the mantle to operate, it can be argued that plate tectonics is another element linking the biosphere to the evolution of the planet's interior. Single-plate tectonics associated with stagnant lid convection would allow for transfer water from the interior through volcanism but a simple recycling mechanism is lacking for this tectonic style. Stagnant lid convection will evolve to thicken the lid and increasingly frustrate volcanic activity and degassing, though. The question of whether or not extrasolar earthlike planets more massive than the Earth are likely to have plate tectonics or rather single-plate tectonics is hotly debated. We would argue that the large interior pressure and its effect on the rheology of the mantle of these planets may frustrate plate tectonics and magnetic field generation altogether. We would even argue that surface volcanic activity may become increasingly difficult with increasing mass of a rocky planet. On Earth, mantle melt is buoyant at depths smaller than $200 - 300$km. At larger than this critical depth, the melt will be negatively buoyant because of its greater compressibility in comparison with that of solid rock. The critical depth below which melt ceases to be buoyant will decrease with increasing mass of the planet and may become shallower than the depth to the base of the stagnant lid of mantle convection on massive terrestrial extrasolar planets. However, the lid thickness should also decrease with increasing planetary mass because of the planet's greater heat content. Our calculations suggest the ratio between the two very little with planetary mass therefore allowing for volcanic activity mostly independent of the mass of the exoplanet. The great diversity of extrasolar planets may suggest a diversity of life forms and associated habitability parameters, however, and extrapolations from the Earth may be overly naive.

Mantle convection models featuring plates

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Plates play an important role in the dynamics and evolution of the mantle convection system and must therefore be considered in mantle convection models. The generation and evolution of plate-like surface motion is studied in self-consistent models that apply a fully rheological approach [e.g. 1,2]. In particular, a temperature-dependent viscosity is necessary for the formation of rigid plates atop the convecting bulk. Further, a stress-dependent viscosity allows for the break-up into several moving plates. Due to the extreme local viscosity changes the computational requirements of these models are demanding. Therefore the evolution of plates over long time periods have generally been studied when specifying the existence of plates explicitly [e.g. 3]. This means that the surface motion is imposed as a time-dependent boundary condition by the modeler. The modeler can also configure a specific plate setup that does not arise naturally in the self-consistent models but allows to investigate the influence of this specific plate setup on the mantle convection system [e.g. 4] (Fig. 1a).

The force-balance method is one way of dealing with specified plates by ensuring that the stresses of the plates are balanced with the convecting stresses [5]. In this way plates neither drive nor resist convection. By adding a temperature-dependent viscosity to the force-balance method we bring this method closer to the self-consistent approach. In our modified version plate viscosity and plate thickness are no longer prescribed but arise as a dynamic consequence. As the mantle convection model uses a spectral formulation we implemented an approximated temperature dependence which uses the geotherm rather than the full temperature field.

We compare flow regimes and scaling laws resulting from the different model approaches and approximations.

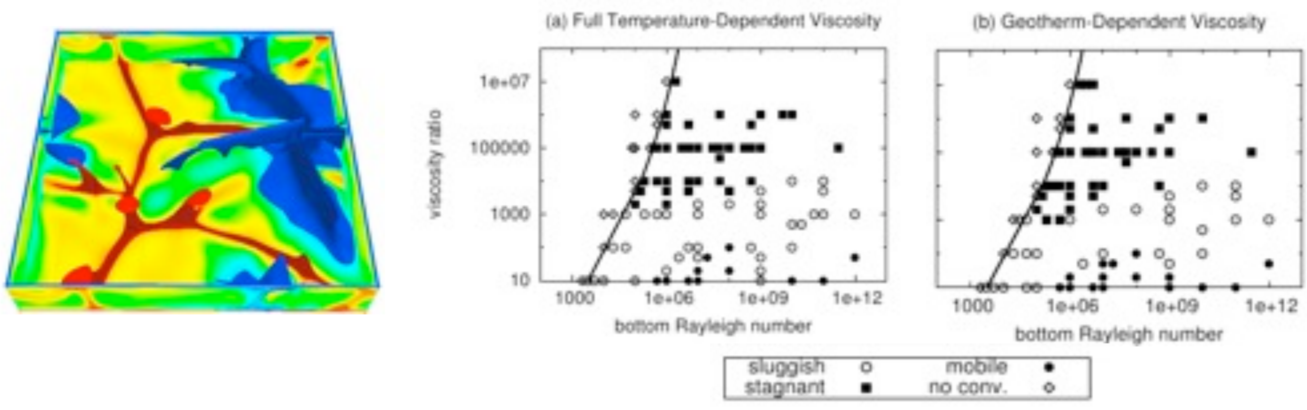

Figure 1. Temperature field snapshot of a 3D mantle convection model featuring plates with a specific plate setup (left) and regime plots for thermoviscous convection with a full temperature-dependent and a geotherm-dependent viscosity (right).

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On the possible deep origin of large-scale gravity anomalies on Moon and Mercury

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Like on the Earth and Mars, but notably different from Venus, the non-equilibrium equipotential shape of the Moon and Mercury are dominated by very long wavelengths, in particular spherical harmonic degree two. We extend here a method that we previously applied to the Earth, Venus and Mars to study which part of the gravity anomalies have likely a sublithospheric mantle origin. The method is based on the assumption that density anomalies in both the mantle and the lithosphere of planets and the Moon have the same spectral characteristic as inferred on the Earth from seismic tomography. We then apply a presumed pressure and temperature dependence of viscosity, that is based on mineral physics and consistent with other constraints on viscosity structure for the Earth's mantle to construct radial viscosity profiles. We compute geoid kernels for the planetary bodies, assuming a viscous mantle and an elastic lithosphere. Combining geoid kernels and density spectra, we can predict gravity spectra arising from density anomalies both in the convecting mantle and the lithosphere.

By comparison, we infer which part of the observed spectra is likely derived from the convecting mantle. Our previous results had indicated that this is probably the case up to about spherical harmonic degree l=30 for Earth, 40 for Venus and 5 for Mars. Here we conclude that a sublithospheric convecting mantle origin is likely up to l=5 for the Moon. For these degrees, radially averaged mantle density anomalies can be inferred. Similar to the Earth and Mars, the Moon can be interpreted to have a dominant degree-two convection pattern. However, we cannot exclude that the lunar geoid represents a frozen-in signal derived from a previous state of convection. The degree-two non-hydrostatic shape modelled here also includes excess flattening, such that it is not necessary to invoke a "fossil" bulge derived from a previously faster rotation. In contrast, we find that "static" anomalies – corresponding to heat mainly transported by conduction, fit the spectrum better for Mercury.

For the Earth and Mars, interpretations are further corroborated, and long-term stability of the convection pattern is suggested by the distribution of volcanism in space and time: On Mars, recorded volcanism through its entire history tends to occur primarily in regions above inferred present-day low mantle density. On the Earth, the reconstructed eruption locations of Large Igneous Provinces of the last 300 Myr mostly fall above the margins of "Large Low Shear Velocity Provinces", interpreted as piles of hot but chemically heavier material in the lowermost mantle, stable for hundreds of Myr and underlying presumed upwellings of the large-scale degree-two convection pattern. However, for the Moon and Mercury, no such obvious correlation is found, and further testing is needed.

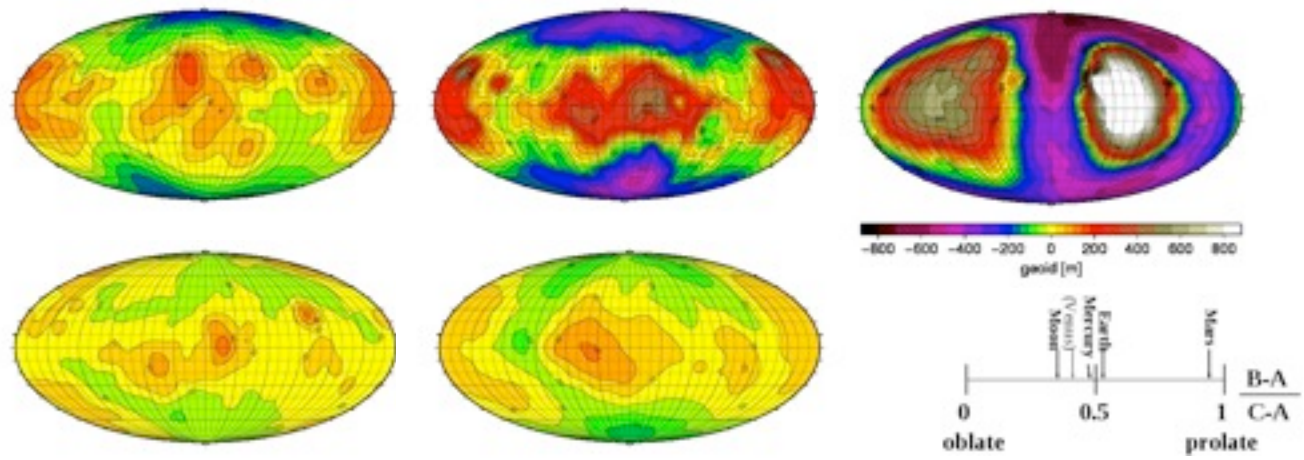

Figure 1. Equipotential surfaces ("geoid") of Mercury (top left), Venus (bottom left), Moon (top center), Earth (bottom center) and Mars (top right). Bottom right: Triaxiality of the equipotential shapes

Interior Structure of Mercury

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Mercury is unique among the terrestrial planets for its comparatively low mass but high average density. After more than 30 years without spacecraft observations, radio tracking of the NASA spacecraft MESSENGER has yielded a spherical harmonics expansion of Mercury's gravity field. Using recent geodetic observations Smith et al. [1] could estimate the moment of inertia factor C/MR^2 and the moment of inertia of the planet's rigid outer shell C_m/C, based on the theory of Peale [2]. The obtained constraints translate into a cumulative knowledge of Mercury's interior structure.

Exploring the resulting model space, we construct a few hundred radially symmetric models (see Figure 1) with varying crustal thicknesses, core radii and sulfur contents satisfying Mercury's observational constraints such as the mass $M = (3.3012 \pm 0.0004) \times 10^{23}$ kg and radius $R = 2439.1$ km. All models have the same four layer type structure consisting of a crust layer predominantly composed of plagioclase, a peridotite mantle, an iron-rich Fe-FeS liquid outer core and a pure iron solid inner core. Assuming a hydrostatic equilibrium and thermal steady state the depth dependent densities are calculated by the respective equations of state and Voigt-Reuss-Hill averaging.

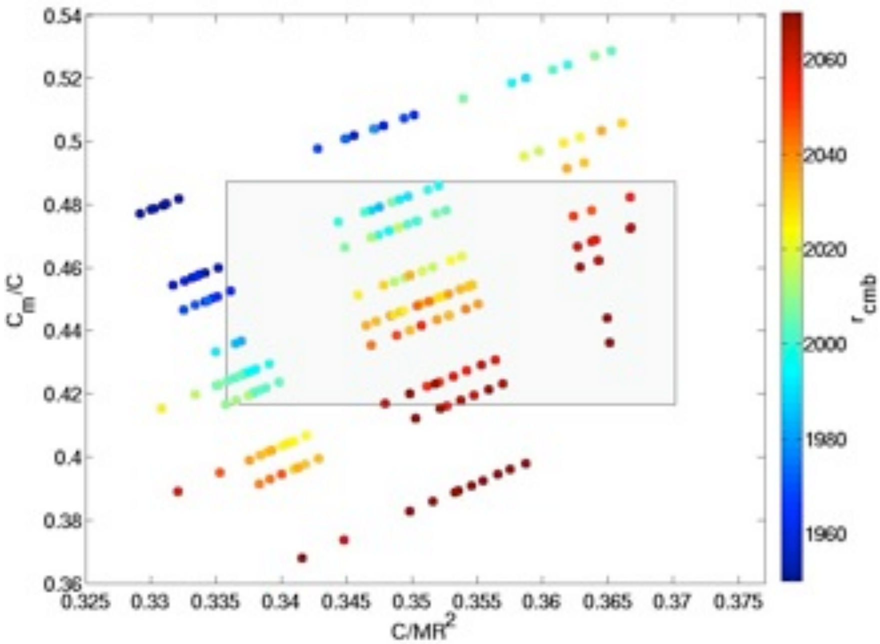

Figure 1. Overview of resulting C/MR^2 and Cm/C values. Shaded box gives model space within the constrains' uncertainties $C/MR2 = 0.353 \pm 0.017$ and $Cm/C = 0.452 \pm 0.035$ given in Smith et al. [1].

The resulting moment of inertia factor and moment of inertia of the outer shell are compared with observed values. We find that MESSENGER gravitational field data can be satisfied by an average mantle density between 3200 kg/m3 and 4300 kg/m^3 and a core radius r_{cmb} between 1980 km and 2080 km. Yet the inner core radius and crust thickness cannot be constrained by C_m/C and C/MR^2 alone. However, with the given constraints, assumed core composition we find that the solid inner core radius is less than half the core radius.

Further key parameters of Mercury's interior could be determined by future seismic experiments using elastic waves e.g. from impact sources. We derive velocities of seismic P and S waves from the elastic properties of the constituents in each layer and show the existence of a seismic shadow zone for fayalite-rich mantle compositions.

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The influence of a compositional stratification on the thermo-chemical convection in the interior of Mars

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Thermal and chemical convection drive the slow creeping flow of the silicate mantle of a planetary body and are responsible for the heat transport efficiency, magnetic field generation and the formation of geological structures on the surface of the planet. The role of compositional buoyancy is important in understanding the thermo-chemical evolution of terrestrial planets. A gravitationally unstable compositional stratification in planetary mantles, which can arise from fractional crystallization of the magma ocean in the early evolution of a terrestrial planet, can lead to a rapid overturn of the whole mantle and influence the onset and evolution of thermal convection [1,2]. After the overturn, a stable compositional stratification forms, which may suppress or delay thermal driven convection and reduce the heat flux out of the mantle. In this work, we use numerical experiments in a 2D box geometry [3] to investigate the thermo-chemical convection in the mantle of Mars. We consider an initially unstable stratified fluid which is cooled from above and heated from within and below. The aim of the study is to understand how a varying strength of the compositional buoyancy, which is described by the chemical Rayleigh Number Ra_C, influences the convective evolution of the mantle. A simple scaling law that quantifies the role of compositional buoyancy is the rate of mixing M which indicates how strong the mantle material is mixed at a certain time [3]. The effects are examined both on an isoviscous fluid and a fluid with a temperature-dependent viscosity. A strongly temperature-dependent viscosity reduces the available thermal buoyancy in cold regions which leads to the effect that convection does not involve the whole mantle but takes place in distinct layers. Especially at the cold surface a stagnant lid forms which does not participate in the convective motions of the mantle (see Figure 1).

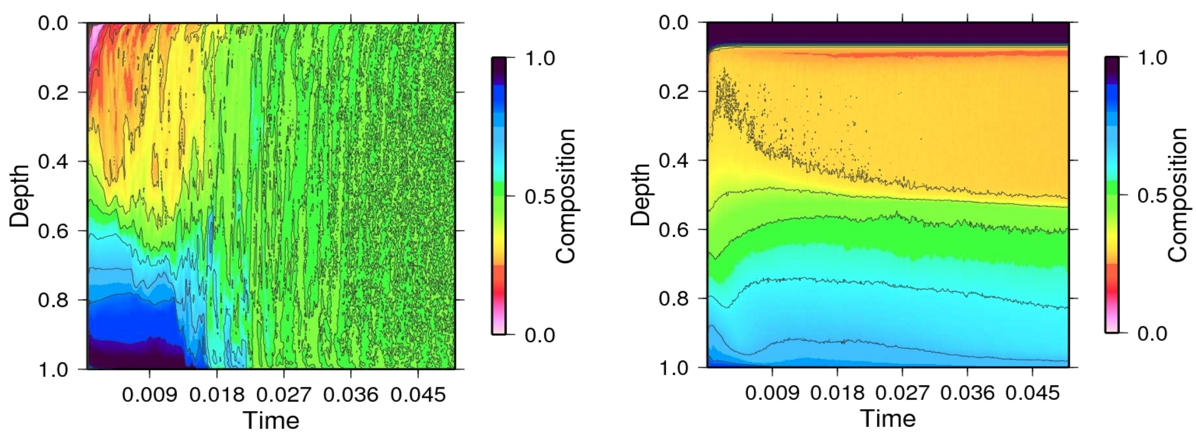

Figure 1. Time evolution of the composition field for an isoviscous mantle (left plot) and a temperature-dependent rheology (right plot) for a buoyancy ratio Ra/Ra_C=0.8. In the isoviscous case layers mix and form a homogeneous mantle starting with a non-dimensional time of 0.016. The temperature-dependent rheology preserves a high density layer at the top of the convecting mantle due to the stagnant lid formation. Below the stagnant lid a stable stratification is reached with distinct layers where convection takes place.

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Why thermodynamics (and petrology) matter to geodynamic modelling

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To improve our understanding of the processes in the deep Earth interior we need to provide a better description of the physical parameters involved in the numerical models. The geodynamic simulations should be able also to reproduce the largest possible number of geological observations.

The idea of combining a thermodynamic formulation with geodynamic models is becoming widely accepted. To produce reliable results, a compilation of thermodynamic properties of geological materials over a large range of P,T and compositions is essential. In recent years, thanks to the effort of individual scientists (e.g. Ghiorso, Saxena, Stixrude), thermodynamic databases have been made available. However the complexity of the problem and the continuous release of new experimental data require a long term multidisciplinary effort to maintain, improve and refine the thermodynamic datasets. A group of researchers from several countries (the so-called "ThermoDynaMix group", http://www.dias.ie/ThermoDynaMixIII/index.html) has started a discussion on how to develop an openly supported thermodynamic database for the Earth science community.

With the support of a thermodynamic computation, we can develop more accurate sets of thermo-physical parameters (e.g. density, heat capacity, viscosity, thermal conductivity). In figure 1, for example, it is shown a thermal plume under a moving plate that is obtained by combining a thermodynamic model (Saxena, GCA, 1996) with a geodynamic simulation which incorporates a mineralogical dependent viscosity model. The thermal effect of phase transitions (e.g. ppv→pv, pv+wu→rw) is accounted for by incorporating the entropy change that has been retrieved from the thermodynamic calculation.

Petrological and geochemical data on igneous and metamorphic rocks provide useful constraints on the processes in the Earth's interior. Thermodynamic models, when combined with geodynamic simulations, allow us to simulate the compositional evolution of mantle and crustal rocks in space and time. Melting in mid-ocean ridges has been studied extensively; however certain observations such as the formation of dunite channels remain elusive. In figure 2 are reported the preliminary results of a two-phase flow model applied in combination with a thermodynamic formulation of mantle melting to investigate whether dunite channels may be related to chemical heterogeneities in the source of mantle melting.

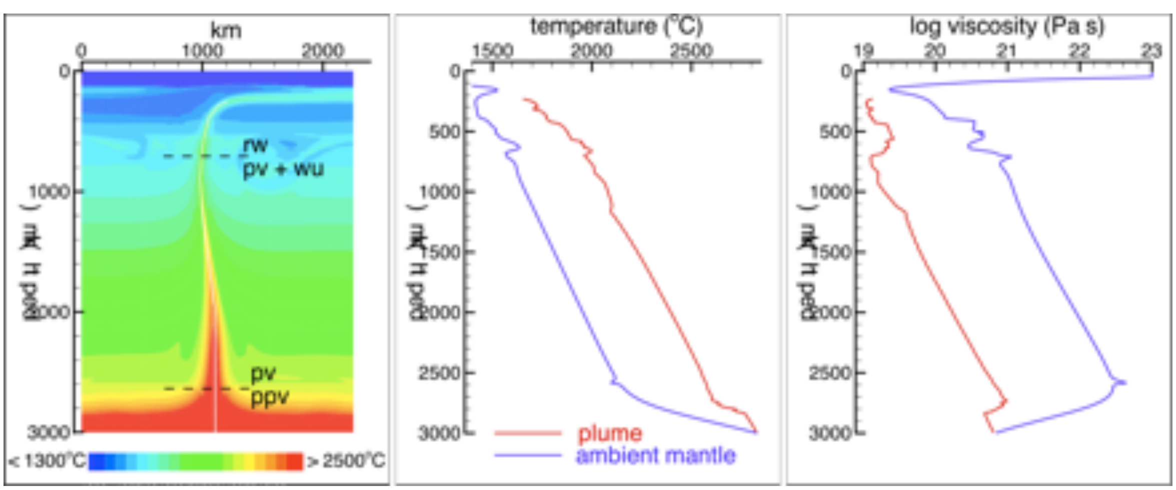

Figure 1. ***Left:*** *plume thermal model. The mineral assemblage at each depth is obtained from thermodynamic calculations. Viscosity and other properties are function of T,P and minerals proportion. Thermal effect of phase transitions is also included.* ***Middle:*** *thermal profile along the upwelling plume and the ambient mantle.* ***Right:*** *lateral variations of viscosity*

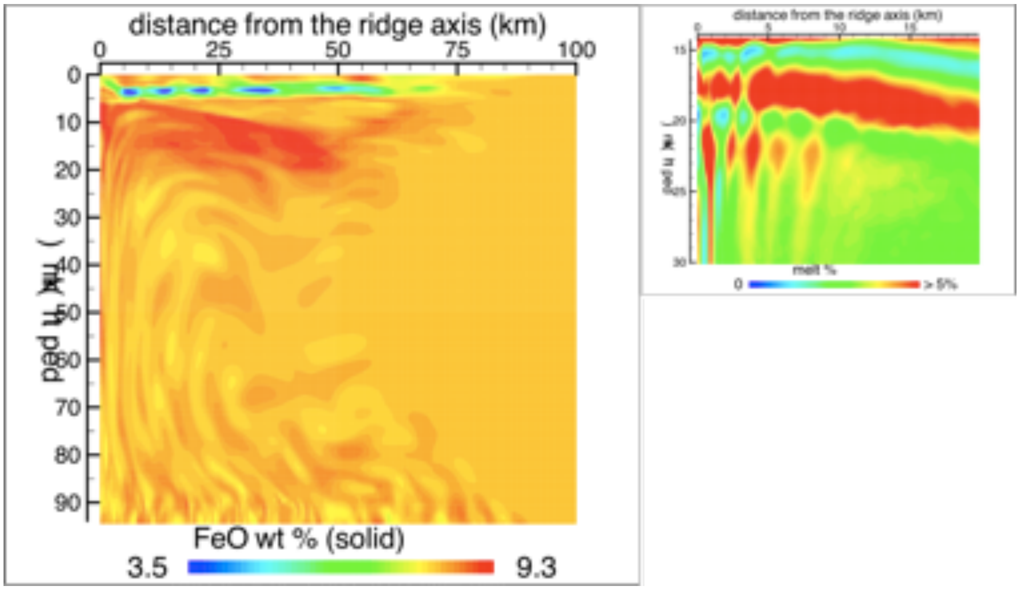

Figure 2. Two-phase flow model of a spreading ridge. The thermodynamic model is used to determine the solid and melt composition. Initial composition of the upwelling mantle is not homogeneous. ***Left:*** *Iron content in the solid mantle.* ***Right:*** *melt distribution in proximity of the ridge axis.*

Mantle dynamics from analytical parametrization of thermal expansivity and conductivity

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In most numerical simulations of mantle convection in the Earth and terrestrial planets it is commonly assumed that the coefficients of thermal expansion a and thermal conduction k are either constant or at most pressure-dependent. Pressure changes are generally computed using simple parametrizations that often rely on extrapolations of low-pressure experimental data for a single upper mantle phase. Here we collect data for both the pressure and temperature dependence of a from a database of first-principle calculations [1], and of k from recent experimental studies [2,3]. We use these data sets to construct analytical parametrizations of a and k for each of the principal upper- and lower mantle phases that can be easily incorporated into existing mantle convection codes. We then analyze the impact of such parametrizations on Earth's mantle dynamics through simple numerical models of thermal convection with multiple phase transitions. On the one hand, when the thermal expansivity is the only variable thermodynamic parameter, both its temperature- and pressure-dependence enhance hot plumes and tend to inhibit the descent of the cold downwellings, thus making subduction more difficult. On the other hand, holding a constant and taking into account a variable k determines a strong increase of the mantle temperature. This reduces the buoyancy available to amplify bottom boundary layer instabilities and causes mantle flow to be driven solely by the instability of the cold lithosphere. When both parameters are considered in concert yet another regime is observed with an increased propensity to local layering which favors slab stagnation in the transition zone and subsequent slab thickening in the lower mantle. We also demonstrate that the values of k near the core-mantle boundary would ultimately determine the effect of this parameter on mantle convection, which stresses the importance of accurately estimating the thermal conductivity of the post-perovskite phase. The phase-, pressure- and temperature-dependence of the thermal conductivity and expansivity exert a first order influence on the style of mantle convection, indicating that the variability of these two parameters should be routinely included in geodynamic simulations.

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Mercury's thermo-chemical evolution from numerical models constrained by MESSENGER observations

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The Messenger spacecraft, in orbit around Mercury for more than year, has been delivering a great deal of new information that is changing dramatically our understanding of the solar system's innermost planet. Tracking data of the Radio Science experiment yielded improved estimates of the first coefficients of the gravity field that permit to determine the normalized polar moment of inertia of the planet (C/MR^2) and the ratio of the moment of inertia of the mantle to that of the whole planet (C_m/C). These two parameters provide a strong constraint on the internal mass distribution and, in particular, on the core mass fraction. With C/MR^2= 0.353 and $C_m/C = 0.452$ [1], interior structure models predict a core radius as large as 2000 km [2], leaving room for a silicate mantle shell with a thickness of only ~400 km, a value significantly smaller than that of 600 km usually assumed in parameterized [3] as well as in numerical models of Mercury's mantle dynamics and evolution [4]. Furthermore, the Gamma-Ray Spectrometer measured the surface abundance of radioactive elements, revealing, besides uranium and thorium, the presence of potassium. The latter, being moderately volatile, rules out traditional formation scenarios from highly refractory materials, favoring instead a composition not much dissimilar from a chondritic model. Considering a 400 km thick mantle, we carry out a series of numerical simulations of the thermochemical evolution of Mercury's mantle. We model in a self-consistent way the formation of crust through partial melting using Lagrangian tracers to account for the partitioning of radioactive heat sources between mantle and crust and variations of thermal conductivity. Assuming the relative surface abundance of radiogenic elements observed by Messenger to be representative of the bulk mantle composition, we attempt at constraining the degree to which uranium, thorium and potassium are concentrated in the silicate mantle through a broad exploration of the parameter space. We analyze how different rheologies, buoyancy variations associated with mantle depletion and the absence or presence of a primordial crust influence the thermal history of Mercury, the duration of convection and the formation of partial melting with its associated crustal production. Additionally, we calculate the global radial contraction of the planet resulting from secular cooling, mantle differentiation and inner core growth, and compare it with the traditional estimate of 1-2 km which was recently confirmed by the analysis of Messenger's images [5].

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Effects of rheology, composition and surface erosion during collision of India and Eurasia

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The collision of northward moving Indian and relatively stationary Eurasian tectonic plate, beginning at around 55Ma, has formed the Himalayan orogen and Earth's largest and highest plateau: Tibet. Lying on the western syntaxis of Himalaya, the Pamir-Hindu Kush is well known for being the locus of enigmatic intermediate depth seismicity and large Gneiss domes. Although the Pamirs and Tibet are belonging to the same collision zone, the former one has been subjected to extreme Cenozoic shortening, with the strains by more than 2 times higher than in Tibet.

As members of the TIen Shan - PAmir GEodynamic program (TIPAGE), our aim is to find lithospheric scale models and controlling factors consistent with all major geodynamic observations, e.g. timing of uplift events of the Tien Shan and the occurrence of anomalous high temperatures below northern Tibet. Furthermore the existence of the Tarim basin in western Tibet in contrast to the high Tibetan plateau and the steep mountain front at the southern side of Himalaya needs it be explained.

Since lithosphere exhibits elastic, brittle and viscous properties, highly sophisticated numerical tools are necessary to explain these diverse effects. For this purpose we employ the Finite Element code SLIM3D/2D developed in our group in Potsdam additionally equipped by routines modeling phase transformations in the crustal rocks and surface erosion and sedimentation routines. We run several N-S oriented 2D cross section models, studying the influence of rheological and compositional parameters during the India-Eurasia collision in the model that starts at 60 Ma and includes part of Neo-Thetys, cratonic India and Greater India extension as well as Eurasia, that includes mechanically stronger lithosphere of Tarim and Tadjik basins.

Three key findings are:
1) Mantle lithosphere delamination below is necessary to generate high temperatures in the crust. The main contributing effect for this is eclogitization of Eurasian crust, which itself depends on pressure, temperature and kinetic (threshold) temperature.
2) The strength of the Tarim micro plate must be much larger than strength of the rest of the Asian lithosphere. When tectonic deformation approaches Tarim lithosphere, it begins moving to the North as rigid body transferring tectonic deformation to the Tien Shan. The strength of the Tadjik basin in Pamir must have been much lower than that of Tarim. Therefore in contrast to the lithosphere of Tarim, lithosphere of Tajik basin has failed and underthrusted southward.
3) Monsoon driven windward erosion is necessary to get a steep topography gradient at the Himalayan front. In models this can be accomplished by a high precipitation rate and an orographic barrier at around 5km altitude. This also leads to minimal Cenozoic erosion in Tibet.

Effect of density changes on convection flow pattern caused by enrichment in consequence of melting and emplacement

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Melting, melt transport, and emplacement is linked with depletion and enrichment. With changes of pressure, temperature and composition the mineral assemblage and petrology is modified, physical properties particularly density are altered. Hence resulting gravitational forces depending on the sign of density change, directed up- or downward, affect convection.

What are the implications of enrichment associated with density changes? Is convection sensitive to the corresponding forces? And, if so, will streaming behavior and flow pattern be influenced? Further, are events as delamination prevented or enhanced?

In the context of a special rift scenario – rift induced delamination (RID) with melt induced weakening (MIW) ([1-4]) – the questions are investigated by numerical modeling. RID was proposed as a geodynamic process explaining the extreme elevation of the Rwenzori Mountains in the western branch of the East African Rift System. MIW is based on a fast upwardly transport of melt substituted by extraction and emplacement of melt and its heat in a given level. By reduction of viscosity and strength it may lead to dripping, asthenospheric upwelling and failure of the lower crust triggering detachment of cold and dense mantle lithosphere. It is a more realistic and self-consistent process with moderate given anomalies.

Modeling tool is FDCON. With the Method of Finite Differences, it supports the conservation equations of mass, momentum, energy, and the composition for a two-phase multi component medium consisting of fluid and viscous solid matrix [1]. The Compaction Boussinesq Approximation and the high Prandtl number approximation are used, elasticity is neglected and geometry is restricted to 2D. Rheology is temperature and stress dependent. Melting and solidification are modeled using a simplified linear binary solid solution model.

Petrology is complex, at least for a geophysicist. Rocks consist of an assemblage of minerals with different portions, every one having its own properties like density (where we are interested in), crystal structure, composition of chemical elements including water content and ability to phase changes depending more or less on temperature and pressure. For modeling with FDCON all this must be subsumed in one mantle material, determined by a solid matrix density, a density for depletion, which will be calculated from accumulated melt production, a fluid density and two densities for enriched material. Enrichment is obtained by the accumulated fraction of solidified melt. A phase boundary is assumed in a certain depth level which subdivides the usage of one ($\rho_{\mathrm{enr,B}}$) or another density ($\rho_{\mathrm{enr,A}}$). Below this level $\rho_{\mathrm{enr,B}}$ contributes to the total density weighted by the enrichment part, above the level $\rho_{\mathrm{enr,A}}$ is applied, respectively. All the densities additionally depend via expansion coefficient on temperature.

Variations of $\rho_{\mathrm{enr,A}}$ will reveal the importance and sensitivity of this parameter. Negative or positive buoyancy promotes descending or ascending flow. The effect on the highly coupled feedback mechanism can not be foreseen. At the time final outcomes are in process. Interim findings let assume differences in particulars, both in time and space. But essential occurrences as updoming, dripping and delamination sustain enrichment caused density variations.

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Constraints for a solid lunar inner core

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Various geophysical data have been interpreted to suggest a small core within the Earth's Moon with a radius between 300km and 400km. The present state of the core is important in view of the absence of a lunar self-sustained magnetic field and in light of the evidence for an early magnetic field that caused the remanent magnetisation of parts of the lunar crust. In earlier publications [1] we had argued for an entirely fluid lunar core at present as the most straightforward explanation for the lunar magnetic history. However, recent reanalysis of Apollo seismic data [2] did not only determine the size of the lunar core more accurately but also suggested the presence of a solid inner and a fluid outer core.

In order to constrain under which circumstances a solid inner core can form, we calculated a suite of three dimensional thermal evolution models of the Moon. The principle of this convection model is widely accepted and is used for thermal evolution models of terrestrial planets [3,4]. Assuming the lunar core to consist of iron and some weight percent of a of lighter alloying component a solid inner core forms as soon as the core adiabat intersects with the liquidus temperature of the core alloy. We systematically varied the core thermal parameters and the rheological parameters of the mantle from a dry to a wet rheology and included the thermal effects of a regolith layer.

The onset of core freezing depends on the actual model parameters, where the sulphur content has the largest influence. Figure shows the inner core radii evolution with time for various sulphur concentrations. As soon as iron starts to freeze out latent heat is eased due to the phase change from liquid to solid. Additionally gravitational energy is released and lost as heat eventually. The freezing slows down as the decrease of the CMB temperature is slowed down, too. Furthermore the remaining liquid part of the core becomes more and more iron depleted (or FeS enriched), which causes the liquidus temperature of the core alloy to be shifted to lower temperatures. Henceforth the growing of the inner core becomes slower with ongoing evolution.

Our simulations show that the Moon can well have a solid inner core surrounded by a liquid layer. The computed radii for the inner core are consistent with analysis of Apollo seismic data from [2]. The actual choice of the core size as well as the thermal effects of a regolith layer do not have a strong influence on the resulting inner core size. The absence of a present lunar self-sustained magnetic field can be explained by the very slow - if not stalled - growth of the inner core.

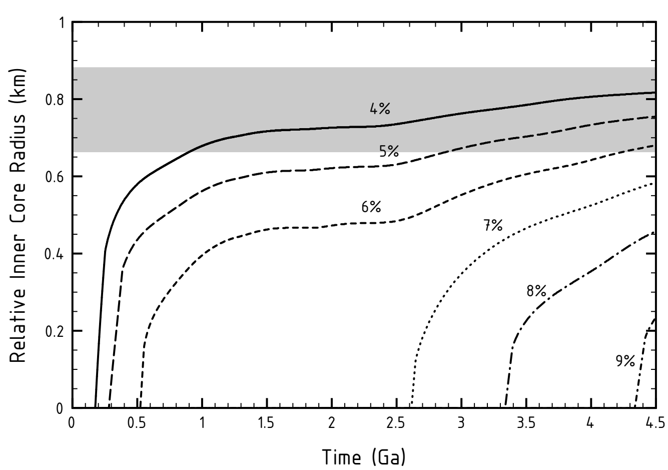

Figure 1: Inner core sizes depending on sulphur content

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