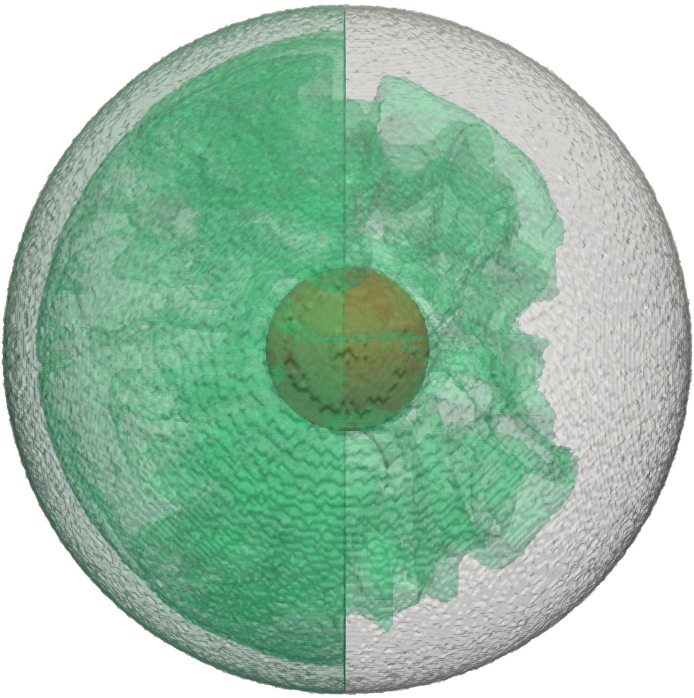
German-Swiss Geodynamics Workshop 2016

11.09 - 14.09.2016, Schloss Schney, Lichtenfels



BGI Geodynamics
BGI Bayerisches Geoinstitut
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Local organizers

Gregor Golabek
Marcel Thielmann

Program

Sunday, September 11

14:00-18:00	Arrival
18:00-19:00	Dinner
19:00-	Icebreaker

Monday, September 12

7:30-9:15	*Breakfast*
9:15-9:30	Introduction
9:30-10:15	Microstructure modeling (*Convenor: K. Marquardt*)
10:15-11:00	*Coffee + Group picture*
11:00-12:30	Mantle dynamics (*Convenor: A. Rozel*)
12:30-14:00	*Lunch*
14:00-20:00	Excursions
20:00-21:00	*Dinner*

Tuesday, September 13

7:30-9:00	*Breakfast*
9:00-10:30	Lithosphere processes (*Convenor: M. Thielmann*)
10:30-11:00	*Coffee*
11:00-12:30	Planetary Dynamics (*Convenor: G. Golabek*)
12:30-14:00	*Lunch*
14:00-15:00	Discussion
15:00-18:00	Poster session
18:00-19:00	*Dinner*
19:00-	Poster session

Wednesday, September 14

7:30-9:00	*Breakfast*
9:00-10:30	Numerical advances (*Convenor: H. Schmeling*)
10:30-11:00	*Coffee*
11:00-11:45	Discussion
11:45-12:00	Wrap-up
12:00-14:00	*Lunch*
14:00-open end	Departure

Scientific Program

Monday, September 12

9:30-10:15	Numerical modelling of micro-scale ductile deformation processes and their implications for larger-scale dynamics (*P. Bons*)
11:00-11:45	Thermochemical Piles: Implications for Plate Tectonics (*C. Stein*)
11:45-12:30	Self consistent plate tectonics in mantle convection models: recent progress (*P. Tackley*)

Tuesday, September 13

9:00-9:45	Lithospheric processes: From oceanic lithosphere accretion to hydrothermal cooling (*H. Schmeling*)
9:45-10:30	3D models of plate collision, slab breakoff and subduction initiation (*B. Kaus*)
11:00-12:30	Thermochemical evolution of Mercury, the Moon and Mars: Constrains from space missions and planetary samples data (*A.-C. Plesa*)
11:00-12:30	Modelling the interior and surface processes of Earth-size or super-Earth bodies (*L. Noack*)
14:00-15:00	Discussion
15:00-18:00	Poster session
19:00-	Poster session

Wednesday, September 14

9:00-9:45	Robust Multigrid Solvers for Geodynamics (*P. Sanan*)
9:45-10:30	A parallel modeling tool for lithospheric deformation (*A. Popov*)
11:00-11:45	Discussion
11:45-12:00	Wrap-up

Abstracts

Viability of Archean Subduction Initiation from Gravitational Spreading

Adams, Andrea, Thielmann, Marcel, Golabek, Gregor

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The development of plate tectonics and Earth's early tectonic environment are currently not well understood. Modern plate tectonics are characterized by the sinking of dense lithosphere at subduction zones; however this process may not have been feasible if Earth's interior was hotter in the Archean, resulting in thicker and more buoyant oceanic lithosphere than observed at present (van Hunen and van den Berg, 2008). Previous studies have proposed gravitational spreading of early continents at passive margins as a mechanism to trigger early episodes of plate subduction (Rey et al., 2014). This study utilizes 2D thermo-mechanical numerical experiments using the finite element code MVEP2 (Kaus, 2010; Thielmann et al., 2014) to investigate the viability of this mechanism for subduction initiation with Archean mantle conditions. The model is comprised of a 55-km-thick continent above 170 km of strongly depleted lithospheric mantle and surrounded by a 15-km-thick oceanic lid. A range of possible densities and viscosities were investigated for the different layers, and results show that lithospheric stresses may vary between 250-750 MPa. Because lithospheric stresses are crucial to subduction initiation, the model includes elasticity in order to better accommodate this large stress range. This model also includes free-surface boundary conditions to allow the development of isostatic topography, which is a factor not considered previously. Preliminary results indicate that the magnitude and location of lithospheric stresses varies for cases with and without isostatic uplift being taken into account. Subduction initiation was previously shown to occur due to large intra-lithospheric gravitational stresses from a spreading continent, but these intra-lithospheric stresses may be insufficient in cases with lithospheric elasticity and continental uplift. Critical factors are expected to be the magnitude of continental buoyancy and the degree of decompression melting from the depleted mantle layer.

Numerical modelling of micro-scale ductile deformation processes and their implications for larger-scale dynamics

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Shear zones on all scales are commonly observed in exposed metamorphic rocks and indicate that shear localisation is the rule in crustal rocks, rather than an exception. Crustal rocks are usually polymineralic and heterogeneous (e.g. sedimentary layering). It is less clear whether ductily deforming (almost) monomineralic rocks show the same degree of localisation. Examples are mantle rocks and ice in polar ice sheets. Direct observations on deformation structures are almost impossible in both cases (rare surface exposure or a few deep drill cores, respectively). We simulated high-strain deformation in single- and polyphase materials with a full-field approach with a spectral solver (Fast Fourier Transform, FFT). The FFT-approach simulates visco-plastic deformation by dislocation glide, taking into account the different available slip systems and their critical resolved shear stresses. The approach is, therefore, particularly well suited for strongly non-linear anisotropic minerals, such as mica and ice Ih. We modelled single- and polyphase composites of minerals with different anisotropies and strengths, roughly equivalent to ice Ih, mica, quartz and feldspar. The FFT-code was combined with the Elle-platform to attain large strains and include dynamic recrystallisation. Shear localisation is observed in all cases. In single-phase materials, localisation is due to the development of a lattice-preferred orientation (LPO) that makes the aggregate mechanically anisotropic. Homogeneous deformation is generally energetically unfavourable in anisotropic materials. However, dynamic recrystallisation can mask any shear localisation in the final microstructure, making it difficult to detect in, for example, polar ice. Reorganisation of the mineral distribution in polyphase materials adds an additional mechanism for shear localisation. Movies of the simulations show that in polyphase aggregates too, the distribution of both strain rate and of finite strain is much more heterogeneous than the finite microstructure tends to indicate. That shear localisation on the micro-scale appears almost inevitable raises the question whether there is a larger length scale where shear localisation is averaged out. Analyses of strain-rate and finite strain distributions indicate that these have multi-fractal characteristics. This suggests that, even in monomineralic rocks, shear localisation is to be expected at all scales. This can be explained by the fact that the reason for localisation, mechanical anisotropy, is a property with no length scale. The assumption that ice sheets flow homogeneously on scales much larger than the grain scale is probably unwarranted, which may have serious implications for the interpretation of climate signals obtained from deep drill cores in the polar ice sheets.

The influence of water on mantle convection and plate tectonics

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Water has a significant influence to mantle rheology and therefore also to the convection of the mantle and the plate tectonics. The viscosity of the mantle can be decreased by up to two orders of magnitude when water is present in the mantle. Another effect of the water is the change in the solidus of the mantle and therefore the melting regime. This two effects of water in the mantle have a significant influence to mantle convection and plate tectonics. The influx of water to the mantle is driven by plate tectonics as wet oceanic lithosphere is subducted into the mantle and then brought back to the lithosphere and the surface by MOR-, arc- and hotspot volcanism. Studies show that the amount of water in the mantle is about three times bigger than the water in the oceans. To model this water cycle multiple additions to StagYY are necessary. A water diffusion to complement the water transport due to advection and water dependent viscosity law are implemented. This additions to StagYY will be followed by implementations of a pressure-temperature law for water content, additional transport mechanisms for water, water dependent solidus functions and the implementation of recent values for plate velocities and water capacities in subducting slabs. This will allow to research the influence of water to the mantle convection and rheology of the past 200Ma.

Melting-induced chemical differentiation at the base of the Earth's Lower Mantle

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Geophysical data shows presence of so-called Ultra-Low Velocity Zones (ULVZ) just above the Core-Mantle Boundary (CMB). There are several hypothesis to explain this phenomena, including Post-Perovskite Layer and ponds of partial melt. In our numerical simulations we try to answer which consequences may have solid-melt differentiation.
Our numerical model is StagYY code (e.g. [Tackley et al., 2008], which simulates convection of mantle, thermal fluxes in it, and some other physical properties including melt segregation and transportation, if it is formed. This code uses an empirical model of melting and physical properties of coexistent phases based on experimental and computational data of [Andrault et al., 2011, 2014], [Boukare et al., 2015], [Fiquet et al., 2010], [Hirose et al., 1999], [Liebske, Frost, 2012], [Kato et al., 2016], [de Koker et al., 2013], [Mosenfelder et al., 2007], [Nomura et al., 2014], [Stixrude & Lithgow-Bertelloni, 2011], [Thomas et al., 2012], [Tateno et al., 2014], [Zerr et al., 1998]. Density difference between solid and melt is used to calculate velocity values for Darcy flux. Latent heat of melting, viscous dissipation, adiabatic heating, and heating due to partitioned radioactive elements are considered.
We performed a set of numerical experiments with vertical resolution 13 km per cell nearby CMB, variable CMB temperature above the solidus (4000-4500K), and uniform pyrolytic composition (8 mol.% of FeO). Simulated time intervals were 100 Ma.
In case of CMB temperature the lowermost layer of cells becomes totally molten. Dense iron-enriched (up to 30 mol. % FeO) melts push solids out of cells. Atop this layer with molten iron-enriched material another layer of iron-depleted material (3.5 mol. % of FeO) forms.

Post-magma ocean mixing of reservoirs inside the angrite parent body

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Angrites are a rare group of mafic volcanic-plutonic meteorites with only 25 samples listed by the Meteoritical Society that formed within the first 10 Myr after the formation of the solar system. Studies of siderophile elements showed that core formation in the angrite parent body occurred at super liquidus temperatures [1, 2]. Despite experiencing an early magma ocean, Hf-W data suggest the presence of at least two distinct mantle reservoirs [3]. A possible explanation for the isotopic variations (coupled with elemental variations) could be delivery of new planetesimal material during the post-magma ocean stage and imperfect mixing of the resulting mantle reservoirs. To test this theory we use the 2D/3D finite difference marker-in-cell code family I2ELVIS/I3ELVIS [4] to study the mixing of reservoirs in bodies with radii ranging from 50 to 300 km. Numerical results show that mixing in 3D models is more efficient than in their 2D counterparts, related to the lack of toroidal flow patterns in 2D geometry [5]. Based on the numerical results we derive a semi-analytical scaling law describing the mixing efficiency. Using the available constraints on formation time of the angrites, the activity of an early dynamo [6] and the modelled thermal evolution, we put constraints on the size of the angrite parent body.

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[4] T. V. Gerya, D. A. Yuen. Robust characteristics method for modelling multiphase visco-elasto-plastic thermo-mechanical problems. *Phys. Earth Planet. Sci.*, 163: 83–105, 2007.
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Double diffusive finger convection at low buoyancy ratios – fingers where they shouldn't be?

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In double diffusive convection the density of a fluid is determined by two parameters, e.g. heat and a chemical component. It occurs in a wide range of systems including stellar interiors, Earth's oceans and presumably Earth's mantle. Peculiar phenomena can often be observed in double diffusive systems including the self organized formation of layers, oscillatory motions and so called salt fingers. We investigate a fluid with stable heat stratification and unstable chemical stratification, i.e. hot, saturated material lying over cold, depleted material. In such a set-up finger convection can occur due to the different diffusivities of the two components. For each of the two components a Rayleigh number is defined and their ratio is denoted as R_ρ (the so called buoyancy ratio). According to classical theory (for instance cf. [1]), fingers can only form if $R_\rho > 1$. In contrast to that, laboratory experiments also proved fingers for $R_\rho < 1$ going down to values of R_ρ to the order of 0.01 [2]. A subsequent theoretical work was able to explain these observations in parts by extending an existing theory and thus shifting the previous boundary of the finger regime to lower values of R_ρ in dependence of the Prandtl number [3]. We present investigations of finger convection in dependence of Prandtl and Lewis numbers for which we use a numerical finite volume model. We find finger-like instabilities at low R_ρ that can not be explained by any existing finger theory. A first approach to explain our findings is the influence of thermal and chemical boundary layers on the dynamics of the flow.

[1] J. S. Turner. *Buoyancy Effects in Fluids*, Cambridge University Press, 1973.

[2] E. Hage, A. Tilgner. High Rayleigh number convection with double diffusive fingers. *Physics of Fluids*, 22(7):076603-1–7, 2010.

[3] R. W. Schmitt. Thermohaline convection at density ratios below one: A new regime for salt fingers. *Journal of Marine Research*, 69(4-6):779–795, 2011.

The influence of internal heat sources on mantle convection with phase transitions

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Changes of mineral phases (e.g. *olivine* $\mapsto$ *wadsleyite, ringwoodite* $\mapsto$ *perovskite*) are known global features within the Earth's mantle affecting the style of convection. For example the endothermic phase change at 660 km depth is supposed to break down convection into two layers. In general, phase transitions are characterised by a density jump $\Delta\rho$ and the Clapeyron-slope $\gamma = \mathrm{d}p/\mathrm{d}T$, where exothermic phase transitions ($\gamma > 0$) enforce convection and endothermic phase transitions ($\gamma < 0$) hinder convection. Since phase transitions correspond to a certain temperature and pressure it is likely that they are affected by the rising internal temperature due to internal heat sources. To examine how, and under which circumstances internal heating influences phase transitions, a systematic numerical study has been carried out using a two-dimensional, isoviscous mantle convection model.

The results exhibit that the phase transition is deflected from its equilibrium depth in the presence of internal heat sources. The strength of this deflection depends on the magnitude of the Clapeyron-slope and the amount of internal heating on the total heat flux. Besides, the study indicates that the transition from single- to double-layer convection gets broader and less sharp for an increased internal heating rate. Using the mass flux across the phase boundary as a measure for the degree of layering, one can show that internal heating produces a more permeable phase transitions if convection is layered. Contrary the phase transition gets less permeable in the case of single-layer convection. Despite the influence of an internal heat production on the equilibrium depth and the width of transition from single- to double-layer convection there is no evidence for a shift of the actual threshold to layered convection, i.e. the critical Clapeyron-slope appears to remain unaffected by internal heat sources.

Self-consistent generation of continental crust in global mantle convection models

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We present preliminary results of our mantle convection code in which the continental crust is generated self-consistently. The silica-rich continental crust appears to have been formed by fractional melting and crystallization in episodes of relatively rapid growth from late Archaean to late Proterozoic eras (3-1 Ga) (Hawkesworth and Kemp, Nature 2006) which has also been linked to the onset of plate tectonics around 3 Ga. It takes several stages of differentiation to generate continental crust. First, the basaltic magma is extracted from the pyrolitic mantle. Second, it goes through eclogitic transformation and then partially melts to form Na-rich Tonalite-Trondhjemite-Granodiorite (TTG) which rise to form proto-continents (Rudnick, Nature 1995; Herzberg and Rudnick, Lithos 2012). TTGs dominate the grey gneiss complexes which make up most of the continental crust. Melting of hydrated basalt at garnet amphibolite, granulite or eclogite facies conditions is considered as the dominant mechanism for generation of Archean TTGs. Based on the melting conditions proposed by Moyen (Lithos, 2011), we parameterize TTG formation and henceforth, the continental crust. Numerical modeling commonly shows that mantle convection and continents have strong feedbacks on each other, but the continents are always inserted a priori while basaltic (oceanic) crust is generated self-consistently in such models (Philips and Coltice, JGR 2010; Rolf et al., EPSL 2012; Heron and Lowman, JGR 2014). We aim to implement self-consistent generation of continental crust in global models of mantle convection by solving equations for compressible Stokes flow using StagYY (Tackley, PEPI 2008). Continental crust can also be destroyed by subduction or delamination. We will investigate continental growth and destruction history in the models spanning the age of the Earth.

3D models of plate collision, slab breakoff and subduction initiation

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Subduction and collision of lithospheric plates is a 3D process, that is frequently modeled in 2D. In many cases, 2D models are sufficient, but in some cases 3D matters. Here I will discuss a number of topics we have recently worked on, using 3D numerical simulations performed with LaMEM that employ (in many cases) visco-elasto-plastic rheologies. The models address: 1) present-day India-Asia collision, 2) the formation of large scale strike-slip shear zones in the Tibetan plateau, and 3) plate collision in the Caribbean where the rifting of North and South America produces a young oceanic plate that was subsequently subjected. Particularly the last topic shows that unexpected results, such as slab breakoff and a switches in the subduction polarity, occur in 3D models as a result of using realistic thermal cooling profiles for the oceanic lithosphere, which you miss in 2D models.

A thermo-mechanical ‘Goldilocks’ regime for impact splash chondrule formation

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Chondrules found in meteorites provide vital clues to the physical and chemical conditions present in the solar nebula from which the planets formed. Their vast chemical and textural varieties pose challenges to understand their formation principles. Diverse mechanisms have been proposed to explain the chondrule origin, including the X-wind model, disk lightning, nebular shocks, and planetesimal collisions. The latter are attractive because they link chondrule formation to important dynamical events that must have occurred near the right place at the right time in planet forming circumstellar disks. To date, some of the greatest drawbacks of collision models are their difficulties in explaining retained metal blebs or rings inside or at the periphery of chondrules, bulk chondrite Fe/Mg ratios, the observed majority of porphyritic textures and intra-chondrite chemical diversity.
Here we present a collision scenario that takes advantage of (i) the expected initial planetesimal size distribution from recent streaming instability models; (ii) renewed understanding of the early thermal evolution of small planetesimals; and (iii) the expected dynamical interactions of the planetesimal swarm in the inner solar system during the first few million years of evolution. In the model chondrules form from low to intermediate velocity collisions of small bodies ($<$ 20–30 km in radius) that are only partially melted from aluminum-26 decay heating, and thus largely preserve metal blebs, bulk Fe/Mg ratios and porphyritic textures.
The model invokes a large diversity of pre-chondrule material composition and is consistent with the vast majority of thermal and chemical constraints. The collision regime favored in this formation scenario poses strong constraints on the timing and location of the formation of the first planetesimals and therefore the onset of terrestrial planet formation.

Heterogeneous layer folding

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When a mechanically strong layer embedded in a weaker matrix is subject to compression, mechanical instabilities in the layer will result in folding of that layer. In nature layer folding can be found on both the kilometer-scale in regions like the Himalaya or the Alps and on the millimeter-scale in rocks. Field observations show that such layers are not homogeneous, but may contain inclusions. The effect of those inclusions on the folding instability is not yet fully understood. For this reason, we study the influence of circular inclusions of the folding instability using 2D numerical models.
We employ the finite element code MVEP2 to compute the mechanical response of a strong layer (containing circular inclusions) under compression. The accuracy of the code has been verified by comparing numerical results of the growth rate of an inclusion-free layer to analytical solutions.
In a next step we consider a strong layer with circular inclusions. Three different inclusion distributions are considered: i) a rectangular lattice ii) a triangular lattice and iii) completely random. We then vary both packing fraction and radii of the inclusions to determine their impact on the growth rate of the folding instability. Preliminary results show that the incorporation of strong inclusions results in a larger effective layer viscosity, which in turn results in larger growth rates and dominant wavelengths. We then investigate whether classical homogenization approaches to determine the effective layer viscosity correctly capture the mean behaviour of the strong layer or whether numerical models are needed to fully describe the mechanical behaviour of a strong layer with inclusions.

Modelling the interior and surface processes of Earth-size or super-Earth bodies

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For planets from Earth's size on, the compressibility, rheology and mineralogy of the solid mantle become increasingly important for the convective behaviour and thus thermal evolution of a planet.
Here we give a review of the current state-of-the-art of modelling of rocks in the high-pressure and -temperature regime, and the implications for the evolution of rocky planets in or outside the Solar System.
We investigate the outgassing efficiency of rocky stagnant-lid planets with masses ranging from Mars-size to super-Earth size for different compositions and interior structures. We find that planets lacking plate tectonics can have strong volcanic limitations if their mass and/or iron content exceeds a critical value, which has significant influences on secondary atmospheres.
Greenhouse gases in the atmosphere allow for liquid water at the surface of the planet for a wide range of distances from the host star (defined as habitable zone). For planets with limited volcanic activity, however, the outer boundary of the habitable zone would move inward (see Fig. 0.1), setting an important restriction to the possible surface habitability of these planets.

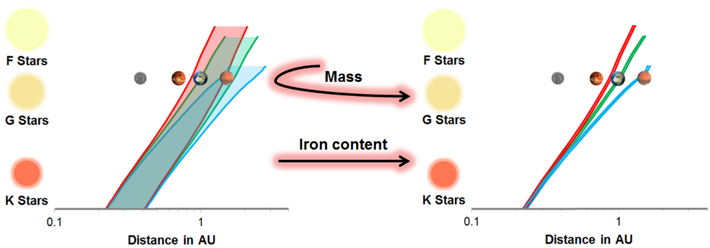

Figure 0.1 Habitable zone without constraints (left) and without greenhouse gases (right) at different stellar ages 0 Gyr (red), 4.5 Gyr (green) and 10 Gyr (blue).

Role of elasticity in stagnant lid convection

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A present limitation of global thermo-chemical convection models is that they assume a purely viscous or visco-plastic flow law for solid rock, i.e. elasticity is ignored. This may not be a good assumption in the cold, outer boundary layer known as the lithosphere, where elastic deformation may be important. Elasticity in the lithosphere plays at least two roles: It changes surface topography, which changes the relationship between topography and gravity, and it alters the stress distribution in the lithosphere, which may affect dynamical behaviour such as the formation of plate boundaries and other tectonics features.
In the present work we study these effects in the context of stagnant lid convection. We use StagYY (Tackley, 2008) enhanced to include elasticity through adding advected elastic stresses to the momentum equation and replacing viscosity by the "effective" one (the method described in e.g. Moresi et al., 2002). First, a test example with a cylinder rising below the lithosphere (Crameri et al., 2012) is considered in various geometries and the effect of elasticity on the resulting topography and geoid is evaluated. Both free-slip and free-surface upper boundary condition is considered.
Second, comparison of stagnant lid convection models with and without elasticity is performed. It is shown that global characteristics of the convection do not change when a realistic value of shear modulus is employed and that the stress pattern in the lithosphere is very similar. The most important effect is that stresses build up gradually when elasticity is considered and thus the stress picture is more stable in the time domain in the elastic than in the viscous case. Viscoelastic lithosphere thus filters internal dynamics more effectively than a purely viscous one, responding only to features which stay stable for times comparable to its relaxation time. This effect is clearly recognizable only when free-surface upper boundary condition is considered. The role of viscosity cut-offs is discussed.

Effects of the differentiation on geodynamic of early Earth

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Archean geodynamic processes are not well understood, and there is an open debate about the mode of convection of the mantle. On the other hand, there are not doubts that the mantle potential temperature was higher than present, and that as consequence significant amounts of melt were produced both in the mantle and in the overlying crust. The differentiation of these melt has likely resulted in the production of a continental like crust and it could had affected the geodynamics of the early Earth (e.g. the depletion of the mantle source could be resulted into a significant compositional changing and thus a density change and viscosity of the depleted mantle). An early attempt to study the relationship between differentiation and mantle dynamics was made by Johnson et al. (2014), who used numerical modelling in conjunction with representative phase diagram to investigate the crust production and its recycle. The results show that there is a positive feedback between the crust production and its recycle. The crust growth induces mineral assemblage changes that create dense material. The dripping of this material into the mantle causes asthenosphere return flow and its partial melting and as a result production of new crust. Whereas the simulations provide useful insight, they were simplified in many aspects: 1) the rheology employed was viscous, and elasticity, pressure dependency of both plasticity and viscous creep law were not considered; 2) the 100 % extracted melt was transformed into volcanic rocks; 3) the effects of the free surface boundary condition were not studied; 4) the effects of the mantle depletion. In order to understand how these simplification affects the development of the experiments, we provide additional simulation to study the effects of these parameters.

Thermochemical evolution of Mercury, the Moon and Mars: Constrains from space missions and planetary samples data

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Over the past decades, numerous space missions to the terrestrial planets of our Solar System have returned a variety of data that helped improve our understanding of the thermochemical evolution of these bodies. Surface features like volcanoes, rifts and tectonic plates are directly linked to the dynamics of the deep interior, and numerical simulations of planetary mantles have become one of the most powerful approaches to understand their formation and evolution.
In this work we discuss the thermochemical evolution of Mercury, the Moon and Mars and present constraints offered by mission data and laboratory analysis of planetary samples. For example, tectonic landforms imaged over the surface of Mercury by MESSENGER indicate a significant cooling of the planet with a radius decrease by as much as 7 km [1]. The Moon is the only planetary body beside Earth on which in-situ heat flow and seismic measurements have been performed constraining the internal heat budget and the interior structure. Moreover, analysis of the samples returned by the Apollo missions has delivered strong evidence for the presence of a liquid magma ocean in the early stage of lunar evolution (e.g., [2]). For Mars, morphological and spectral data indicate that once liquid water was present on its surface, crustal remnant magnetization hints at a past magnetic field and isotopic analysis of the Martian meteorites suggests the presence of geochemical reservoirs that have been preserved in the interior of the planet over its entire thermochemical evolution (e.g., [3]). Moreover, its large volcanic provinces and, perhaps, also the crustal dichotomy are thought to be surface expressions of the planet's interior dynamics.
Future missions will continue to improve our understanding of the processes active in the interior of terrestrial planets. Nevertheless, the link between present-day observations and numerical evolution models is of utmost importance to obtain a global integrated picture of the history of the terrestrial bodies of our Solar System.

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Grain boundary diffusion experiments using the bicrystal setup to test the effect of ionic size

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The solubilities and diffusion rates of different rare earth elements in yttrium aluminium garnet (YAG) polycrystals are important for solid state laser technology as YAG is one of the most extensively used laser media for high power lasers. Polycrystalline ceramic lasers can be produced at lower costs and their efficiency can be optimized by higher doping concentrations along grain boundaries [1]. Lanthanum is believed to improve the optical properties of YAG lasers and acts as a sintering aid [2]. The presence of trace elements, such as Fe^3 , in YAG can quench the emission of laser active elements dependent on concentration so that understanding the diffusion behaviour of La and Fe in YAG is important. Furthermore, grain boundary diffusion governs numerous geological phenomena, such as Coble creep deformation and recrystallization, which affect large-scale geodynamics although occurring on the nm scale (or even below). In our experimental setup we used the direct wafer bonding method to produce a synthetic bicrystal. A lanthanum-, iron-, and magnesium-containing thin-film, deposited by pulsed laser deposition (PLD) perpendicular to the grain boundary, serves as diffusant source. The diffusion experiment was carried out in a gas mixing furnace at 1450°C and ambient atmosphere (air) for 24.1 hours. We investigated the grain boundary structure prior to and after annealing on atomic scale using high resolution TEM (HRTEM) and mapped the concentration distribution of the interested elements by energy dispersive X-ray spectroscopy in scanning (S)TEM. For determining diffusion coefficients from (S)TEM element maps we use a numerical code that simulates diffusion along the grain boundary accompanied by comparatively slow volume diffusion into the bicrystal lattice in 2D. Lattice diffusion is simply governed by the 2D version of Fick's second law, whereas grain boundary diffusion is affected by the segregation factor and the effective grain boundary width. Diffusive flux normal to the boundary, anisotropic lattice diffusion, and surface diffusion are considered, too. Grain boundary diffusion coefficients for La, Fe, and Mg in YAG are extremely high and can be estimated to D_{gb} (La^{3+}, Fe^{3+}, Mg^{2+}) > 3e-16 m^2/s as the end of grain boundary profile is not observed. Primary results show lattice diffusion coefficients for Fe^{3+} and Mg as follows: $D_{lattice}$(Fe^{3+}) = 5e-19 m^2/s and $D_{lattice}$ (Mg^{2+}) = 0.5e-20 m^2/s. La is found to be highly incompatible due to its large ionic size and does not diffuse into the lattice at all. High dopant levels of Fe^3 and Mg in YAG are easily obtainable, whereas homogenous doping with La is more difficult. The present experimental/analytical setup and the numerical code will be used in future work to study REE diffusion along differently oriented forsterite grain boundaries.

A parallel modeling tool for lithospheric deformation

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We describe a software framework LaMEM (Lithosphere and Mantle Evolution Model) focused on the thermo-mechanically coupled modeling of 3D lithospheric deformation. The code employs a staggered grid finite difference discretization together with a marker in cell approach. To achieve scalability on massively parallel computers, we use the discretization objects and solvers from PETSc library. The coupled nonlinear equations are solved by the Jacobian Free Newton Krylov method preconditioned with Galerkin geometric multigrid. We also derive the analytical Jacobian expressions for the visco-elasto-plastic rheology. The code is tested by a range of benchmarks and example problems.

Determining scaling laws from geodynamic simulations using adjoint gradients

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Whereas significant progress has been made in modelling of lithospheric and crustal scale processes in recent years, it often remains a challenge to understand which of the many model parameters is of key importance for a particular simulation. Determining this is usually done by manually changing the model input parameters and performing new simulations. For a few cases, such as for crustal-scale folding instabilities (with viscous rheologies, e.g. [1]) or for Rayleigh-Taylor instabilities, one can use existing scaling laws to obtain such insights. Yet, for a more general case, it is not straightforward to do this (apart from running many simulations). Here, we test a different approach which computes gradients of the model parameters using adjoint based methods, which has the advantage that we can test the influence of an independent number of parameters on the system by computing and analysing the covariance matrix and the gradient of the parameter space. This method might give us the chance to get insights on which parameters affect for example subduction processes and how strong the system depends on their influence.

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Euler-Bernoulli vs. Timoshenko Beam Bending: Does It Matter at Lithosphere Subduction?

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Oceanic lithosphere undergoes permanent deformation during subduction once the stresses exceed the elastic limit. Departures from elastic behavior occur by brittle failure in the shallow lithosphere and by a combination of several low- and high-temperature (viscous) creep processes at greater depths.
For the estimation of viscous bending stresses at greater depth, two specific theories can be employed: The conventional Euler-Bernoulli Beam Theory (EBT), or the more advanced Timoshenko Beam Theory (TBT).
Both theories assume the existence of inextensible lines normal to the central axis by removing the Poisson effect, thus neglecting the ϵ_{xx} strain component, which allows for simpler derivations and the use of one-dimensional constitutive relations for the principle of virtual generalized displacements and equations of motion.
However, in extension of the classical concept, the Timoshenko theory relaxes one of the EBT assumptions and takes into account a shear correction factor that accounts for the shear energy present in the beam while undergoing bending.
Both approaches are compared with respect to a viscously deforming subducting slab of oceanic lithosphere in the deep mantle.

Generation of TTG rocks in the Archean: insight from numerical simulations

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We study the creation of primordial continental crust (TTG rocks) for the first time employing fully self-consistent numerical models of thermochemical convection on a global scale. Starting from a pyrolytic bulk composition and an initially hot core, we first generate oceanic crust and depleted mantle. In our model, the basaltic material is both erupted and intruded at the base of the crust following a predefined partitioning. Second, we track the pressure-temperature conditions of the newly formed hydrated basalt and check if it matches the conditions necessary for the formation of primordial continental crust. We show that the "heat-pipe" model (assuming 100% eruption and no intrusion) proposed to be the main heat loss mechanism during the Archean epoch [2] is not able to produce continental crust since it forms a cold and thick lithosphere. We systematically test various mechanical properties of the brittle domain (friction coefficients). Using our parameter study, we are also able to show that an intrusion fraction close to 70% (in agreement with [1]) combined with a friction coefficient of 0.2 produces the expected amount of the three main petrological TTG compositions previously reported [3]. This study represents a major step towards the production of self-consistent convection models able to generate the continental crust of the Earth.

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A combined petrological geodynamical model for understanding the magmatic evolution of the West Eifel volcanic field

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The dynamics and chemical evolution of a plume related intracontinental volcanic field, above old alpine subducted slabs beneath Europe, are analysed by using a 2D coupled petrological-thermo-mechanical numerical model. To understand the magmatic evolution of a heterogeneous mantle source, a series of 2D numerical experiments are executed that include different initial source compositions, melt extraction algorithm with chemical output of 12 oxides for new generated magmatic rocks and pre-computed phase diagrams from in different degree depleted mantle rocks. The temporal change of the melt chemistry is compared with natural rock samples from Eifel (West-Germany), whose magmatism was supposedly linked to an uprising mantle plume. The developed method tracks the petrological evolution of the source rock and corresponding volcanic and plutonic rocks in a more complex way than previous studies by combining a geodynamic code with a thermodynamic model for magma generation and evolution (pMELTS). Our results show the strong effect of a variable geothermal gradient, amount of extracted melt and plume excess temperature as well as an abnormal enriched plume component, on the magma chemistry and deliver insight into the complexity of intracontinental plume related magmatism. A heterogeneous asthenospheric mantle source in an uprising mantle plume is able to produce two different types of rocks that agree with expectations for the chemical evolution of the West Eifel volcanic field.

Robust Multigrid Solvers for Geodynamics

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We demonstrate several approaches to improving the robustness of linear multigrid solvers for highly heterogeneous Stokes flow.
Multigrid methods provide scalable solvers for this problem, essential for large-scale simulation. However, optimal ("textbook") multigrid solvers can be elusive for problems with non-grid-aligned and large coefficient jumps, yet these problems are often those of greatest scientific interest. In addition to absolute performance, robustness, here characterized by acceptable performance over a set of related problems, is key. To this end, we first present results of using complex preconditioners for a Q2-Q1 finite element code, focusing on the novel component of using incomplete factorizations for local smoothing. We show that this can exhibit useful robustness to geometric distribution of high-viscosity inclusions, when compared to an approximate block factorization (ABF) approach. Secondly, we present results of software development to make these tools available via the composable solver library PETSc: we present a wrapper for the ILUpack library to make approximate factorization of saddle point matrices available, and finally show results of attempts to increase the robustness of the multigrid solver within StagYY by wrapping it in an outer Krylov method.

Lithospheric processes: From oceanic lithosphere accretion to hydrothermal cooling

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The oceanic lithosphere is formed by accretion and partial melting of ascending hot, weak asthenosphere at mid-oceanic ridges (MOR). As a consequence of plate tectonic constraints MORs migrate with respect to each other, but still show symmetric accretion with maximum deviations of up to 10-15%. This is in strong contrast to plate dominated convection on lava lakes which sometimes exhibits extremely asymmetric spreading ridges. Using temperature and stress dependent visco-plastic rheology dynamically self-consistent models of MORs also show symmetric lithospheric accretion accommodated by ridge migration even for cases where asymmetric kinematic boundary conditions are applied at the model sides. Applying lateral temperature variations e.g. by forcing the MOR to override a plume does only marginally force a MOR to deviate from symmetric spreading. This remarkable behavior will be discussed further in view of the contrasting behavior of lava lakes.
The rising asthenosphere exceeds the solidus temperature due to decompressional melting. A long standing problem has been which mechanism focusses the melt towards the MOR. Melt percolation within the framework of two-phase flow with porosity-dependent bulk and shear viscosity resolves this problem [1] and strong asymmetries in melting may be encountered for the case of laterally varying mantle potential temperature [2]. Yet, asymmetric spreading has not been considered in those models.
Once the crust has formed at a MOR and spreads away from the MOR cooling follows the square root age law as a first order approximation. However, at MORs hydrothermal convection is known to strongly affect the cooling history. A parameterized hydrothermal cooling approach [3] is applied to data sets of heat flow and bathymetry. Using a downhill simplex approach best fitting lithospheric cooling and hydrothermal convection parameters are determined, showing that hydrothermal cooling significantly influences plate cooling during the first 10 Ma. Best fit models predict hydrothermal convection decaying exponentially after 5 -10 Ma plate age, the first 1.5 Ma with an open surface boundary condition.

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Finding regions of low and high mixing in geophysical systems using Lagrangian coherent structures

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Extracting coherent structures in dynamical systems is a well known tool for identifying regions of high and low mixing. The earth's mantle's mixing properties for instance are still not well quantified. Since the Prandtl number of the mantle is in the limit of $Pr \to \infty$, the velocity field reacts instantaneous to buoyancy changes and is an indicator for particle motion. Nevertheless, features like intermittent flow reversals ([2]) are known to enhance mixing.
Lagrangian coherent structures are the most attracting or repelling material lines or surfaces in a system and can separate regions of different compositions. It is legit to compute them in mantle convection, because the system is not too turbulent.
We developed a code for extracting Lagrangian coherent structures in several geophysical systems using the method described in [1]. Using the DNS data of Rayleigh-Bénard convection at different Rayleigh numbers from $Ra = 10^5$ up to $Ra = 10^9$, infinite Prandtl number and different aspect ratios $\Gamma = 2$ and $\Gamma = 3$, we extracted coherent structures and also applied statistical analysis on the Finite Time Lyapunov Exponent field. Also a short outlook on applying the method on DNS data of highly turbulent jet-streams to extract regions of higher and lower shear will be given.

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The effects of compositional density variations on topographic-isostatic geoid anomalies and the behaviour of Atlantic-type continental margins

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Lithospheric density and thickness variations are important contributors to the topographic-isostatic geoid anomalies, and Isostatic equilibrium is a good approximation for passive continental margins. In these regions, geoid anomalies are proportional to the local dipole moment of density-depth distributions, which can be used to constrain the density structure and thickness of lithospheric jumps. We consider a five- or three-layer model for the oceanic and continental lithosphere, respectively, composed of water, a sediment layer (both for the oceanic case), the crust, the mantle lithosphere and the asthenosphere. The mantle lithosphere is defined by a mantle density, which is a function of temperature and composition, due to melt depletion. In addition, a depth-dependent sediment density associated with compaction and ocean floor variation is adopted. We analyzed satellite derived geoid data and, after filtering, extracted typical averaged profiles across the Western and Eastern passive margins of the South Atlantic. They show geoid jumps of 8.1 m and 7.0 m for the Argentinian and African sides, respectively. Together with topography data at the conjugate margins these jumps are interpreted as isostatic geoid anomalies and yield best-fitting crustal and lithospheric thicknesses. In a grid search approach different parameters are systematically varied, namely the density and thicknesses of the sediment layer, the oceanic and continental crusts and the oceanic and the continental mantle lithosphere. The set of successful models reveals significant effects of the lithospheric density variation on the topography and geoid. Preferred models predict a sediment layer at the Argentine margin of 3-6 km and at the South Africa margin of 1-2.5 km. Moreover, we derived a linear relationship between, oceanic lithosphere, sediment thickness and lithospheric jumps at the South Atlantic margins.

Thermochemical Piles: Implications for Plate Tectonics

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Thermochemical piles have been considered to explain the seismologically observed large-low shear wave velocity provinces (LLSVPs) beneath Africa and the Pacific [1]. Typically, the formation of piles results from a dense layer covering the core-mantle boundary (CMB), that strongly interacts with the convective currents in the mantle. The dense CMB layer, being a remnant of the magma ocean phase, is swept up by sinking currents to form piles beneath the upwelling currents.

However, dense material does not only act passively in mantle flow, it also has a restoring effect on rising plumes. As a consequence thermochemical piles can have a strong influence on the lithospheric plates. For example, plate mobility is strongly hindered if the piles have a too high density or cover too large a volume [2]. Similarly, the onset of plate tectonics can be hindered.

Utilizing a mantle convection code with a fully rheological model, self-consistent plate formation is studied [3]. The starting condition is set after the magma ocean period, where generally an initial dense layer is assumed to cover the lower model boundary. Here, the hardly constrained density and mass of the compositionally distinct layer have to be assumed ad hoc. Therefore we present a further setup in which a thermochemical CMB layer forms self-consistently as a result of the model's boundary conditions.

In a large parameter setting, the onset time of plate tectonics is analysed. In particular, the density and volume of the piles is varied. Additionally, we consider different initial temperatures. Furthermore, as recent results of magma ocean modelling suggest that the dense particles could have possibly been kept in suspension due to rotational forces [4], we investigate how the depth of a dense layer affects the onset time of plate tectonics.

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A comparison of lithospheric thickness models

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The outermost layer of the solid Earth consists of relatively rigid plates whose horizontal motions are well described by the rules of plate tectonics. Yet, the thickness of these plates is poorly constrained, with different methods giving widely discrepant results. Here, we discuss a recently developed procedure to derive lithospheric thickness from seismic tomography with a simple thermal model. Thickness is calibrated such that the average as a function of seafloor age matches the theoretical curve for half-space cooling. Using several recent tomography models, predicted thickness agrees quite well with what is expected from half-space cooling in many oceanic areas younger than ~110 Myr. Thickness increases less strongly with age for older oceanic lithosphere, and is quite variable on continents, with thick lithosphere up to ~250 km inferred for many cratons. Results are highly correlated for recent shear-wave tomography models. Also, comparison to previous approaches based on tomography shows that results remain mostly similar in pattern, although somewhat more variable in the mean value and amount of variation. Global correlations with and between lithosphere thicknesses inferred from receiver functions or heat flow are much lower. However, results inferred from tomography and elastic thickness are correlated highly, giving additional confidence in these patterns of thickness variations, and implying that tomographically inferred thickness may correlate with depth-integrated strength. Thermal scaling from seismic velocities to temperatures yields radial profiles that agree with half-space cooling over large parts of their depth range, in particular for averaged profiles for given lithosphere thickness ranges. However, strong deviations from half-space cooling profiles are found in thick continental lithosphere above depth ~150 km, most likely due to compositional differences.

Self consistent plate tectonics in mantle convection models: recent progress

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Understanding the origin of plate tectonics is one of the grand challenges in solid Earth geoscience. In global mantle convection models with strongly temperature-dependent viscosity it has long been established that introducing a simple yield stress or friction coefficient gives an approximation of plate tectonics behaviour, but the necessary value is about an order of magnitude lower than laboratory values, indicating that the details of what is happening at plate boundaries are not correctly treated. Nevertheless, despite this limitation, such models can reproduce some of the key statistical characteristics of Earth's plate tectonics. The age-area distribution of oceanic lithosphere is reproduced in 3D spherical models that include continental cratons (Coltice et al., 2012). This distribution is presently ?triangular" but varies with time (Coltice et al., 2013). The plate size-frequency distribution is also reproduced in similar models (Mallard et al. 2016), with the generation of small plates being related to lateral curvature (tortuosity) of subduction zones. Recent models have shown that the presence of laterally varying crust, such as basaltic crust produced by melting, increases the propensity to plate tectonics behaviour, which may help to bridge the gap between laboratory measurements and models (Lourenco et al., 2016). Global models that evolve over billions of years can display different tectonic modes as a function of time. Early tectonics tends to be more episodic with short-lived downwellings. Initial conditions are a problem in such models. To avoid this, we now have the ability to start with a magma ocean and integrate forwards to the present day; such models will be presented.

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Shear localization due to grain size evolution and shear heating: an energy perspective

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Localization of ductile deformation due to thermomechanical feedbacks has been shown to result in intermediate-depth earthquakes and lithosphere-scale shear zones. Recently, it has also been shown that the feedback between grain size evolution and shear heating promotes thermal runaway and pseudotachylite formation.
However, the efficiency of this feedback loop is still not very well constrained as i) the values for material parameters (rheology, grain size evolution etc.) of mantle rocks are still somewhat uncertain and ii) it is not clear which deformation mechanisms are dominant during lithosphere deformation. Recently, dislocation accommodated grain boundary sliding (disGBS) has been suggested to result in strain localization.
Here, I use 0D and 1D numerical models to explore the material parameter space and to assess the relative impact of different material parameters on the thermal and microstructural evolution of a shear zone. I also evaluate the relative importance of different creep mechanisms during that process. To reduce the parameter space, I rewrite the governing equations in terms of their respective energy, which allows to nondimensionalize the governing equations in a consistent manner. The governing equations are then solved using an implicit time stepping scheme. Nonlinear terms are treated using Newton-Raphson iterations.

Calibrating mixing-length theory for highly viscous fluids

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The internal dynamics and thermal evolution of terrestrial planets is mainly governed by the efficiency of convective heat transfer through the viscous mantle [1]. Since it is computationally challenging to investigate a large parameter space while precisely modelling the full convective heat flux, parameterised descriptions of thermal convection are essential. A simple method to calculate quickly the convective heat transport is known as the mixing-length theory [2, 3]. In this study, we present a calibration of the mixing-length parameter in the local mixing-length theory. The parameterisation is derived from a comparison between sophisticated three-dimensional (3-D) numerical experiments and the one-dimensional (1-D) mixing-length theory with a varying mixing length. We find that the mixing length depends on both viscosity contrast and Rayleigh number of the convective system. Moreover, different convective regimes could be identified and corresponding scaling relationships for the mixing length are presented. For mobile-lid convection at low to medium viscosity contrasts, mixing length has to be larger when compared to its conventional formulation as distance to the nearest thermal boundary. Furthermore, peak depth of the mixing length occurs in the mid-region of the convective system. For stagnant-lid convection at high viscosity contrasts, mixing length is substantially lower and its peak depth is found at greater depths. The proposed calibration establishes the mixing-length theory as simple 1-D approach for calculating the thermal evolution of rocky planets.

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Atmosphere–interior co-evolution: Implications for the long-term evolution of the global carbon cycle

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The global carbon cycle plays a key role in regulating the Earth's climate by controlling the concentration of CO_2 in the atmosphere. Its long-term stability is provided by internally-driven processes such as the presence of plate tectonics [1]. However, the tectonic regime of planetary bodies may depend on surface temperature according to recent geophysical studies of Venus [2, 3]. To study the complex interplay between interior dynamics and climate evolution, we present a geophysical model that simulates the cycling of carbon through all relevant reservoirs. A special emphasis is placed on the effect of different convective regimes on both degassing and regassing efficiency. By systematically varying the critical yield stress, our numerical calculations suggest that planets with mobile plates on top of the convecting mantle outgas significantly more CO_2, when compared to their one-plate counterparts. For mobile-lid convection, degassing rates are mainly driven by volcanic activities at regions where cold surface material is transported into the interior. Elevated volcanic activity ensures a steady CO_2 flux from the interior to the atmosphere, which is, in the long run, balanced by removal of atmospheric CO_2 due to silicate weathering. For stagnant-lid convection, degassing is controlled by hot upwellings originating at the core-mantle boundary. Since these mantle plumes need time to rise to the surface, we observe extended periods in which no CO_2 is released into the atmosphere, leading to strong fluctuations in atmospheric CO_2 concentration and surface temperature.

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Exploration of relaxation of peak compactive stress in a high viscous lithosphere

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While studying viscous stresses caused by melt intrusion into a strong lithospheric level numerical models yielded peak values of several GPa. Since these stress amplitudes seem to be too high with respect to the time scale we try to implement an elastic relaxation of volumetric stresses. Therefore, we assume a certain compressibility of the matrix skeleton and if the relaxation time is in the range of time steps stress peaks will be reduced. Arguments and observations from poroelasticity, e.g. Biot's coefficient, possibly could be applied.
Background is a study is to deepen understanding the role of melt processes while the lithospheric evolution by means of numerical modelling. In the sense of plate tectonics, on the one hand, stresses are transferred by stiff lithospheric plates, on the other, lithosphere is deformed, broken, or modified in various ways. Melting often plays an important role but is not easy to model numerically due to all the interactions of physics, phase changes, non-linearities, time scales, petrology, heterogeneities and chemical reactions.
We restrict on a thermo-mechanical model of visco-plastic two phase flow with partial melting. Viscosity is temperature-, stress- and depth-dependent. Freezing and melting are determined by a simplified linear binary solid solution model. The fast melt transport through and into the lithosphere, acting on a short time scale, is replaced by melt extraction and intrusion in a given emplacement level. Numerical approximation is done in 2D with Finite Differences with markers in an Eulerian formulation.
In an appropriate model melt is emplaced; its fluid pressure extends the matrix and freezes. In a high viscous region dilatation generates high compaction pressure. We try to formulate a stress relaxation, realize it in the code and test it. Results, successful or not, will be presented and discussed.

Excursions

On Monday afternoon, there is free time which can be used for excursions. There are several things to do around Lichtenfels (most of them involve the visit of a beer garden at some point). We have collected information for three possible excursions. Excursions will not be guided, thus feel free to make your own arrangements.

Staffelberg hike: The hike from Staffelberg Station to Staffelberg mountain takes approximately 45-60 minutes. Follow the signs mentioning *Staffelberg*. Staffelberg-Klause on top of the mountain offers snacks (Brotzeit) and drinks. From the top of the mountain you can enjoy a beautiful view over the Main valley. A map of the Lichtenfels area is attached.

Bamberg city tour: The city center of Bamberg is a few hundred meters from the train station. Bamberg has a population of approximately 72,000 inhabitants and is one of the few German cities with an intact old town. We recommend you to visit the old city hall on a small island in the Regnitz river and the cathedral from the early 11th century. A map of Bamberg's old town is attached. The tourist information offers audio guides for a fee of 7.90 €(for 4 hours). Alternatively, the guide can also be downloaded as an app from both the iTunes store and GooglePlay (look for "iTour City Guide", the Bamberg tour can be bought for 3.99 €). Note that there are also a number of other apps that also offer information about Bamberg (some of them are for free).

Obermaintherme: The Obermaintherme is 300 m from the Bad Staffelstein train station. It is open until 9 pm. Entrace costs 9 €(7.90 €) for 2 hours, 12.50 €(11 €) for 4 hours and a day pass costs 14.50 €(12.70 €). Prices in brackets are reduced prices for students.

Please keep in mind that sunset will be at **7.34 pm** and dinner will begin at **8 pm**. Those of you not planning to participate in the dinner on Monday, please inform the front desk of Frankenakademie.

There ...

Trains from Schney station to Lichtenfels Station

13.18	Schney (Direction Hof)
13.21	Lichtenfels Station
13.37	Schney (Direction Lichtenfels)
13.40	Lichtenfels Station
15.18	Schney (Direction Hof)
15.21	Lichtenfels Station
16.18	Schney (Direction Bayreuth)
16.22	Lichtenfels Station

Buses from Schney Raiffeisenbank-Volksbank bus stop to Lichtenfels Station

14.43	Bus line 1204 (Direction Lichtenfels)
14.57	Lichtenfels Station
15.43	Bus line 1204 (Direction Lichtenfels)
15.57	Lichtenfels Station

Trains from Lichtenfels Station via Bad Staffelstein to Bamberg Station:

13.56	Lichtenfels (Direction Bamberg)
14.01	Bad Staffelstein
14.18	Bamberg
14.04	Lichtenfels (Direction Nürnberg)
14.08	Bad Staffelstein
14.20	Bamberg
14.36	Lichtenfels (Direction Bamberg)
14.41	Bad Staffelstein
14.59	Bamberg

15.03	Lichtenfels (Direction Nürnberg)
15.07	Bad Staffelstein
15.21	Bamberg
15.36	Lichtenfels (Direction Nürnberg)
15.40	Bad Staffelstein
16.01	Bamberg

... and back again

Trains from Bamberg Station via Bad Staffelstein to Lichtenfels Station:

17.58	Bamberg (Direction Coburg)
18.16	Bad Staffelstein
18.22	Lichtenfels
18.13	Bamberg (Direction Saalfeld(Saale))
18.35	Bad Staffelstein
18.39	Lichtenfels
18.34	Bamberg (Direction Hof)
18.53	Bad Staffelstein
18.57	Lichtenfels
18.38	Bamberg (Direction Sonneberg(Thür))
18.47	Bad Staffelstein
18.52	Lichtenfels
18.55	Bamberg (Direction Lichtenfels)
19.16	Bad Staffelstein
19.21	Lichtenfels
19.13	Bamberg (Direction Kronach)
19.30	Bad Staffelstein
19.35	Lichtenfels
19.36	Bamberg (Direction Jena Saalbf)
19.50	Bad Staffelstein
19.54	Lichtenfels

Trains from Lichtenfels Station to Schney:

17.39	Lichtenfels Station (Direction Bad Rodach)
17.41	Schney
18.38	Lichtenfels Station (Direction Bad Rodach)
18.40	Schney
19.38	Lichtenfels Station (Direction Bad Rodach)
19.40	Schney
21.33	Lichtenfels Station (Direction Bad Rodach)
21.35	Schney

Buses from Lichtenfels Station to Schney Raiffeisenbank-Volksbank bus stop

16.30	Bus line 1204 (Direction Schney Neuensorger Str.)
16.41	Schney Raiffeisenbank-Volksbank bus stop
17.30	Bus line 1204 (Direction Schney Neuensorger Str.)
17.41	Schney Raiffeisenbank-Volksbank bus stop


LICHTENFELS
STAFFELSTEIN
Staffelberg
Vierzehnheiligen
Klosterlangheim
Mistelfeld
Oberlangheim
Uetzing
Frauendorf
Stublang
Loffeld
Horsdorf
Romansthal
Wolfsdorf
Grundfeld
Reundorf
Schönbrunn
Unnersdorf
Unterzettlitz
Seubelsdorf
Oberau
Mönchkröttendorf
Roth
Lahm b. Lichtenfels
Serkendorf
Weingarten
Kösten
Schwabthal
Seeranger
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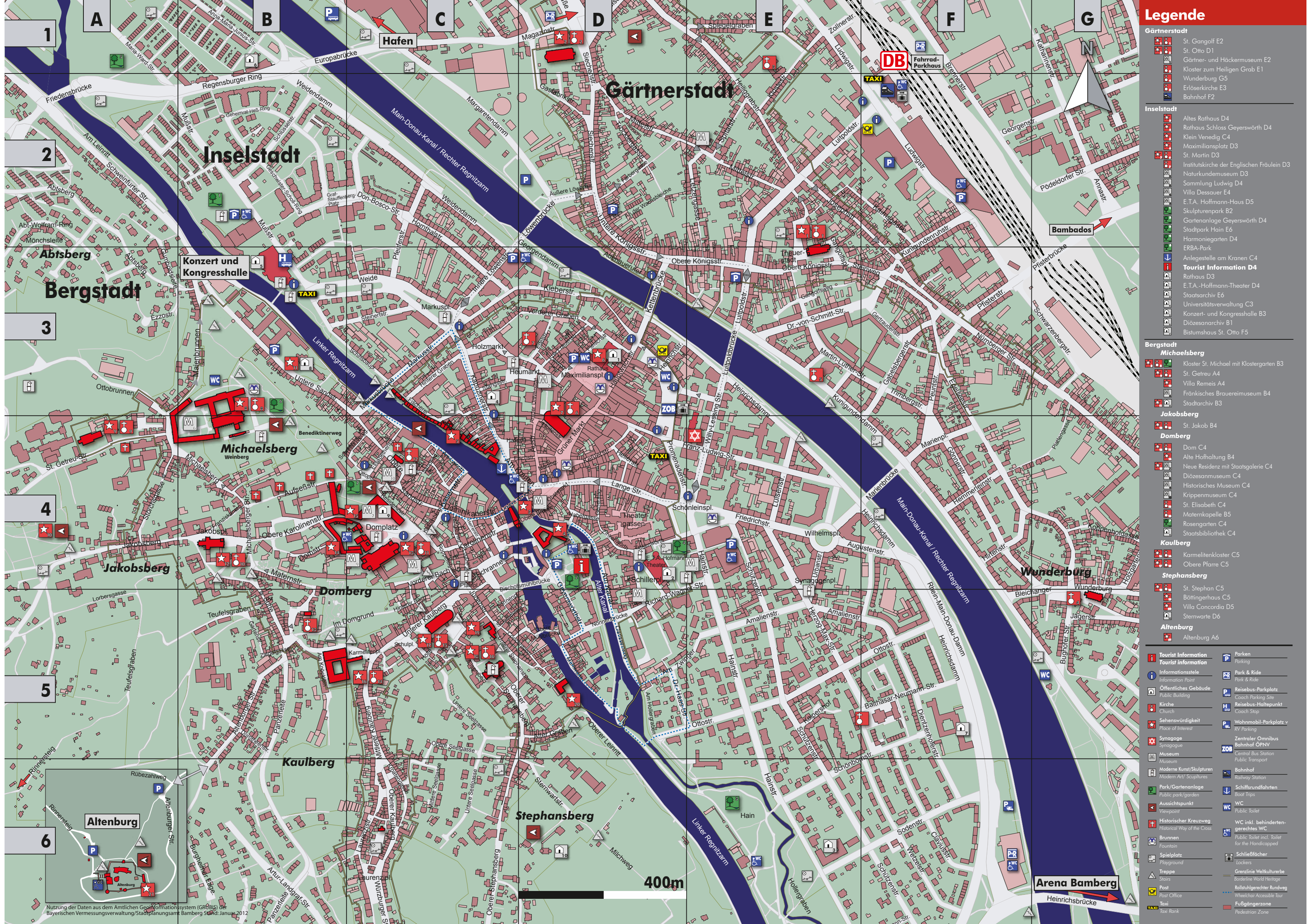
Gärtnerstadt
Inselstadt
Bergstadt
Abtsberg
Michaelsberg
Jakobsberg
Domberg
Kaulberg
Stephansberg
Wunderburg
Altenburg
Hafen
Konzert und Kongresshalle
Bambados
Arena Bamberg
Fahrrad-Parkhaus
DB
Main-Donau-Kanal / Rechter Regnitzarm
Linker Regnitzarm
Rhein-Main-Donau-Kanal / Rechter Regnitzarm
Alter Kanal
Europabrücke
Friedensbrücke
Löwenbrücke
Kettenbrücke
Luitpoldbrücke
Markusbrücke
Marienbrücke
Heinrichsbrücke
Maximilianspl.
Grüner Markt
Domplatz
Hain
400m
N
A
B
C
D
E
F
G
1
2
3
4
5
6
Legende
Gärtnerstadt
St. Gangolf E2
St. Otto D1
Gärtner- und Häckermuseum E2
Kloster zum Heiligen Grab E1
Wunderburg G5
Erlöserkirche E3
Bahnhof F2
Inselstadt
Altes Rathaus D4
Rathaus Schloss Geyerswörth D4
Klein Venedig C4
Maximiliansplatz D3
St. Martin D3
Institutskirche der Englischen Fräulein D3
Naturkundemuseum D3
Sammlung Ludwig D4
Villa Dessauer E4
E.T.A. Hoffmann-Haus D5
Skulpturenpark B2
Gartenanlage Geyerswörth D4
Stadtpark Hain E6
Harmoniegarten D4
ERBA-Park
Anlegestelle am Kranen C4
Tourist Information D4
Rathaus D3
E.T.A.-Hoffmann-Theater D4
Staatsarchiv E6
Universitätsverwaltung C3
Konzert- und Kongresshalle B3
Diözesanarchiv B1
Bistumshaus St. Otto F5
Bergstadt
Michaelsberg
Kloster St. Michael mit Klostergarten B3
St. Getreu A4
Villa Remeis A4
Fränkisches Brauereimuseum B4
Stadtarchiv B3
Jakobsberg
St. Jakob B4
Domberg
Dom C4
Alte Hofhaltung B4
Neue Residenz mit Staatsgalerie C4
Diözesanmuseum C4
Historisches Museum C4
Krippenmuseum C4
St. Elisabeth C4
Maternkapelle B5
Rosengarten C4
Staatsbibliothek C4
Kaulberg
Karmelitenkloster C5
Obere Pfarre C5
Stephansberg
St. Stephan C5
Böttingerhaus C5
Villa Concordia D5
Sternwarte D6
Altenburg
Altenburg A6
Tourist Information
Tourist information
Informationsstele
Information Point
Öffentliches Gebäude
Public Building
Kirche
Church
Sehenswürdigkeit
Place of Interest
Synagoge
Synagogue
Museum
Museum
Moderne Kunst/Skulpturen
Modern Art/ Sculptures
Park/Gartenanlage
Public park/garden
Aussichtspunkt
Viewpoint
Historischer Kreuzweg
Historical Way of the Cross
Brunnen
Fountain
Spielplatz
Playground
Treppe
Stairs
Post
Post Office
Taxi
Taxi Rank
Parken
Parking
Park & Ride
Park & Ride
Reisebus-Parkplatz
Coach Parking Site
Reisebus-Haltepunkt
Coach Stop
Wohnmobil-Parkplatz
RV Parking
Zentraler Omnibus Bahnhof ÖPNV
Central Bus Station Public Transport
Bahnhof
Railway Station
Schiffsrundfahrten
Boat Trips
WC
Public Toilet
WC inkl. behindertengerechtes WC
Public Toilet incl. Toilet for the Handicapped
Schließfächer
Lockers
Grenzlinie Weltkulturerbe
Borderline World Heritage
Rollstuhlgerechter Rundweg
Wheelchair Accessible Tour
Fußgängerzone
Pedestrian Zone
Nutzung der Daten aus dem Amtlichen Geoinformationssystem (GRUBIS) der
Bayerischen Vermessungsverwaltung/Stadtplanungsamt Bamberg Stand: Januar 2012