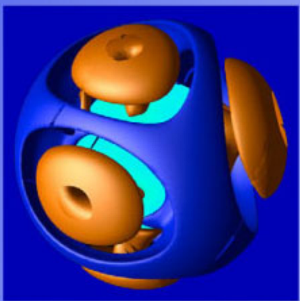
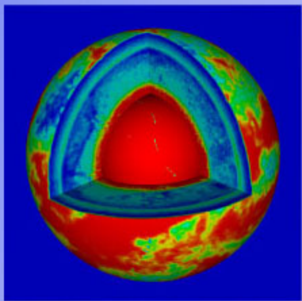
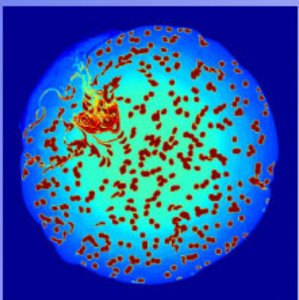
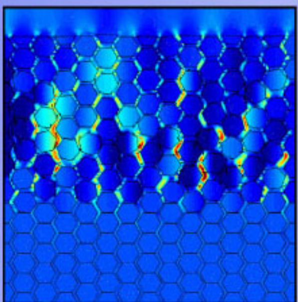
11th International Workshop on Modelling of Mantle Convection & Lithospheric Dynamics

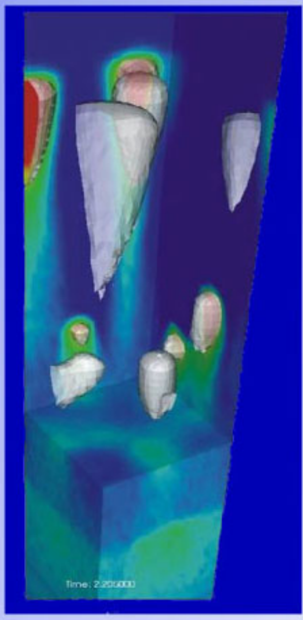
28 June - 3 July 2009, Braunwald, Switzerland











11^{th} International Workshop on Modelling of Mantle Convection and Lithospheric Dynamics

Braunwald, Switzerland
28 June – 3 July 2009

Local Organizing Committee (ETH Zürich)

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Meeting Location

Klausen Resort Hotel Waldhaus
Braunwald
CH-8784 Switzerland
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Sponsors

Swiss National Science Foundation (SNF)
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Contents

Program

Sunday 28 June

Arrival

18:00 Ice breaker reception and dinner

Monday 29 June

Oral session - Lithospheric dynamics & tectonics

09:00 Edi Kissling (ETH Zürich) - Tectonics and geodynamics of the Alps (*p17*)
10:00 Guy Simpson (University of Geneva) - Mechanisms and effects of coupling between tectonics, climate and surface processes (*p21*)
11:00 Break
11:30 Stefan Sobolev (GeoForschungsZentrum Potsdam) - Three dimensional numerical modeling of lithospheric dynamics and transform fault tectonics (*p22*)
12:30 Lunch

Poster session 1 - Lithospheric dynamics and topography

14:00 Short (1 min, 1 slide) advertisements of posters
14:45 Students' meeting with speakers
18:30 Summary & discussion
19:00 Dinner

Tuesday 30 June

Oral session - Plate processes and mantle heterogeneity

09:00 Magali Billen (University of California, Davis) - Subduction zone and slab processes (*p10*)
10:00 Thorsten Becker (University of Southern California) - Past and present seafloor age distributions and the temporal evolution of plate tectonic heat transport (*p10*)
11:00 Break
11:30 Lapo Boschi (ETH Zürich) - The European upper mantle as seen by surface waves (*p11*)
12:30 Lunch

Poster session 2 - Plumes, subduction and links to the deep mantle

14:00 Short (1 min, 1 slide) advertisements of posters
14:45 Students' meeting with speakers
18:30 Summary & discussion
19:00 Dinner

Wednesday 1 July

Oral session - Deep mantle; Numerical advances

09:00 Carolina Lithgow-Bertelloni (University College London): Dynamical origin and consequences of chemical heterogeneity in Earth's mantle (*p19*)

10.00 John Hernlund (University of California, Berkeley) - Deep mantle seismic structure and dynamics (*p14*)

11:00 Break

11:30 Marcin Dabrowski (University of Oslo) - Development of efficient numerical tools for geodynamic modelling (*p13*)

12:30 Lunch

14:00 Students' meeting with speakers

Free time (choice of activities)

19:00 Dinner

Thursday 2 July

Oral sesion - Planetary interiors; Magmas and two phase flow

09:00 Doris Breuer (Deutsches Zentrum für Luft- and Raumfahrt, Berlin) - What do we know about the interior structure, dynamics and thermal evolution of terrestrial planets? (*p12*)

10:00 Richard Katz (University of Oxford) - The dynamics of magma in a convecting mantle (*p17*)

11:00 Break

11:30 Patrick Jenny (ETH Zürich) - Multi-scale modelling of multi-phase flow in porous media (*p15*)

12:30 Lunch

Poster session 3 - Mantle dynamics in Earth and planets; numerical methods

14:00 Short (1 min, 1 slide) advertisements of posters

14:45 Students' meeting with speakers

18:30 Summary & discussion

19:00 Dinner

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Oral session - Differentiation & evolution; Numerical advances

09:00 Henri Samuel (Universität Bayreuth) - The Dynamics and Consequences of Core Formation in Terrestrial Planets (*p20*)

10:00 Stéphane Labrosse (École normale supérieure de Lyon) - Evolution of the basal magma ocean through Earth history (*p19*)

11:00 Break

11:30 David May (ETH Zürich) - Preconditioning variable viscosity Stokes flow problems associated with a stabilised finite element discretisation (*p20*)

12:30 Lunch

14:00 Students' meeting with speakers

Close of meeting and departure

Poster Sessions Program

Poster Session 1 - Lithospheric Dynamics and topography (Monday pm)

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Relationship between variations in spreading rate of the Pacific plate and time-dependent subducting slab dynamics. ***Lee, Changyeol***

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Postglacial rebound with spatially varying lithospheric thickness. ***Schmidt, Peter***

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Abstracts

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Past and present seafloor age distributions and the temporal evolution of plate tectonic heat transport

T. W. Becker[1], C.P. Conrad, B. Buffett, D. Muller, S. Loyd, C. Lithgow-Bertelloni, F.A. Corsetti
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The thermal evolution of Earth is controlled by the convective motion of oceanic plates, and variations in the rates of seafloor generation and recycling have potentially far-reaching consequences for sea level, ocean chemistry and climate. A parameterized framework to describe such variations could guide the study of non-uniformitarian plate tectonic activity, but there is little agreement on the appropriate mechanical description of the surface boundary layer, should it exist. A strong constraint on the statistics of oceanic convection systems comes from the preserved seafloor age distribution, and additional inferences are possible when paleo-seafloor is modeled based on plate motion reconstructions. Based on previously reconstructed seafloor ages, we recently inferred that oceanic heat flow was larger by ~15% at 60 Ma than today. This signal is mainly caused by the smaller plates that existed previously in the Pacific basin with relatively larger ridge-proximal area of young seafloor. The associated rates of change are outside those expected from secular cooling and therefore hint at cyclic behavior in plate tectonics. We also consider area-per-age statistics for the present-day and back to 140 Ma from new paleo-age reconstructions. Using a simplified seafloor age evolution model we explore which physical parameterizations for the average behavior of the oceanic lithosphere are compatible with broad trends in the data. In particular, we show that a subduction probability based on lithospheric buoyancy (√age) leads to results that are comparable to, or better than, that of the probability distribution that is required to obtain the "triangular" age distribution with age-independent destruction of ocean floor. The current, near triangular distribution of ages and the relative lull in heat flow are likely only snapshots of a transient state during the Wilson cycle. Current seafloor ages still contain hints of a ~60 Myr period, cyclic variation of seafloor production, and using paleo-ages for 140 Ma, we find a ~400 Myr best-fitting variation that is broadly consistent with geologically based reconstructions of production rate variations. From the new reconstructions, a consistent decrease of total oceanic heat flow by ~ -0.25%/Myr over the last 140 Ma is inferred. Our study provides some of the required input for an improved understanding of the non-uniformitarian evolution of plate tectonics and the interplay between continental cycles and the self-organization of the oceanic plates.

Subduction zone and slab processes

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Recent dynamical models demonstrate that many different aspects of idealized subduction zones, including the overriding plate, 3D geometry, slab and mantle rheology and mineralogy, and compressibility, do affect slab dynamics and the evolution of subduction zones. However, as each of these factors are added to simple physical models, it is not always clear which ones have a first order effect on processes in all subduction zones, or how these different factors interact. Therefore, we still face a range of unsolved paradoxes in subduction dynamics. For example:

* Some slabs appear to subduct into the deep lower mantle, while others get stuck in the transition zone and mid-mantle: why is it that, so far, only physical models with an unrealistically large clapeyron slope for the 660-km phase change and weak slabs can trap slabs in the mid-mantle?
* Rheological constraints predict that slabs should deform plastically at high effective viscosities: why are physical models with weak or moderately-strong slabs successful?
* Geological observations of surface deformation call for long-term coupling between overriding and subducting plates: why are models without an overriding plate successful?
* Rheological and seismological constraints predict that the upper mantle deforms by dislocation creep (non-Newtonian rheology): why are Newtonian models of slab dynamics successful?
* Tomographic images of slabs in the deep mantle imply significant thickening of slabs (5-10 x): why are most physically-modeled slabs so thin 1.5-2.0 x)?

These paradoxes ask us to consider: Do we have the right answer with the wrong physics? Further advances in understanding the dynamic role of subduction zones in the mantle-convection plate-tectonic system will require systematic incorporation and testing of experimental constraints on material properties in both 2D and 3D models, testing of models using complementary suites of observational constraints, and breakthroughs in modeling methods.

The European upper mantle as seen by surface waves

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We present a new global, three-dimensional tomographic model of horizontally and vertically polarized shear velocities in the upper mantle. The model is based on a recently updated global database of Love- and Rayleigh-wave fundamental-mode phase-anomaly observations, with a good global coverage and a particularly dense coverage over Europe and the Mediterranean basin (broadband stations from the Swiss and German seismic networks). The model parameterization is accordingly finer within this region than over the rest of the globe. The large-scale, global structure of our model is very well correlated with that of earlier shear-velocity tomography models, based both on body- and surface-wave observations. At the regional scale, within the region of interest, correlation is complicated by the different resolution limits associated to different databases (surface waves, compressional waves, shear waves), and, accordingly, to different models; while a certain agreement appears to exist for what concerns the grand tectonic features in the area, heterogeneities of smaller scale are less robustly determined. Our new model is only one step towards the identification of a consensus model of European/Mediterranean upper-mantle structure: on the basis of the findings discussed here, we expect that important improvements will soon result from the combination, in new tomographic inversions, of fundamental-mode phase-anomaly data like ours with observations of surface-wave overtones, of body-wave travel times, of ambient ``noise", and by accounting for an a-priori model of crustal structure more highly resolved than the one employed here.

What do we know about the interior structure, dynamics and thermal evolution of terrestrial planets?

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To better understand our own planet, it is worth taking a look at our terrestrial neighbours. Terrestrial planets have a similar composition and structure, i.e., an iron rich core, a silicate mantle and a crust, and it is generally accepted that the main cooling mechanism is by thermal convection in their mantles. However, although the dynamic processes in the interior are in general similar, they have shaped and influenced these planets differently – considering that mantle convection is responsible for a lot of surface features such as volcanoes and tectonic structures. For instance, the most prominent characteristic of the Earth mantle dynamics, the plate tectonics, does not exist for the other terrestrial planets. These are presently in the so called stagnant lid regime in which convection takes place underneath a rigid plate. But even among the stagnant lid (or one-plate) planets, differences in the dynamics can be identified judging from the planetary surfaces: Venus shows a comparatively young crustal surface with an average age of about 700 Ma that possibly formed during a global resurfacing event. Mars consists of a much older surface with an average age of about 4 Ga but also very recent volcanism has been observed in a few locations. In addition, the Martian surface is dived into two different hemispheres, the crustal dichotomy, with an old, heavily cratered southern hemisphere and a superficially younger northern hemisphere. Although Moon and Mercury are small in comparison with the other terrestrial planets, which suggests that they are comparatively cool and inactive, their volcanic activity has been minor but still long lasting. At the Moon, volcanism has been found in form of mare volcanism, which probably lasted a few billion years. For Mercury, the existence of volcanic regions has been debated since a long time but has been recently confirmed by the two flybys of the NASA Messenger mission. Not only are the planetary surfaces witnesses indicating the large differences between the planets in the dynamics and thermal evolution, also the magnetic fields provide hints for their diversity. Earth generates a present-day magnetic field in its iron-rich core as does Mercury, but the field of the latter is much weaker. Venus, Mars and the Moon lack present dynamo action but Mars and the Moon had an early internally generated field indicated by remanent magnetization of old crust – for Venus data are not available. The question that one can pose from this comparison is how can we explain the observed similarities and differences? Is it simply that the mantle dynamics and the related surface structures reflect the influence of the planetary radius? Probably not, but which further role plays the interior structure, e.g., the relative core size, the mantle phase changes and the composition? In the present talk I want to address these questions and present an overview of what we believe to know today about the interior structure, the dynamics and the thermal evolution of the terrestrial planets.

Development of efficient numerical tools for geodynamic modeling

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Numerical modeling is becoming a standard tool for studying thermo-chemo-mechanical processes in geodynamics. Complex rheology of rocks, non-linear coupling, large deformation, and a wide span of spatial and temporal scales have to be addressed. However, method formulation, computational accuracy, performance of numerical solvers, and code implementation still pose challenges. Modeling the deformation of each heterogeneous rock mass requires a tailored numerical code. One of the challenges is to resolve the interfaces between the rock-forming phases and track their shape evolution during the simulation. Our method of choice is to use body-fitting, deformable computational meshes and finite element method (FEM) discretizations of the Stokes and Darcy equations. Using the mixed FEM formulation ensures the stability of the resulting system of linear equations. Employing unstructured FEM allows a straightforward implementation of the mesh refinement based on an a posteriori error estimate. Adaptive remeshing increases the accuracy of calculation without adding an excessive number of mesh nodes to the model and is especially suited for problems involving strongly localizing deformation, as encountered in anisotropic or non-linear materials. The drawback of using unstructured FEM rather than finite volume methods (FVM) is an increased code complexity. More importantly, efficient solvers such as geometrical multigrid cannot be used. Yet, trade-off between the gained accuracy and the difficulties arising during the solution step should be thoroughly examined. In this context, I suggest as a benchmark the numerically and analytically obtained pressure and stress fields inside and outside an ellipsoidal heterogeneity using FVM/FEM methods and structured/unstructured computational meshes. The mixed FEM discretization of both Stokes and Darcy problems results in an indefinite system of linear equations. In our 2D Stokes solver MILAMIN, we exploit the block structure of the global matrix. The Schur complement technique allows us to restore the positive-definiteness of the solved systems. Preconditioning the outer pressure iterations with the penalty method decreases the conditioning number. We employ a sparse direct solver performing the Cholesky factorization in the inner iterations. However, this approach fails in 3D due to a prohibitive scaling of the direct solver, both in terms of memory usage and computation. In this case, we resort to Krylov space methods. Here, several issues arise in the context of unstructured FEM, e.g.: an efficient and scalable implementation of the sparse matrix-vector multiplication, or the choice of a suitable preconditioner. During my talk, I will compare the results of numerical simulations with analytical solutions of the inclusion/host problem, effective mechanical properties of composite materials, porous convection and viscous folding.

Deep mantle seismic structure and dynamics

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Models Seismic imaging of the deep mantle and improved mineral physics experiments at deep mantle pressures and temperatures is revolutionizing our understanding of dynamical processes in the core-mantle boundary region. A critical task is to interpret these features in a dynamically self-consistent way in order to obtain a integrated theory for the structure and evolution of the deep mantle. Sometimes the results are surprising and unexpected, and I will discuss several examples. One area of current interest is the presence of partial melt, which has been advocated to explain low shear velocities in the deep mantle at both large and small scales. However, the expectation of melt buoyancy is that melt would have drained out of the pore spaces it occupies in solid inter-granular intersticies by percolation and compaction long ago, rendering a partially molten state implausible over geological time scales. However, when considered in the broader context that structures in the deep mantle undergo viscous deformation, one finds that melt buoyancy is almost completely irrelevant in some cases and that matrix stresses often dominate melt migration. Another exciting area under rapid development is the equilibrium between perovskite (Pv) and post-perovskite (pPv) phases of MgSiO$_3$, which also involves solid solutions in ferrous iron and alumina that broaden the two-phase region of the Pv-pPv phase diagram that complicate interpretation of the seismic discontinuities in D". I have used analytical and numerical models to explore how this affects the formation of pPv and any related seismic discontinuities in the deep mantle, and the additional conditions this imposes on deep mantle heat flux and temperature variations. Contrary to many people's expectations, a broadening of the two-phase region does not lead to a similar broadening in the gradient of phases and seismic velocities. In actuality, the gradient becomes even sharper at the top (and bottom, in the case of a pPv double-crossing) when a larger two phase region is present, even when the two phase region is large enough to prevent the extinction of the Pv phase in the core of the pPv-bearing region. Finally, one of the major goals of all these studies is the determination of heat flux variations in the deep mantle from seismic constraints. It is possible to cast the problem for inversion of temperature, pPv fraction, and composition variations in a way that combines most of the uncertainties in just a few parameters. Interestingly, the results of the inversions are roughly the same over a very large parameter space, implying that the basic picture of chemically distinct low shear velocity provinces and pPv coupled primarily to temperature variations in the surrounding mantle is very robust.

Multi-scale methods for flow and transport simulations in heterogeneous porous media

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Flow and transport problems arise in many areas of engineering and natural science, e.g. in hydrology, oil reservoir simulation and CO_2 sequestration. In order to perform accurate and efficient calculations, the simulation algorithms and codes have to cope with the typically large problems, which often involve highly heterogeneous permeability fields with complex spatial correlation structures. Due to computational limitations, it is in general not possible to resolve all relevant scales and therefore, from early on, upscaling techniques have been developed and are still applied with considerable success [3]. However, in particular if multi-phase flow is considered, it is difficult to obtain accurate results with upscaled models, in which the fine scale variability of the solution is disregarded. This shortcoming has been addressed with multi-scale methods by including a reconstruction step, i.e. such methods target fine scale solutions of the flow and transport problems. Several techniques have been developed and most of them can be categorized as multi-scale finite element methods (MsFEM) [5], multi-scale mixed finite element methods (MsMFEM) [1], or multi-scale finite-volume (MSFV) methods [6]. All these methods have in common that they rely on basis functions, which are numerically computed on local domains, where the fine-scale permeability field of the original problem is employed. Fine scale pressure and/or velocity solutions are approximated by superpositions of these basis functions and the coefficients are computed by solving a coarse system. The only approximation compared to a direct solution of the problem consists in the local boundary conditions, which are required in order to compute the basis functions on their local domains independent of the global solution. Different are the three multi-scale approaches with respect to the number of degrees of freedom (dof) of the resulting coarse problems and with respect to the reconstructed fine-scale velocity fields. There exists one dof/coarse cell in the coarse problems of MsFEM and MSFV methods. In MsMFEM on the other hand, dof not only include coarse pressure values, but also mean velocities at all coarse cell faces. A disadvantage of the MsFEM compared to the other two approaches is their inability to provide a conservative fine-scale velocity reconstruction, which is important if also transport equations have to be solved. All these methods have been applied for a large variety of elliptic problems and in order to reduce the rate of recomputing the basis functions as e.g. the mobility evolves, an adaptive strategy was introduced, and in order to apply large time steps, a sequentially implicit solution algorithm based on Schwarz overalp for transport was devised. Later, the MSFV framework was extended for compressible multi- phase flow [8] and the introduction of correction functions [9] allowed to include gravity, capillary pressure and complex wells [11,7]. An important development is a recently published iterative MSFV (iMSFV) method, which allows to use the multi-scale framework as an efficient linear solver [4]. This is achieved by iteratively improving the localization boundary conditions based on the previous MSFV solution. In algebraic form, the iMSFV method can be interpreted as a particular two level domain decomposition or multi-grid method [10]. This is of interest, since it allows more easily to apply multi- scale methods in combination with general unstructured grids. An attractive aspect of the iMSFV method is that it can be applied anywhere between the original MSFV method an a fine-scale linear solver and that the resulting velocity field is always conservative. Moreover, it was shown that infrequent updates of the localization conditions is sufficient, thus in practice the iMSFV method is not significantly more expensive than the original MSFV method. A further topic is multi-scale modeling of transport, which becomes more relevant as the cost for the flow computations is significantly reduced. A successful strategy consists in adaptively switching between coarse and fine transport equations depending on the local saturation/concetration variation. However, efficient and accurate treatment of transport in heterogeneous porous media remains a challenging research topic with many open questions. Finally, the presentation will cover the potential of such multi-scale methods for multi-physics applications, e.g. for coupled systems, where different sub-domains are governed either by the Navier-Stokes equations or Darcy's law [2].

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The dynamics of magma in a convecting mantle

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I will derive and review a standard formulation of the "magma dynamics" equations governing conservation of mass and momentum for the magma/mantle system. To build insight into the behavior of the system, I will review the results of a series of model calculations of increasing complexity. These calculations will focus on wave and localization phenomena in magma dynamics. I will then show how a thermodynamic formulation adapted from the metallurgical literature (the Enthalpy Method) can facilitate the solution of tectonic-scale problems in magma-dynamics. Enthalpy Method-based simulations of magma genesis and transport beneath a mid-ocean ridge will be presented as an illustration of the power of this approach.

Tectonics and geodynamics of the Alps

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This presentation aims to serve as an introduction to geology, tectonics, and geodynamics of the Alps in combination with the proposition of a few plate tectonic hypotheses testable by geodynamic modeling that are based on current knowledge of deep structure and orogen evolution. By modeling Alpine lithospheric structure with simplified generic plate-tectonic processes we aim to further our understanding of current and past orogenic driving forces.

The Alps are the product of a classical Wilson cycle that begun with the opening of the Alpine Tethys between Eurasia in the north and Africa -with Adria attached- in the south in mesozoic times. In contrast to the wide ocean further east, by mid cretaceous time the western Tethys consisted of a series of relatively small ocean basins of different ages interconnected by even narrower channels largely underlain by oceanic and sometimes by extended continental lithosphere. Furthermore, the region between the two large plates over the past few 100Ma contained a number of small-sized and micro-continental plates that variably separated from and amalgamated with the larger plates similar to the current situation in the Mediterranean. Convergence between the two large plates Africa and Europe since late cretaceous lead to subduction of oceanic lithosphere and subsequent collision of continental lithosphere in the tertiary. A number of peculiarities, however, distinguish the Alpine orogeny from others and they left their specific marks clearly visible in current deep lithosphere structure and tectonics. Presently, the Alps exhibit an uplift rate of about 2mm/y, a similar erosion rate and in relation to this vertical motion a very slow convergence rate of only 1-2mm/y. This slow convergence corresponds with relatively short and small lithosphere mantle slabs that exert only limited pull to the Adriatic micro plate in the south and negligable pull to the large Eurasian plate. Furthermore, geometry of the two slabs and lower crustal indentation structure in the Central and Western Alps suggests the subduction-collision zone is largely locked. The two almost opposing slabs correspond well with surface geology where in the east the Austraalpine nappes –remnants of a cretaceous orogeny- are thrusted over the tertiary orogen particularly well exposed in the western and central Alps.

The European lithosphere slab is obviously denser than asthenosphere and is to weak to elastically support its own weight. Rather, it hangs beneath the Central Alpine crustal root adding to the isostatic load of the orogen. Recent studies about Alpine isostasy confirmed earlier findings that the central Alps have a much to large crustal root compared with the topographic load and in relation to a to positive Bouguer gravity anomaly. As we know today from seismic tomography results, the bouyancy of the large crustal root of up to 28km is compensated by the topographic load and by the load of the mantle lithosphere slab still attached to European continental lithosphere in the western and central Alps. The stress field derived from focal mechanisms of local earthquakes in the western Alps shows compression in the northern foreland and southern hinterland and extension in the axial region of the orogen. This peculiar stress distribution in and alonside the orogen may be interpreted as the result of slow continued convergence of Europe and Adria in combination with isostatic rebound of the axial orogenic region due to erosional unloading of topography and shifting of the load excerted by the mantle lithosphere slab due to northwestward migration of crustal delamination.

The length of the remaining lithospheric slab attached to Europe and estimates of postcollisional crustal shortening coincide well lending further support to the hypothesis of oceanic lithosphere slab break-off upon continent-continent collision. By applying this kind of lithosphere rather than crustal balancing technique, we may also attempt to unravel some earler stages in the evolution of Alpine orogeny. One of the intriguing peculiarities of Alpine orogeny is the closure of small ocean basins like the Penninic ocean or the even smaller Valais trough by subduction and another the clearly southvergent subduction of Alpine Tethys while the Adriatic micro continent moved north. Based on paleomagnetic record, Europe did not move south significantly during the past 120 My. Rather, Africa sometimes jointly with the Africa-derived micro plate Adria moved first east, then northeast, and finally north. In addition to the northward migration, for Adria a 30 degree anti clockwise rotation is also documented. Furthermore, during this subduction slivers of upper continental crustal layers now forming the Penninic nappes were exposed to pressures correlating up to 100km depths followed by excessively fast exhumation rates. A simple solution to explain all these observables in a plate tectonic context is provided by a model of slab roll back affecting the oceanic lithosphere of the Alpine Tethys basins. Very strong bouyancy contrast between the upper crustal slivers like the Brianconnais and the felsic Penninic nappes on one side and the dense oceanic or oceanized mantle lithosphere led to delamination of the crustal units during subduction and their rapid exhumation within the non-compressive subduction channel.

The subduction of the oceanic lithosphere was followed by continent-continent collision when the continental part of the European plate was reached by the retreating trench and was forced to enter subduction beneath the Adriatic plate. As long as the continental crust is attached to mantle lithosphere, continental lithosphere as a whole is bouyant. Hence, subduction of European lithosphere slowed significantly, inevitably causing extreme stress and necking in the long slab near the continent-ocean transition. The weight of the subducted oceanic lithosphere –of Alpine Tethys basins– forced the European lithosphere below the Adriatic plate that continued to move slowly toward NNW. Eventually, the long oceanic slab broke of and the collision continued further by delaminating the European mantle lithosphere and wedging of the continental crust. Once the continental crust has been sheared off, the denser mantle lithosphere sinks in the asthenosphere again starting to roll back since it remains attached to the European plate. This roll back delamination process is very slow since most of the original slab weight has been lost due to break off and since it is controlled by the delamination process near Moho level.

Evolution of the basal magma ocean through Earth history

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Accretion of the Earth and its segregation into a dense iron core and a silicate mantle provided enough gravitational energy to melt a large fraction of the mantle. Because of the complex chemistry of the mantle and the important pressure range involved, the density difference between melt and solid in equilibrium has been predicted to change sign at some intermediate depth, which could lead to crystallisation from that depth both up- and downward, therefore defining two independent magma oceans. Whereas the surface magma ocean is thought to freeze in a few 10 Myr, the basal magma ocean (BMO) crystallisation is limited by heat transfer across the overlying solid mantle and the thermal equilibrium with the core and is found to freeze on an e-folding time-scale of about the 5Gyr. This naturally explains the present observations of partial melt at the bottom of the mantle, as commonly invoked to explain the ultra low velocity zones (ULVZs). The low viscosity of the dense melt makes it unlikely to be entrained by convection in the solid mantle and the BMO therefore represents an ideal hidden reservoir for geochemistry. The inventory of the Earth in incompatible elements can be closed when compared to chondrites if the residual melt, the ULVZs, have a concentration in these incompatible elements comparable to that of the crust. In this case, about 4 TW of heat production is currently produced in these zones and, when extrapolated backward in time, this can lead to an important shielding of core cooling. The cooling of both the basal magma ocean and the core must pass the bottleneck of convection in the solid mantle, so that an initially massive BMO leads to a very slow cooling of the core early in Earths history. In some cases, the geodynamo can only start about 1Gyr after core formation. The thermodynamical model of the basal magma ocean therefore provides a framework in which the present seismic observations of the deep mantle, geo- and cosmochemistry and paleomagnetism can be combined to provide informations on the conditions pertaining to formation of the Earth.

Dynamical origin and consequences of chemical heterogeneity in Earths mantle

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Recent geophysical studies have highlighted the importance of seismic anomalies of non-thermal origin, including the anti-correlation of density and bulk sound velocity with shear-wave velocity in the lowermost mantle. Many explanations for these features have focused on variations in iron and calcium content, but without any genetic connection to geodynamic processes. On the other hand mantle convection simulations have shown for quite some time that the separation of basaltic crust from the rest of the slab gives rise to a mantle, which is chemically heterogeneous at all scales, and where there is likely a compositional gradient driven by the segregation of basalt into the lower mantle. This picture has important

consequences for the 1-D and 3-D seismic structure of Earths mantle. I will touch upon recent and old results that focus on subduction as the primary driver of thermal and chemical heterogeneity in Earths mantle, combining a self-consistent thermodynamic method for predicting phase equilbria and physical properties with instantaneous models of mantle flow to look at the seismic and thermal structure of the mantle in the asthenosphere and transition zone as well as global surface fields such as plate motions, dynamic topography and the geoid.

Preconditioning variable viscosity Stokes flow problems associated with a stabilised finite element discretisation

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The polynomial pressure projection stabilisation [1] of the finite element discretisations for Stokes flow is an alternative spatial discretisation to classical mixed finite element methods. The stabilised approach permits equal order, bilinear (2D) / trilinear (3D) interpolation for both the velocity and pressure spaces. Such a formulation is attractive as it is simple to implement in contrast to macro element techniques and in addition, the same mesh data structure can be used for both the velocity and pressure fields.

In this talk I will (i) demonstrate the reliability and accuracy of the stabilised discretisation when applied to variable viscosity Stokes flow and (ii) describe a robust and optimal preconditioning strategy for the resulting discrete flow problem.

To valid the effectiveness of the proposed preconditioner, I will present results from a number of numerical experiments which utilise a wide range of different viscosity structures motivated from models of mantle convection, melt migration, viscous buckling and lithospheric deformation.

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The dynamics and consequences of core formation in terrestrial planets

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Core formation is the first major differentiation event that sets up the initial conditions from which terrestrial planets have evolved until the present. Geochemical chronometers suggest this early stage of evolution was completed within less than 100 Myrs for planets such as the Earth or Mars. During this relatively short time window, various overlapping processes acting on a broad range of time and length scales have occurred. Among them, the gravitational separation of metal and silicates in terrestrial planets is likely to generate substantially large amounts of heat by conversion of potential energy into thermal energy via viscous heating. This gravitational heat release for an Earth or a Mars-like planet represents a temperature increase of a few hundred to a few thousand degrees Kelvin. This heat combines with a comparable amount of energy provided by the impact of incoming accreting planetesimals and heating provided by the disintegration of short-lived nuclides. Diffusion also plays an important role in redistributing heat and chemical species within the young planet. For instance, the overabundance of siderophile elements in present day Earth's mantle indicates that during core formation, significant chemical exchanges between metal and silicate phases have occurred. Although observations help constrain the mechanisms of core formation in terrestrial planets, various possible scenarios remain to be tested dynamically in order to answer fundamental questions, such as:

What is the most likely core formation scenario for a given terrestrial planet? What is the corresponding timing for complete core formation? What is the chemical state of a young planet after its core has been formed? How does gravitational and impact heating partition between the metallic core and the silicate mantle?

Addressing these questions requires a multi-disciplinary approach in which challenging geodynamic modeling is coupled to mineral physics and geochemical considerations. I will present the results of geodynamic studies that focus mainly on negative diapirism, a plausible core formation in which metal diapirs sink through a lighter solid, partially molten, or fully liquid proto-mantle. Practically, we model numerically the sinking of a single iron-rich diapir through a lighter viscous silicate proto-mantle. We varied systematically over broad ranges the governing quantities such as the diapir Reynolds number (covering both creeping flow and intertial regimes), the amount of viscous heating and rheological parameters. We derived simple scaling laws to describe the heat partitioning and chemical exchanges between the metal and silicate materials. These scaling laws can subsequently be applied to planetary scales, using parameterized accretion-differentiation models.

Mechanisms and effects of coupling between tectonics, climate and surface processes

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Although it is recognized that tectonics, surface processes and climate are linked, the mechanisms of coupling and feedback underlying this coupled system remain poorly defined and understood. Tectonic processes create and destroy topography which modifies climate by changing patterns of ocean and atmospheric circulation and enhancing orographic precipitation. On the other hand, the climate modifies erosion and sedimentation rates and thus potentially affects tectonics in several ways. First, erosion and sedimentation cause isostatic adjustment of the lithosphere, leading to changes in rock and surface uplift. Second, because thickening related to deformation requires work against gravity, erosion, by reducing topography, makes continued deformation more favorable. Third, rapid erosion coupled with deformation may advect hot and thus weak rock into the upper crust, causing it to weaken and further localize deformation. These different mechanisms operate over different time and length scales and will involve different strengths of coupling between surface processes and tectonics. In some cases, erosion and deposition may be coupled to tectonics without influencing it. In others, one can anticipate coupling involving dynamic feedbacks, leading to self regulation. In this presentation I will review, discuss and give examples of these various mechanisms responsible for interactions between tectonics, climate and surface processes. The focus will be mainly on how erosion and sedimentation influence the internal deformation of evolving fold-thrust belts and accretionary prisms. Finally, I will address whether erosion and deposition at the surface are relevant to deeper geodynamic processes.

Three dimensional numerical modeling of lithospheric dynamics and transform fault tectonics

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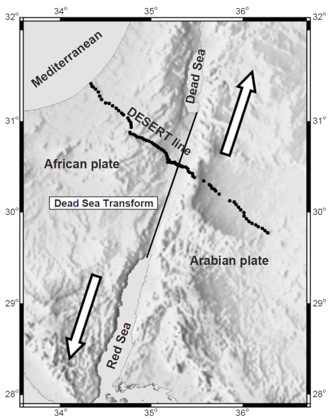
Although Earth's lithosphere is 3D and has complicated non-linear rheology, in many cases the geodynamic problems can be fortunately reduced to 2D and to simplified linear rheology, which is one of the reasons of enormous progress in geodynamics during last few decades. However, sometimes neither 3D nor complicated rheology can be avoided. I'll focus here on those particular cases. One of them is birth and evolution of continental transform plate boundaries. Lithospheric-scale transform faults are zones of localized large shear strain. Proper modeling of strain localization within lithosphere requires elasto-visco-plastic rheology. Moreover, high strain rates typical for plate boundaries, force to consider non-linear ductile flow lows. In our modeling we use different self-developed FEM thermo-mechanical techniques, capable to deal with such rheology in extended 2D [1] or in 3D [2,3].

The classic example of the continental transform boundary is the Dead Sea Transform (DST) which accommodates about 105 km of left-lateral strike-slip motion between African and Arabian plates during the last 15-17 Mln. years. Modeling [1] demonstrates that DST localizes in the region of minimum strength controlled by thicknesses of the crust and lithosphere and dramatically modifies viscosity of the lithosphere (Fig.1).



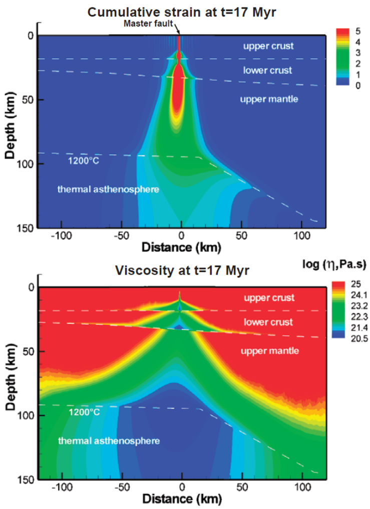


Fig.1. Left: Dead Sea Transform. Right: modeled [1] distribution of cumulative strain (upper section) and viscosity at the cross-section normal to the DST at DESERT seismic line

I'll show our recent model of localization and evolution of the DST driven by dynamic boundary conditions. This model fits very well geological observations and suggests that strain localization at the DST may have been triggered by thermal erosion of the lithosphere of the Arabian Shield that happened some 20 Mln. years ago, probably in relation with the rifting in the Red Sea. The characteristic feature of the DST is also a string of pull-apart basins, with the more than 10 km deep Dead Sea basin as a most well-known one. Modeling [2,4] demonstrates that existence of a pull-apart basin itself as well as the thickness of its sediments, topography of Moho and intracrustal boundary constrains friction at the bounding transform faults, thickness of the brittle layer and viscosity of the lower crust and mantle lithosphere beneath the basin. For instance ductile rheolgy of the lithosphere beneath the Dead Sea basin appears to be controlled by Peierls creep with the Peierls stress up to 2 times lower than experimental data for the dry olivine.

Another example of the essentially 3D and complex-rheology process is global motion of plates and net rotation of the lithosphere driven by mantle convection. We use a thermo-mechanical technique [3] to model a 300 km thick upper layer of the Earth in 3D assuming for it a non-linear temperature- and stress-dependent visco-elastic rheology according to laboratory data for crustal and mantle rocks, combined with Mohr-Coulomb frictional plasticity. The mantle below the 300 km depth is modeled using Hager and O'Connell's mantle flow spectral modeling technique with present day density and viscosity distribution based on either interpretation of global seismic tomography or history of subduction. The upper layer and mantle modeling domains are coupled by continuity of tractions and velocities at 300 km depth. Plate boundaries are represented by the narrow zones of elasto-visco-plastic rheology with much lower frictional strength than within the plates. Modeling shows that deep convection generates plate tectonic-like velocity pattern only when effective friction at subduction plate boundaries becomes less than 0.1. Both magnitudes and directions of plate velocities are reproduced very well at friction in subduction zones around 0.005-0.05 and friction at other plate boundaries of 0.05-0.1. The best fit of the plate velocities as well as of the net rotation of the lithosphere is obtained assuming that asthenosphere is significantly more "wet" than lithosphere.

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Abstracts

Poster Presentations

Coseismic subduction zone strain-release as a constraint for slab dynamics

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Slab rheology and the lateral viscosity variations in the ambient mantle in subduction zones are key controls on upper mantle dynamics but still poorly constrained. We analyze the co-seismic strain-rates that are recorded by the global centroid moment tensor (gCMT) catalog in conjunction with the temperature anomaly distribution and slab morphology that can be inferred from seismic tomography. Mantle flow modeling puts seismic strain-rates into the context of regional subduction dynamics and global mantle circulation, and our goal is to arrive at a globally consistent model of plate motion and slab deformation.

Our analysis of gCMTs confirms the global patterns that were established by Isacks and Molnar [1] where intermediate depth in-slab extension merges into deep in-slab compression in some, but not all subduction zones. We find that weak slabs (~250 times the upper mantle) and a strong lower mantle (~10-100 times the upper mantle) provide the best match to global strain patterns for simple dynamic models. The large increase of seismic data over the last tens of years allows spatial refinements of Kostrov summations. Those show ubiquitous, second-order complexity on regional scales, perhaps due to effects such as slab tears. Our fluid dynamical modeling builds on the 2-D analysis of Vassiliou & Hager [2] and regional 3-D studies by Billen & Gurnis [3]; we strive to explore the role of improved temperature- and depth-dependent slab strength, and kinematic boundary conditions.

A better understanding of the interaction of the large-scale flow with subducting slabs as imaged by seismicity motivates improved 3-D models. Those can provide background information for what slab deformation states are predicted based on global plate dynamics, and what component of strain-release may be indicative of regional, possibly transient tectonic effects.

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3-D Spherical modelling of the thermo-chemical evolution of Venus' mantle and crust

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Several first-order aspects of the dynamics of Venus' mantle remain poorly understood. These include (i) how Venus' mantle loses its radiogenic heat, which is expected to be about the same as Earth's, despite the presence of stagnant lid convection. Hypotheses that have been advanced (summarised in [1]) are conduction through a thin lithosphere, episodic overturn of the lithosphere, magmatic heat transport, and concentration of almost all heat-producing elements into the crust, but there are problems with all of these taken individually. A thick lithosphere may not be consistent with admittance ratios, magmatic heat transport would require a too-large resurfacing rate, and a large concentration of heat-producing elements in the crust would cause weakness and possibly melting in the deep crust. (ii) The relatively long-wavelength distribution of surface features, which is surprising because numerical models and analogue laboratory experiments of stagnant-lid convection produce relatively short-wavelength convective cells. (iii) The inferred (from crater distributions [2]) relatively uniform surface age of 500-700 Ma. (iv) Whether the highlands are above mantle downwellings as on Earth or above mantle upwellings [3]. To study some of these questions, we are performing integrated thermo-chemical convection modelling of Venus' evolution over 4.5 billion years, in 3-D spherical geometry as well as 2-D spherical annulus geometry [4]. These models include realistic ("laboratory") rheological parameters for diffusion creep and dislocation creep based on [5][6], which are also composition-dependent, and plastic yielding based on Byerlee's law, which might cause changes in tectonic regime (e.g., episodic plate tectonics). Crustal formation and the resulting differentiation of the crust and mantle are modelled using a self-consistent melting criterion and the mean age of the crust. Phase transitions in both the olivine system and pyroxene-garnet system are included. The concentration of heat-producing elements is assumed to be the same as in bulk silicate Earth and decreases with time, and cooling of the core is tracked using a parameterised core heat balance. Geoid and surface topography are calculated using a self-gravitating formulation. Thus, the model constitutes an attempt to incorporate as much realism as is presently feasible in global-scale 3-D spherical simulations. Simulations are performed using StagYY, which uses a finite volume multigrid solver on the Yin-Yang spherical grid [7], and is developed from the earlier cartesian Stag3D [8]. We are running a systematic suite of simulations varying uncertain properties and parameters related to rheology, melting & eruption, initial condition. We compare model results to observations of surface topography (e.g. hypsometric distribution), geoid (e.g. admittance ratios), mean surface age and distribution of surface ages, crustal deformation rates in the last part of the evolution (e.g., [9]), crustal thickness and the time evolution of heat flux through the CMB. Of particular interest is whether a smooth evolution can satisfy the various observational constraints, or whether episodic or catastrophic behaviour is needed, as has been hypothesised by some authors. Simulations in which the lithosphere remains stagnant over the entire history indicate that over time, the crust becomes as thick as the mechanical lithosphere, with delamination occuring from its base, and magmatism being the dominant heat transport mechanism. A thick crust is a robust feature of these calculations. Higher mantle viscosity results in larger topographic variations, thicker crust and lithosphere and higher admittance ratios, to match those of Venus, the upper mantle reference viscosity is about 10^{20} Pa s and internal convection is quite vigorous. Several large plumes persist throughout the model history, as the core does not cool as much as in Earth due to the lack of slabs arriving at the CMB. The most successful results in matching observations are those in which the evolution is episodic, being in stagnant lid mode for most of the evolution but with 2-3 bursts of activity caused by lithospheric overturn. If the last burst of activity occurs ~1 Ga before present, then the present day displays low magmatic rates and mostly conductive heat transport, consistent with observations. In ongoing work we are examining the effect of crustal rheology and a more accurate melting treatment.

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Stresses in a shallow-dipping subduction slab

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We analyzed stresses in the crust and mantle of a shallow-dipping, Andean-like subducting slab by high-resolution 2D thermomechanical modeling with complex elasto-visco-plastic rheology. Viscous rheology incorporates diffusion, dislocation and Peierl's creep. Kinematic boundary conditions include slab pull- and push- velocities as well as velocity of the overriding plate. The down-going slab is separated from the upper plate by a dynamic subduction channel, defined as a few km thick (usually 3 elements) zone of specifically weak visco-plastic rheology. For our shallow-dipping overridden slab, the dominant stress is unbending stress at 50-100 km depth. This stress reaches 1-1.5 GPa and strongly prevails over the slab bending stress near the trench, which is naturally limited by the frictional plastic yield at shallow depth. Unbending creates double (5-10 km distance between maximums) compression zone in the upper (outer) part of the slab and a zone of extension some 20-30 km below (inner part of the slab). Pressure in these zones differs from the lithostatic pressure to as much as plus/minus 0.8 GPa. Details of the distribution and magnitude of bending and unbending stresses in the slab are mainly controlled by the overriding velocity and direction of the slab-pull force. Interestedly, that seismic observations (e.g., [1]) often demonstrate not compression but down-dip extension in the outer part of the slab. We made further modeling experiments including volumetric effects of main crustal and upper mantle phase transformations into our model [2]. Phase transformations in the crustal (gabbro-eclogite) and in the mantle (breakdown of serpentine) parts of the subducting slab may strongly change the stress state of the slab due to their large volumetric effects (10-30%). Thus, gabbro-to-eclogite transformation in the oceanic crust takes place at around 100-150 km depth and affects the first stress invariant (sI) to as much as 1 GPa, changing it from local over- to under-pressure, i.e., from local compression to extension. Similarly, de-serpentization of the uppermost mantle of the slab (in assumption of full fluid escape) strongly reduces over-pressure in the second (upper mantle) compression beam starting from 70 km depth and even converts it into extension below 100-120 km depth.

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Isotopic tracer from the subducting slab and the mantle wedge: numerical modelling

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Understanding the subduction factory and geochemical interactions between subducting slab and the overlying non homogeneously depleted mantle wedge requires better knowledge of passways of slab-derived fluids and melts and their interactions with the melt source in the mantle wedge.

Our approach of understanding subduction-related processes consists in coupled geochemical-petrological-thermomechanical numerical geodynamic modelling of subduction zones. With this method we can simulate and visualize the evolution of various fields such as temperature, pressure, melt production etc. Furthermore we extend this tool for 2D and 3D modelling of the evolution of various geochemical signatures in subduction zones.

Implementation of geochemical signatures in numerical models is based on marker-in-cell method and allows capturing influences of various key processes such as mechanical mixing of crustal and mantle rocks, fluid release, transport and consuming and melt generation and extraction. Concerning the isotopic signatures, we focus at the first stage on a limited number of elements: Pb, Hf, Sr and Nd. These incompatible elements are transported by hydrated fluids and/or melts through the mantle wedge and therefore they are good tracers for presenting the interaction between mantle wedge and slab. The chosen incompatible elements are also well explored and a large data set is available from literature. At this stage we focuss on intra-oceanic subduction and numerical modelling predictions are compared to natural geochemical data from various modern and fossil subduction zones (Aleutian, Marianas, New Britan, Kermadec arcs, Kohistan, Vanuatu).

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Interaction of the Hawaiian plume with small-scale sublithospheric convection

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The Hawaiian Islands are the classical example of intraplate volcanism on Earth. They are formed on the Pacific Plate when overriding a stationary hot mantle upwelling (i.e., the Hawaiian plume). Diverse geological, geochemical and geophysical data is available for Hawaii, including new high-resolution seismic observations from the PLUME-experiment. However, first-order geodynamical processes related to the interaction of the plume with the overlying lithosphere and their effects on geochemical and geophysical observations are still weakly understood. In particular, some key observations such as oscillations of volcanic activity, geochemical asymmetry of shield stage volcanism, and secondary volcanism are not predicted by traditional plume theory. In this study, we investigate an advanced version of plume theory (i.e., interaction of small-scale sublithospheric convection with mantle plumes) by high-end 3D-numerical modeling. Preliminary results indicate that this mechanism may explain the above key observations altogether. Geochemical and seismological predictions of the numerical models will be quantitatively compared to the dataset of observations in order to test this hypothesis. Such an integrative approach is a promising tool to understand sublithospheric processes (e.g., magma generation), whereas the predictive power of each discipline alone is inherently limited. Furthermore, this understanding will serve to unravel processes in the source region of the Hawaiian plume and thus to shed light on the lowermost mantle.

Tides contribution to geodynamical evolution: towards a self-consistent model

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The remarkable activity on some satellites on the moons of outer planets including intensive volcanic activity on Io or spectacular jets on the south pole of small moon Enceladus as well as a possible existence of subsurface liquid oceans on some moons suggest presence of a strong mechanism which significantly contribute to the their thermal budget. Due the low surface temperatures and low concentration of radiogenic isotopes, these observed features would be hard to maintain if heat power of tidal origin is not considered.

Here, we present a new numerical tool which allows self-consistent coupling between the thermal convection and tidal dissipation in order to analyze the influence of tidal dissipation on thermal evolution of planets and satellites. In our approach, the method Choblet et al. [1] using finite volumes formulation is employed to perform convection simulations with temperature-dependent viscosity and where the average tidal heating over a period is included as a volumetric source of energy. Similarly to Tobie et al. [2], a Maxwell viscoelastic response to tidal forces and tidal dissipation for general three dimensional viscosity field are computed by the time domain approach Cadek [3] originally developed for studying post-glacial rebound.

The preliminary tests for generic planets indicate that the coupling between the tidal dissipation and mantle convection plays an important role. Namely, the lateral and radial variations of the viscosity field inherent to the convection with temperature-dependent rheology influence significantly the distribution of both the deviatoric part of the stress tensor (considering the Maxwell viscoelastic rheology) and the tidal heating pattern.

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Geoid and topography in thermal convection models of Venus

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Important though indirect information about the internal structure of Venus provide the topography and the geoid. An inverse problem, inverting the venusian geoid nad topography to get its mantle viscosity has recently been formulated by Pauer et al. (2006). They supposed a simplified 2D approximation of the density anomalies (their density does not vary with depth) and proposed a group of best fitting viscosity profiles. All best fitting profiles have strong litosphere, low viscosity asthenosphere and increase of viscosity in the lower mantle. Here we use their viscosity profile togehter with several simple viscosity stratifications (constant, linear increase of viscosity). For each of them we carry out the simulation of mantle convection. We concentrate on the question how the geoid spectra computed from density distribution obtained in our convection models correspond with those of the observed data and how far is the Venusian mantle density structure from a simplified 2D approximation used by Pauer et al (2006). Besides we study the effect of temperature-dependent viscosity and extended Boussinesq approximation and the effect of varying Rayleigh number. Further, we compare the topography and geoid of several plumes developed in our models with the observed elevations of Venusian geoid and topography.

Our numerical simulations are performed either in a fully 3D spherical model or in a simplified spherical axisymetric geometry. The influence of the radial viscosity stratification is tested in a fully 3D model, while the more time demanding models (with laterally variable viscosity or higher Rayleigh number) are tested in much faster 2D approximation.

Something completely different: Two-phase physics of volcanic eruptions

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Although volcanic eruptions are complex multi-phase mixtures of gas and magma or ash, they are frequently modeled with the pseudogas approximation, wherein the mixture acts as an effective single-phase gas with an increased density. The mixture density however is controlled both by the volume fraction of gas as well as gas compressibility, both of which vary according to different processes of compaction and compression, respectively. Moreover, the two phases of the mixture separate because of their very different densities, and the interaction forces (viscous and turbulent drag and inertial exchange) can be complex. Here, we develop and explore a model for two-phase, high Reynolds number flow of a compacting suspension of magma particles in a compressible gas. One dimensional analysis of two-phase eruptions in a volcanic conduit show that compaction and compression couple to store elastic energy in the gas during the compactive phase, which is then released in secondary super-sonic explosion. The ``choking" effect in such eruptions can be associated with acoustic shock development, however, sound speed in mixtures is highly variable. Classical pseudo gas sound waves can become unusually slow, however, with phase separation and drag permitted, wave blocking and complete attenuation can occur. Moreover, acoustic and compactive waves coexist, while at low wavelength (high frequency) the two waves are decoupled and propagate at very difference speeds, at long wavelengths they become indistinguishable from each other and have comparable speeds. Overall, acoustic and acoustic-compactive wave propagation is highly dispersive, and thus shock development or choking is strongly dependent on frequency (or wavelength) of perturbations in the eruption column.Generally high frequency (low wavelength) disturbances are less likely to form shocks or choke because sound speed is fast. In contrast, low frequency (long wavelength) disturbances are far more likely to undergoe shocks and choking, however, the shock should cause the disturbances to evolve into short wavelength features, which would then allow them to propagate without shocks. Such dispersion thus provides a mechanism for choking and unchoking in the eruption column.

Coupled evolution of the orbit and internal dynamics of the planets and of their satellites: Application to the primitive Earth-Moon system

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The tidal dissipation associated with the gravitational torque interactions between a satellite and its planet can dramatically affect not only their orbital and spin dynamics, but also their internal heat budget. Tidal dissipation can indeed produce a large amount of heat, as it is the case for Jupiter's rocky moon Io, or Saturn's icy satellite Enceladus. Large dissipation rate is also likely to have occurred during the early history of the Earth-Moon system, just after the Moon-forming giant impact [1]. The strong coupling between orbital motion and internal heat transfer is explained by the exponentially temperature dependent viscosity of the bodies: tens of terawatts may have been produced inside the young hot planet and satellite, while tidal energy has presently a minor contribution to the solid Earth budget.

The goal of this beginning work is to simultaneously compute the tidal interaction between the planet and its satellite and their respective mantle dynamics. We are currently developing a new numerical tool based on the recently proposed spherical annulus geometry [2], under the liquid anelastic approximation [3]. This technique enables us to take into account both viscous and tidal heating in a consistent way. The discretized (finite difference) mass and momentum equations are solved with a hybrid multigrid algorithm, including a SIMPLER-type smoother [4,5] and usual transfer operators. The energy equation will be solved with a classical second-order diffusion scheme combined with an enhanced Godunov[6]-like method for the advective term. The approach for computing the tidal component of heating will be adapted from [7].

When the numerical tool will be completed and tested, we will focus on the young Earth-Moon system in order to better constrain its long-term orbital and thermal evolution. Both fundamental and exotic lunar questions will be addressed, such as possible early volcanism or massive impact-triggered Moon reorientation [8,9]. The model will further be applied to other puzzling bodies, such as the Galilean satellites, particularly Europa and Io, the double-synchronized Pluto-Charon system, or Earth-like exoplanets which are very close to their star.

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Influence of density anomalies in the lower mantle on the geoid

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The influence of the two near-equatorial, antipodal Large Low Shear Velocity Provinces (LLSVPs) in the lower mantle on global mantle dynamics is still a topic of major interest in geodynamics. Whereas a qualitative correlation of the LLSVPs with observed residual (i.e. after subtraction of the geoid anomaly associated with subduction zones) positive geoid anomalies has been established, quantitative exploration of critical parameters like density excess, viscosity of the anomalies, lithosphere and lower mantle and their influence on the associated geoid anomaly remains to be investigated in geodynamic simulations. We test the influence of variation of these parameters on the geoid in our dynamic two-dimensional FEM convection model. In computation of the geoid, we include both the contribution of internal density variations and of surface and core-mantle boundary topography. We compare the results obtained from our simulations with the geoid data acquired by the new geosatellite GRACE and try to constrain realistic parameter ranges from this comparison.

Simple subduction models with Sulec

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Models of geodynamic processes on the scale of the upper crust to upper mantle put demanding constraints on modelling software: codes should be able to handle viscous, elastic and brittle material behaviour, large deformations (even post-failure), free surface behaviour, and interactions between domains of highly variable material properties. We have developed a two-dimensional finite-element code, Sulec, based on known techniques from literature, which gives us modelling flexibility in a stand-alone, non-commercial environment. Sulec is characterised by its ability to solve large-scale deformations for viscoelastic-plastic rheologies, with a free surface.

Sulec solves the momentum equation under the condition of incompressibility. The structured mesh is built of quadrilateral elements that can vary in size. The elements are either linear in velocity with constant pressure, or quadratic in velocity with linear pressure. An accurate pressure field is obtained through an iterative penalty (Uzawa) formulation [1, 2]. Pressures are important not only for pressure-temperature-time paths that can be compared with observations, but the pressure-dependence of brittle behaviour in addition introduces feedback relations to the mechanical flow. Material properties are carried on tracer particles that are advected through the Eulerian mesh. Elasticity is implemented following the approach of Moresi et al. [3], which involves an adjustment of the viscosities, the addition of a force term, and storing stresses and their rotations on the tracers. Brittle materials deform following a Mohr-Coulomb criterion. Brittle stress is kept at the yield value by iterating on an adjusted effective viscosity [see for example 4]. The final effective viscosities are averaged in tracer to element averaging schemes (harmonic, arithmetic or geometric) [5]. The top boundary of our models can be a free surface on which simple surface processes models may be imposed. The free surface is obtained by small adjustments of the Eulerian mesh.

We first show examples of simple models of upper crustal brittle deformation, elastic recovery and viscous flow. We then build on these to derive simple models of ocean-continent subduction, focussing on the near-surface behaviour.

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Dynamics and implications of slab detachment due to ridge-trench collision

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The approach of a buoyant spreading ridge to a subduction zone may lead to detachment of a subducted slab. Previous work has called upon the detachment process as an explanation for observed ridge abandonment and slab-window related magmatism (e.g. in Baja CA/western Mexico), but such a scenario has not been tested using fully-dynamic numerical models. We use dynamic two-dimensional models including a non-Newtonian rheology to study the approach of a spreading ridge to a subduction zone. In models exploring effects of subducted slab length, distance of the ridge from the trench, shear zone strength, and lithospheric yield strength, we find the following dynamics of ridge approach: (a) a decrease in subduction velocity as the ridge approaches the trench, (b) a shrinking surface plate that maintains a uniform subduction velocity, (c) ridge abandonment distances 100-275 km from the trench, and (d) slab gap distances 195-285 km from the trench. These results are consistent with observations in Baja CA, where detachment of the Cocos slab may explain abandonment of observed segments of the East Pacific Rise 50-200 km outboard of the trench (Lonsdale,

1991) and the presence of non-arc related magmatism located 100-250 km inboard of the trench with geochemical signatures separate from that associated with the normal subduction history for the Farallon plate (Pallares et al., 2007). Ridge subduction does not occur within any of our two-dimensional cases of ridge-trench collision.

Plume head–lithosphere interactions in continents

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Mantle-Lithosphere Interactions (PLI) are largely conditioned by mantle plume dynamics, yet also by complex visco-elasto-plastic rheology of the lithosphere, structure and regional intraplate stress field. In continents, PLI are often identified within extensional or compression geodynamic contexts, near boundaries between younger plates (e.g., orogenic) and older stable plates (e.g., cratons), which play role of important geometrical and thermo-rheological barriers that affect plume head emplacement (e.g., Archean West Africa, East Africa, Pannonian – Carpathian system). We address these problems by considering a free-surface thermo-dynamically coupled (continuous phase transformatios) thermo-mechanical numerical model of PLI that treats stratified elasto-viscous-plastic (EVP) continental blocks of contrasting properties submitted to regional compression or extension. We show that: (1) topographic response to PLI is highly different from the predictions of general convection models, in particular, the commonly expected long-wavelength uplift is short-lived and is replaced by multi-harmonic deformation of "tectonic-style" (poly-phase basins and uplifts) characterized by two short wavelengths (50-100 and 200-600 km). (2) tectonic deformation due to far-field forces, such as folding, may interact with lithospheric response to PLI, sometimes in a very complex way; (3) in presence of intra-plate boundaries or blocks, plume head flattening is highly asymmetric and can be blocked from one side by older (and colder) lithospheric block, which leads to the mechanical decoupling of crust from mantle lithosphere and can be accompanied by localized faulting at the margin; (4) the return flow from the plume head results in sub-vertical down-thrusting (delamination) of the lithosphere below the margin, producing vertical cold "subduction" flow that can be traced down to the 400 km depth; (5) plume head flattening and migration towards the younger plate results in concurrent surface extension above the centre of the plume and in compression (pushing), down-thrusting and magmatic events at the cratonic margin (down-thrusting is also produced at the opposite border of the younger plate); these processes may result in continental growth at the "craton side"; (5) the negative Rayleigh-Taylor instabilities in the lithosphere above the plume head provide a mechanism for crustal delamination. This study suggests also that the absence of magmatic events should not be always interpreted as evidence for the absence of plume event, as the hot source plume material stalls below Moho and forms a long-lasting (10-100 Myr) sub-Moho reservoir. This should induce strong crustal melting that may overprint deep geochemical signatures, since this melting yields light low-viscosity rapidly ascending magmas. Drip-like down-sagging of lithospheric mantle and crustal material inside the plume head may contaminate the latter and thus alter the geochemical signature of plume-related magmas.

Modeling of two-phase damage theory in a convective system

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Two-phase dynamics has been broadly studied in Earth science with magma dynamics, crystallization in metal alloys, glaciology and void-volatile self-lubrication models of generation of plate tectonics from mantle flow. Convective System with high viscosity and creeping motion such as lithosphere-mantle system is highly dissipative due to viscous or frictional heating. However, some deformational work is also stored as internal energy associated with defects, microcracks and dislocations in the two-phase system. Damage theory proposed explains the reduction of heat output as more interfacial surface energy is created. Moreover, increased damage causes higher porosity of the steady state in the convection such as melt transport. Further modeling work is required when the damage theory is applied to a dynamic two-phase system combined with fracture mechanics.

The thermochemical structure of the upper mantle as inferred by seismic and gravity data

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We present preliminary results of a cross-disciplinary approach involving mineral physics, seismology and geodynamics. We consider a reference mineral physics model based on current knowledge of material properties at high pressure (P) and temperature (T). The phase equilibria and the elastic properties are computed by using a recent thermodynamical model covering a six oxides (NCFMAS) system. Anelastic properties are implemented with a P, T and frequency dependent law based on available mineral physics knowledge. The model predicts values of physical parameters (e.g., shear velocity, density) as function of pressure (or depth), temperature and composition. Equilibrium compositions or mixtures of different compositions (e.g., MORB and Harzburgite) can be considered. Starting from this model, we adopt a non-linear approach to obtain the average thermal (T) and compositional (C) structures that are able to fit global seismic data, i.e. fundamental modes and overtones data and travel times. Then, we extend our results to 3-D inversion of long period seismic waveforms, which allow us to resolve seismic structure in the whole upper mantle. We produce several T-C models that are able to fit the seismic observations. At the same time, we predict the 3-D density structures related to the T-C fields inverted from the seismic data. Viscosity is evaluated with a similar physical law as the one used to model seismic attenuation. We compute the synthetic geoid for all the models by using the STAGYY code and thus the misfits with observations. The analysis of the results will give a robust interpretation of the thermochemical structure of the upper mantle, it will reduce the trade-off between T and C thanks to the different sensitivity of seismic and density data and it will point out possible problems with uncertain physical properties in the reference mineral physics model used. The procedure is general and can be extended to other seismic data, as P arrival times, and other geophysical observables, as electrical conductivity.

Discussion on resolving sediment subduction

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Geochemical tracers demonstrate that elements of subducted crust are recycled at subduction zones. It was stressed recently that recycling of basalt alone is not sufficient to reproduce the mantle array (isotopic correlation in oceanic rocks, [1]). Studies of hafnium (Hf) and neodymium (Nd) isotopic compositions of ocean-island lavas show that oceanic basalt and subsequent depleted mantle peridotite need to be mixed with a relative amount of oceanic sediments to produce Hf-Nd isotopic compositions that coincide with the mantle array. In addition, several studies have suggested sediment melting as requirement for efficient transfer of the critical elements (Th and Be) to the arc [2,3]. However, experimentally determined sediment solidi (>750˚C) are ~100˚C above temperatures at the top of the slab in thermal models for subduction zones. This observation place important constrains on subduction zone models.

Few numerical studies have addressed the problem of subducting sediments, perhaps because of the numerical difficulties associated with large scale modeling of very detailed features. However, the composition of bulk continental crust requires the existence of sediment [1,4]. Thus, a "realistic" model of subducting crust should contain a layer of sediments, about 500-700 m thick in average, but highly variable with increasing crustal age. The sediments may play an important role in phenomena such as decoupling between the plates, fluid effect in metamorphism, subduction dynamics and the geothermal gradient in the forearc.

We aim to quantify the amount of sediment that can be transported into a subduction zone and estimate the maximum depth to which sediments can be subducted. As a first step, we will discuss observations that constrain sediment subduction and review existing subduction models. We will present first, simple models that investigate decoupling between the plates for different rheological models of sediments.

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Heat transport and mass exchange for a thermally convecting system with a depth dependent viscosity

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A fundamental problem with parameterized thermal convection models is their inability to reconcile calculated thermal evolutions of the Earth that require high Urey ratios with the low Urey ratio inferred from geochemical studies. Many of the geochemical models used to infer the Urey ratio require knowledge of the communication of material in the upper region of the mantle with the rest of the mantle. The problem therefore requires knowledge of not only the heat flow but also the relationship between heat transport and mass transport in the mantle. We present a simple model that consists of a single fluid layer with boundary and internal heating that includes a change in viscosity at a fixed depth in the layer. The upper portion of the fluid layer has a viscosity of μ,1 and a thickness of d1 while the lower portion has a viscosity of μ,2 and a thickness of d2. This model is motivated by studies of the Earth's viscosity structure that suggest that the viscosity of the lower mantle of the Earth could be significantly larger than the viscosity of the upper mantle. The two regions of differing viscosity are not isolated and fluid exchange between the two layers is not prohibited. We present a parameterized model based on the energetics of the system that allows us to quantify both the heat transport through the convecting layer as well as the velocities and mixing rate of the two different viscosity regions. This parameterization does not require extreme or limiting case assumptions and provides a solution that agrees with numerical calculations over a viscosity ratio beginning with 1 and extending over several orders of magnitude. The effect of changing the relative thickness of the two regions as well as the cell aspect ratios is also accounted for. The solution demonstrates that the heat flow through the system, while slightly dependent on the ratio of the two viscosities, is largely limited by the high viscosity region. Mass exchange between the two regions however is strongly dependent on the ratio of the viscosities.

Thermally driven mantle plumes reconcile multiple hot-spot observations

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Hot–spots are anomalous regions of magmatism that cannot be directly associated with plate tectonic processes. They are widely–regarded as the surface expression of upwelling mantle plumes. Hot–spots exhibit variable life–spans, magmatic productivity and fixity. This suggests that a wide–range of upwelling structures coexist within Earth's mantle, a view supported by geochemical and seismic evidence, but, thus far, not fully–reproduced by numerical models. Here, results from new, global, 3–D spherical, mantle convection models are presented, which better reconcile hot–spot observations, the key modification from previous models being increased convective vigor. Upwellings show broad–ranging dynamics, some drift slowly, while others are more mobile, displaying variable life–spans, intensities and migration velocities. Such behavior is consistent with hot–spot observations, indicating that the mantle

must be simulated at the correct vigor and in the appropriate geometry to reproduce Earth–like dynamics. Thermally–driven mantle plumes can explain the principal features of hot–spot volcanism on Earth.

Episodicity in Earth's mantle

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The imaging of subducting slabs in the lower mantle contrasts with the evidence of multiple reservoirs and limiting mixing from geochemistry. One way of reconciling these observations is for Earth to have been a layered system which has broken down. One well-known way to produce a layered system is by the endothermic phase change in the olivine system at around 660km depth. This has been known to be more effective at producing layering at higher Rayleigh number, which is what would be expected earlier in Earth history.

We have undertaken numerical experiments in a spherical model with a range of Rayleigh numbers (Ra) and Clapeyron slopes for the phase change (Cl). These experiments show that there are three domains in the Ra, Cl space. There is a domain of partial layering in addition to the obvious whole mantle and layered domains. Experiments in the partial layering domain show an episodic behaviour where cold material from the upper mantle avalanches through to the lower mantle, collecting hot material at the core mantle boundary and launching upwellings into the upper mantle. While such an avalanche mechanism has been described a decade ago (Tackley et al., 1994), we in addition find that these repeat. We have also run experiments at conditions close to present-day Earth (Ra, Cl) and the episodic nature of the process persists. In addition the work suggests the trajectory of Earth's evolution across the Ra, Cl space. This would very likely have taken it from a layered domain, to a partially layered domain with its episodic major hot upwellings, to a whole mantle domain. Such processes have also been suggested using parameterized models (Davies 1995) and from observational work (Condie 1998).

Should conditions within Earth's mantle be suitable for such processes to occur, the thermal history of Earth could show significant periodicity, which could resolve problems with projecting mantle temperature back in time with parameterized models. It could also provide a mechanism to produce the phases of increased melting inferred by some geochemical studies (Parman 2007).

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Thermo-chemical convection and the survival of reservoirs of dense material in the deep mantle

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Introduction. Increasing evidences suggest the existence of large reservoirs of dense material at the bottom of the Earth's mantle [1,2]. These reservoirs may result from the interaction between an initial layer of dense material that differentiated early in Earth his-tory [3], and mantle convection. Because they are like-ly chemically different from the average mantle, these reservoirs may play a crucial role in Earth's mantle evolution. To determine the parameters that create and maintain large pools of dense material in the lower mantle, we have conducted series of numerical experi-ments of thermo-chemical convection [4,5], and tested the thermo-chemical distributions predicted by these models against those obtained from probabilistic to-mography [2].

Numerical modeling. Numerical experiments are performed with a 3D-Cartesian version of STAG3D [6], which solves the non-dimensional conservative equations of mass, momentum, energy, and composi-tion for an anelastic, compressible fluid with an infinite Prandtl number**.** The size of the box is 4×4×1, with 128 points in each horizontal direction, and 64 points in vertical direction. The system is heated both from the bottom and from within. The chemical field is modeled using 10 million tracer particles of two types, one for the regular material, and one for the dense ma-terial. The density difference between the dense and regular materials is controlled by the buoyancy ratio. Dense particles are initially distributed in the bottom of the system, and at each timestep the compositional field is obtained by calculating the concentration of dense particles in each cell. The 660 km phase change is modeled with a discontinuous phase transition that is controlled by defining a point on the phase boundary and a Clapeyron slope.
mantle.

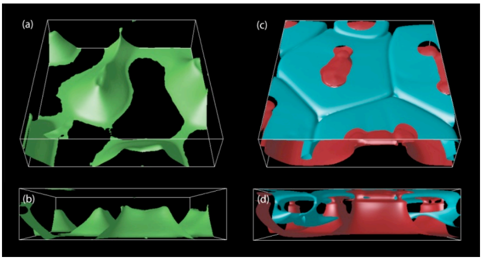

Fig.1: A model of thermo-chemical convection with a buoy-ancy ratio B = 0.2, a thermal viscosity contrast RμT = 106, and a 660-km Clapeyron slope Γ = -2.5 MPa/K. Isosurfaces show the frac-tion of dense particles (left, C = 0.5), and the non-dimensional temperature residuals (right, T = 0.15 and T = -0.225).

Mantle convection: important parameters. We explored the influence of various parameters, including the buoyancy ratio, the fraction of dense material, the Capeyron slope of the 660-km phase transition, and the fluid rheology (thermal and compositional viscosity contrasts, depth variations). Five main conclusions can be drawn from this search. (i) Large (≥

0.3) buoyancy ratios induce stable layering. For buoyancy ratio be-tween 0.15 and 0.25, and if no other ingredient is add-ed, dense material is rapidly entrained upwards. (ii) For strong (≥ 104) thermal viscosity contrasts, large pools of dense material are generated at the bottom of the system and survive convection. (iii) Small chemical viscosity contrasts induce rapid mixing, whereas large chemical viscosity contrasts lead to stable layering. The influence of the chemical viscosity contrast is however of 2nd order compared to those of the buoyan-cy ratio and of the thermal viscosity contrast. (iv) A 660-km viscosity contrast of 30 or more reduce the vertical mass transfer around this depth. (v) An endo-thermic phase transition at 660-km with a Clapeyron slope around –3.0 to –1.5 MPa/K, strongly inhibits the rise of dense material above 660 km (thermal plumes dramatically thin around this depth, and only a very small amount of dense material is entrained upwards), but still allow the penetration of downwellings in the lower mantle. Thus, models that includes both a large thermal viscosity contrast and an endothermic 660-km phase transition (Figure 1) are able to create and main-tain large pools of dense material at the bottom of the system. Interestingly, the power spectra of these ther-mo-chemical structure are in good agreement with those deduced probabilistic tomography. Furthermore, such models globally support the hypothesis that Oceanic Island Basalt (OIB) partially sample an iso-lated reservoir of dense material located in the lower mantle.

Perspectives. Next steps will focus on building models with increased complexity (spherical geometry, self-generation of plate tectonics and the recycling of these plates in the deep mantle), and contraining the balance between the primitive (dense) and recycled material in the thinned plumes.

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Direct numerical simulation of two-phase flow: Effective rheology and pattern formation of particle suspensions

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We analyzed the mechanical behavior of a two-phase system consisting of high viscosity grains and an interconnecting fluid of much smaller viscosity. For this purpose we use 2D direct numerical simulations for either Newtonian or non-Newtonian rheology. Direct numerical simulations solve two-phase flow problems on the spatial scale of individual grains. Effective properties of a two-phase particle suspension can be characterized by using the direct stress-strain rate relationship. On the basis of these results, we derived expressions for the effective viscosity for both Newtonian and non-Newtonian rheologies. We demonstrate that, for large viscosity contrasts between grains and interconnecting fluids, the effective rheology of the assemblage is non-Newtonian only if the fluid has a non-Newtonian rheology (irrespective of the rheology of the higher viscous grains). In case of small porosities (high particle fraction) the strain rates inside the channel walls (between two grains) are locally up to 2.5 orders of magnitude higher than the overall applied background strain rate. It is suggested that this effect might partly explain the experimentally observed change in rheology from Newtonian to non-Newtonian rheology.

Experimental studies also indicate that melt-solid systems behave non-linearly for moderate to higher strain rates. However, the underlying physics is still not fully understood yet. For higher to large strains grains are reorganized and local very high strain rates can occur, which might have an influence on the overall behavior of the evolving system. Therefore further investigation for direct comparison between experimental and numerical results is required. Finite strain analysis will be used to model stress-strain curves, which are calibrated versus experiments in order to derive more accurate flow laws. Moreover, the numerical models will give insights in the relative importance of shear-heating, non-Newtonian melt rheologies, elasticity and finite strain on the effective rheology of the assemblage.

Furthermore, we studied typical flow patterns of particle suspensions. As initial conditions we employ a layer with homogeneously distributed high viscosity grains and interstitial melt overlying a layer of pure melt. The evolving model shows strong interactions between individual grains, which results in macroscopic Rayleigh-Taylor (RT) instabilities for moderate to large melt fractions. For very large melt fractions, we observed a transition from the RT instability to a Stokes-suspension mode, in which grains do not interact but sink independently. An analytical expression is derived that predicts the transition from RT to Stokes suspension mode. The transition is a function of porosity, radius of the grains, distance between the grains, height of the interface and initial amplitude. Systematic numerical simulations are in good agreement with the analytical predictions.

Unravelling slab/mantle coupling with subduction zone kinematics: Insights from laboratory and numerical models

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On Earth two styles of subduction, distinguished by the way subduction velocity is partitioned between trench and plate velocity, can be recognized. In fact, some slabs retreat – trench migrates seaward-, whereas other ones advance – trench migrates toward the overriding plate. The resistance of the slab to bending and its coupling to the surrounding mantle play an important role in subduction dynamics over geological time scales. In this work we propose an alternative way to constrain the ratio between the lithosphere and the upper mantle viscosity by performing laboratory and numerical models and comparing their results with kinetics data from current subduction zones. Finally, we are able to infer the slab/mantle coupling necessary to obtain realistic trench/plate velocity ratios as well as the variability of the subduction styles observed in nature. Our laboratory models are set up with a viscous plate of silicone putty (lithosphere) subducting under its negative buoyancy in a viscous layer of glucose syrup (upper mantle). The viscosity contrast between the lithosphere and mantle has been systematically varied from ~10 to ~10^5. In our three dimensional numerical models, the set up is similar to the experimental one. The relative viscosity and the plate thickness – converted to lithospheric age- are varied in a wide range [5 – 20]x10^2. Modelling results have been compared with the global compilation of kinematic data of present-day subduction zones in different reference frames. This comparison suggests a viscosity contrast between lithosphere and upper mantle around 200 in order to obtain the variety in subduction style recognized on Earth

Parametric laws for temperature into a convecting mantle

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Improving the knowledge of thermal state of mantle of terrestrial planets required a better understanding of its physical and chemical state. Recently, with the help of massive computational resources, significant progresses were achieved in the numerical modeling of planetary mantles convection. Models with a high degree of complexity (including realistic viscosity laws, mixed mode of heating, spherical geometry, thermo-chemical convection, …) are now available. Among the parameters that recently became accessible, spherical geometry is a key ingredient because it affects the relative strength of the top and bottom thermal boundary layers. Despite these progresses, the thermal state of the mantle remain unclear. For instance, no model of Earth's mantle convection fits all available geophysical, geochemical, and geological constraints. With STAG3D convection code meet a yin-yang grid we can control a lot of this physical parameters and observe their influence on the convection into a spherical shell and on it its thermal state. In the first part of the study we have performed severals numericals experiments on ETH cluster : Brutus. For each one we have change some parameters like Rayleigh number, curvature factor (ratio between radius of the core and the planet one), heating (only from below or with an internal heating component), rheology (iso-viscous or temperature dependance). With this results we were able to observe the evolution of the style of convection when we change some parameters and the influence of this last ones on the main physical variables of the convecting shell wich are mainly, Heat flux, Nusselt number, temperature and critical Rayleigh number. Then, when we had enough models available for one parameters we built scaling laws, for instance between Nusselt and Rayleigh number or temperature and curvature factor. The result obtained and their comparaison with previous study show that many extrapolation previously made from Cartesian models can not be used. For instance the most important difference observed was that temperature is not only dependant of geometry (curvature factor) and internal heating but to the Rayleigh number too. It would be appear that difference come from by the attendance of asymmetric thermal boundary layers wich alter their stability. Results obtained with this last study show the importance of carry out numericals experiences with right geometry before extrapolate previous results from Cartesian models. New scaling laws obtained enable to reconsider some aspects of thermal evolution and physical states of terrestrial planets like Earth, Mars, Mercury or some giant planets satellites.

Numerical modelling of spontaneaous slab breakoff and continental collision: implications for topography evolution

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In order to understand coupled dynamics of slab breakoff and topography development, a set of continental collision experiments were run using I2ELVIS code (Gerya & Yuen, 2003). Setup of the experiment involves convergence of two continental plates separated by an oceanic segment. Subduction is imposed by a weak zone and the plates are pushed during a limited timelapse, afterwards continental collision evolves spontaneously under the slab pull. A systematic parameter study is carried out by independently varying the oceanic plate age and convergence rate in 20 numerical experiments.

Results display various continental collision zone behaviour combining several key processes including systematic slab breakoff. Evolution of each model is characterized by a unique topographic pattern where every geodynamic process involved (subduction, collision, breakoff, slab steepening, rollback, eduction etc.) has a specific signal. As reflected by its sharp topographic signal (within <1 Myr) slab breakoff turns out to be a crucial parameter for orogenic structure, topography and evolution.

Slab breakoff can occur from shallow depths (<40 km) to deeper levels (>400 km) depending on the activation of different driving rheological mechanisms (dislocation creep, Mohr-Coulomb failure and Peierls plasticity). Shallow slab detachment are likely to occur within young slabs at fast convergence rate whereas deep detachment mainly affects old slabs. A variety of intermediate behaviours is observed between those end-members.

At lithospheric scale, shallow breakoffs are linked to narrow orogens with moderate topography whereas deep breakoff scenarios produce wider and higher orogens. Narrow orogens mainly remain stable after breakoff while large orogens undergo such a large isostatic response that they are likely to evolve into eduction and extension.

Additional sytematic studies on activation volume of olivine were perform to better understand its effect on slab breakoff. By using activation volume values ranging from 0.8 to 1.4 J/bar, a variety of different slab behaviours were observed involving both cases of breakoff and non-breakoff. Variation of erosion parameters and their effect on topography evolution were also investigated.

The mechanics of deep slab hydration and related geodynamical processes

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Seismological surveys at trenches show that subducting slabs get hydrated down to mantle depths. However, it is unclear how sea-water can percolate so deeply inside the oceanic plate. By modeling spontaneous subduction of an oceanic plate, we show that downward deep fluid flow is attained at the bending area in response to strong variations of the tectonic pressure (due to bending-related normal faulting) that induce the formation of inverted or sub-hydrostatic pressure gradients. The results of the numerical experiment indicate that water can be transported down and stored in the bending area via serpentinization of the normal faults which have important implications for the rheology, seismicity and structure of subducting slabs. As the slab subducts, serpentinized faults acquire a vertical position. The coupled effect of well oriented, highly anisotropic hydrous minerals (serpentine, chlorite, mica) together with high aspect ratio, fluid filled cracks due to the de-hydration of the slab under the arc-forearc system produces significant seismic anisotropy detectable by long wavelength SKS waves. We found that the anisotropy measured above subduction zones seems to be related more to the spatial distribution of the serpentinized faults in the slab than to the flow in the upper mantle.

Topographic signals of mantle flow

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Mantle convection expresses itself in many ways on the surface of terrestrial planets. We focus on the dynamic topography and investigate correlations to the flow structure.
We applied a numerical model which employs the finite-volume-method and the Boussinesq approximation. The fluid dynamical equations of mantle convection are solved self-consistently, so that except for boundary conditions there are no constraints. This also means that the viscosity is not prescribed but depends on temperature, depth and stress. As the model uses primitive formulation, the dynamic pressure is directly available to calculate the topography.
It is known that due to a variation in rheological parameters different regimes of surface behavior in time and space can be found. Solomatov [1] has shown, that several regimes can be identified, in which the surface behaves either mobile, transitional or stiff (like a stagnant lid). Loddoch et al. [2] have shown, that on a very narrow parameter range long periods of a stiff surface are interrupted by burst-like mobilization events. For this regime the topographic signal passes through three different phases, in which its structure and correlation to the interior flow changes. During the Stagnant-Lid-Phase the topography clearly correlates to the internal flow. When subduction is taking place, the topography is dominated by the graben-like subduction zone and at the bottom boundary layer thermal instabilities are pushed towards the upwelling by a large-scale wind. Shortly after the mobilization has ended and new plumes have risen, no clear correlation of the topography to the flow structure can be found and an upwelling does not necessarily result in a topographic elevation.
During the subduction process, small-scale convection arises when the local Rayleigh number reaches the order of 10^8 at the base of the surface plate. Separating the topographic signal of the small-scale convection shows that the signal of the mean flow follows characteristics of the depth-age-curve [3].
Finally we investigate the question if a plume can cause in a topographic depression on the surface. In isoviscous convection a stationary upwelling produces a maximum in pressure and deviatoric normal stress (the two components to derive topography) at the surface. In the presence of a stagnant lid, the sign of the pressure changes and shows a minimum above the upwelling. We show that when a plume starts to rise at the lower boundary the stiff surface can damp the deviatoric stress signal, so that the topography is dominated by its pressure component and results in a topographic minimum. We would like to discuss if this result can give plausible hints for further fundamental questions on surface signals of mantle plumes.

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Heat flow scaling of convection with damage theory and the onset of plate tectonics

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Damage theory, which uses the observation that mineral grains tend to shrink under deformation, making the material weaker, and grow in the absence of stress, making the material stronger, has been proposed as a possible mechanism for shear localization in the Earth. A theoretical description of this rheology for continuum models has been developed [1,2], and it has been shown capable of producing a plate-like style of convection in 2-D convection models [2]. With this rheology, viscosity depends on temperature and grain size, which in turn depends on deformational work and temperature. This results in a convection style that depends on things like surface temperature, as well as material properties [3]. Therefore, convection on the Earth could undergo changes in convection style due to its thermal evolution. A simple thermal evolution model assuming the classical Nusselt number-Rayleigh number scaling shows that two convection states, a stagnant surface and mobile surface, exist depending on material properties and thermal conditions. This is extended by analysis of heat flow scaling relationships with temperature dependent viscosity and damage theory, which has important implications for the thermal evolution model and onset of plate tectonics.

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Subduction stress accumulation and dissipation in Wadati-Benioff zones

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Subduction zones are delineated by Wadati-Benioff seismic zones reaching down from the surface to nearly 700km depth. These planes of seismicity are the result of stress accumulation and dissipation during the subduction process. Stress is accumulated in the downgoing slab through slab pull, bending, thermal expansion, and phase changes. Stress may be dissipated through ductile deformation, dehydration-facilitated brittle faulting, or shear instabilities. These mechanisms are dependent on temperature, pressure, and mineralogy and also interact with each other resulting in complex relationships between parameters.

We use a thermo-mechanical model (powered by MILAMIN, Dabrowski et al, 2008) to simulate the subduction process. We model the thermal, rheological, and mineralogical evolution of subducting slabs and their stresses, varying convergence rate, dip angle, rollback rate, and age of slab; model results allow us to investigate the influence and interaction of these variables. We are particularly interested in applying our results to double and triple Wadati-Benioff zone seismicity, which, despite being observed in many subduction systems, are still poorly understood. From the analysis of steady-state and transient solutions, we hope to better understand the relative contributions of the different mechanisms to the total stress state, and investigate the possible causes of double and triple seismic zones.

Development of Eulerian numerical procedure for free surface toward plate-mantle simulation

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In the geophysical simulation study, one of the great challenges is to reproduce a realistic plate tectonics with mantle convection simulation. We develop an Eulerian numerical scheme for the steady Stokes flow to solve the deformation of rigid material (plate tectonics) induced by thermal convection of soft fluid (mantle convection). Our simulation scheme combines (i) the multigrid method together with a fast and robust smoother algorithm named ACuTE by Kameyama et.al. (2005), and (ii) an low diffusive semi-Lagrangian advection algorithm named CIP-CSLR-CS by Furuichi et.al. (2008). Since it is easy to optimize in vectorization/parallelization, our method is suitable for large scale simulation. According to our recent study, in which we carry out the validity test of our simulation scheme for a large deformation problem by using the fluid rope coiling event Furuichi et.al. (2009), the current approach in the grid resolution of our large scale simulation successfully reproduces not only qualitative but also quantitative behavior of a deformation of curved rigid plate. This indicates that by introducing a proper treatment of a free surface, our scheme may solve the whole system of solid earth on the mechanical model including the surface deformations without serious quantitative errors. In this study, we are trying to simulate self-gravitationg motion of the Stokes flow as the free surface problem.

Benchmark on Prandtl number influence for GeoFlow II, a mantle convection experiment in spherical shells

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Thermal convection is a central objective in geo- and astrophysical research [1]. For purpose of modelling convection dynamics with an experiment focus of the GeoFlow project is the fluid motion in a gap between two concentric spheres, with inner spherical shell heated and outer spherical shell cooled [2]. Central symmetry buoyancy field is set-up by means of a high voltage potential and use of a dielectric liquid as working fluid in the spherical cavity. This technique to realize a self-gravitating force field experimentally requires microgravity conditions in order to reduce unidirectional influence of acceleration due to gravity dominating fluid flow in a laboratory. For GeoFlow this specific conditions are available in the European module COLUMBUS of the International Space Station ISS.

During mission GeoFlow I, which was running on orbit from July 2008 until January 2009, shells were filled with a fluid having approximately constant viscosity, i.e. silicone oil. Motivated by convective motion of the Earth's outer core patterns of convection and their spatial-temporal behaviour are prospected [3-5]. For the planned second mission GeoFlow II (on orbit 2010) working fluid shall be an alcanole having a temperature dependent viscosity, i.e. nonanol. Herewith experimental modelling of mantle convection is going to spotlight.

It is mostly desirable to have preliminary numerical simulations to found out the significant parameter range for the experiments. Governing equations in Boussinesq form for the incompressible Newtonian fluid of nonanol are characterized by inertia. In contrast to traditional simulation work for mantle dynamics the Prandtl number for our planned experiment is reasonable high ($Pr \approx 100$), but not infinite. Therefore in a first step this Prandtl number influence were benchmarked.

For first mission GeoFlow I a numerical database exists for patterns of convection and Nusselt numbers of isoviscous silicone oil, all calculated with a pseudo-spectral code [6], and for $Pr = 64.64$. This data were benchmarked with the spherical code GAIA [7, 8] assuming an isoviscous fluid and set-up with $Pr \to \infty$. From the database axisymmetric, octahedral and cubic patterns were chosen at supercritical Rayleigh number of $Ra_{centr}=5 \cdot 10^3$, which is the specific Rayleigh number for the artificial central force field. GAIA results mode(4,4), mode(3,2) and mode random, respectively are in good agreement with our patterns (Fig. 1). Furthermore the Nusselt numbers conform in the order of 10^{-2}.

As a conclusion for realization of accompanying numerical simulation the Prandtl number can be dropped. Next steps are to simulate variations of thermal forcing (variation of Rayleigh number) with specific viscosity contrast of nonanol.

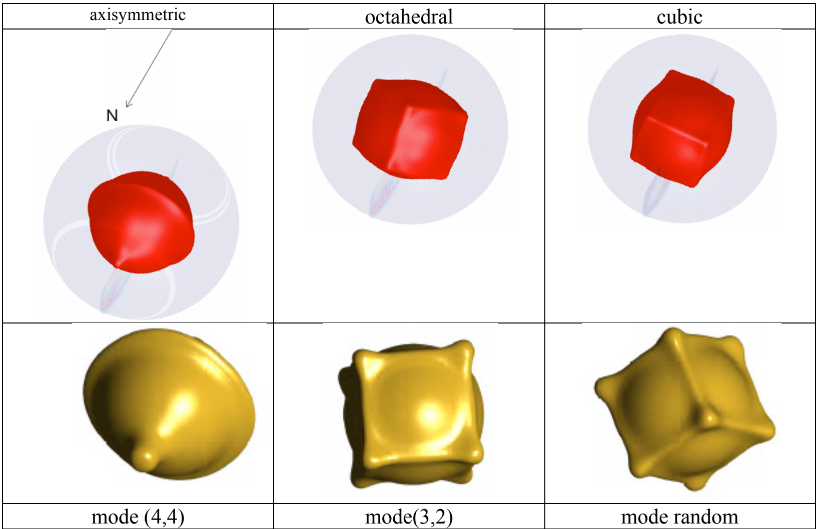

Figure 1: Numerical simulation of thermal convection in spherical shells, filled with incompressible, Newtonian fluid of constant viscosity: Comparison for patterns of convection obtained with pseudo-spectral code [6] for Pr=64.64 (top row) and with GAIA code [7, 8] for $Pr \rightarrow \infty$. Three-dimensional visualization of an isosurface showing temperature pattern in the spherical gap.

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Is there a subsurface ocean within Tritons interior?

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Planetary magma oceans exist in many forms throughout the solar system. Their thermal evolution, influenced by various forms of heating and cooling, is intricately linked to their crystallization, and thus their internal structural evolution. The connection between these parameters can be illustrated in many cases, including the evolution of a cryomagma ocean found within the interior of Neptune's icy satellite, Triton. Several observations of Triton's surface suggest that the satellite may have been geologically active. Triton's young surface, estimated to be between 10 and 100 Myr old, shows evidence of ridge formation, geyser activity, and volatile transport. One possible explanation for these features may be the influence of internal processes on the satellite's geologic activity. Triton is hypothesized to have been captured from an initially heliocentric orbit. As its current orbit is near circular, the satellite's orbit must have undergone circularization after capture by Neptune, which would have allowed for internal heating as a result of tidal dissipation. Heating of the interior likely contributed to the formation of a subsurface ocean. Whether such an ocean still exists at present may determine whether the surface features are a result of recent geologic activity. This research begins to examine the internal structure of Triton in conjunction with the thermal evolution of the satellite to determine whether an ocean does exist at present. Additionally, the study will incorporate the evolution of Triton's orbit as tidal dissipation from the evolving orbit greatly influences the thermal state of the satellite as well. The first results of this study, based on an H_2O and ammonia mix composition, suggest that the existence of a subsurface ocean at present is possible, but the extent to which it occurs within the interior will vary depending on the conditions of the satellite's interior and composition. Ultimately, this model will be adapted to a multiple layer moving boundary problem to determine how Triton's interior has evolved thermally and structurally as a result of orbital influencing since its capture.

The effect of the viscosity and the internal heating on mantle plume dynamics

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Numerical modeling has been carried out to study the effect of the viscosity increasing exponentially with depth and the homogeneous internal heating on the dynamics of plumes and horizontal thermal boundary layers (TBLs). Beyond the conventional parameters (Nusselt number, root-mean-square velocity, thickness of TBLs and the temperature drop across TBLs) numerous characteristics (e.g. average temperature, horizontal and vertical velocity, heat

advection, cross-sectional area, number) of plumes have been observed at different depths of the 3D model box by an automatic plume detecting routine. During the calculations the surface Rayleigh number was fixed (Ra=10^7), the viscosity contrast γ (ratio of the viscosity at the bottom and the top of the model domain) ranged from 1 to 100 as well as the non-dimensional internal heating varied between H=0 and 20 maintaining γ=30.

Increasing the viscosity contrast the surface and the bottom heat flux reduces (Nu_0~$\gamma^{-0.25}$), the model domain cools, the flow slows down and the horizontal TBLs thicken differently. Besides the vertical velocity within hot plumes decreases (w_p~$\gamma^{-0.25}$), while cross-sectional area of hot plumes increases (A_p~$\gamma^{0.45}$) and average temperature of those varies slightly (T_p~$\gamma^{-0.03}$). It means that the heat advected by an individual plume grows by γ. Whereas the number of hot plumes decreases considerably (N_p~$\gamma^{-0.42}$), thus the heat advected by hot plumes is proportional to $\gamma^{-0.25}$ which shows that the cold TBL is controlled strictly by the hot plumes.

The analysis of time series also verifies the intensifying linking among the top TBL, the hot plumes and the bottom TBL. Correlation between the time series of surface heat flux and the heat advected by hot plumes increases from 0.31 to 0.90 by γ. While correlation between the horizontal TBLs was not found in isoviscous models (0.17), for γ=100 it rose to 0.85. Although the correlation between the time series of the heat advection within hot plumes was obvious throughout, it increased from 0.80 to 0.98 by the enhancement of the depth-dependence of the viscosity.

Enhancing the internal heating at the viscosity contrast of γ=30 in some aspects opposite tendencies can be observed. The internal heating warms up the convective cell, and increases the surface heat flux, while the root-mean-square velocity and the thickness of the horizontal TBLs are influenced slightly. The internal heating involves the moderated vertical velocity and reduced cross-sectional area of hot plumes, while the temperature of those increases weakly. Although the increase in the number of hot plumes compensates the decrease of the vertical velocity and the plume area in the heat advection within hot plumes, still the role of that weakens in the surface heat flux.

Analogously, the correlation among the time series of the surface, the bottom heat flux and the heat advected by hot plumes attenuates owing to the internal heating. Practically, the value of H>5 is enough to break down the linking between the horizontal TBLs. Nevertheless, the correlation between the time series of the heat advection within hot plumes and the surface heat flux reduces from 0.77 to 0.40 as H grows from 0 to 20, while the correlation between the heat advected by hot plumes at different depths shows high, but slightly decreasing values (0.95 to 0.86).

The numerical investigation of the quantified plume characteristics and different time series verified that the viscosity increasing with depth cooled down the convective cell by the sluggish bottom TBL, thus enhanced its role and built up a close relationship among the horizontal TBLs and the heat advected by hot plumes. Whereas the internal heating (beside γ=30) warms up the cell again, so weakens the dominance of the bottom TBL and tends to break down or reduce this kind of linking of the convective system.

Scalable robust solvers for unstructured FE modeling applications, solving the Stokes equation for models with large, localized, viscosity contrasts

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The development of scalable robust solvers for unstructured finite element applications related to viscous flow problems in earth sciences is an active research area. Solving high-resolution convection problems with order of magnitude 108 degrees of freedom requires solvers that scale well, both with respect to the number of degrees of freedom as well as having optimal parallel scaling characteristics on computer clusters. We investigate the use of a smoothed aggregation (SA) algebraic multigrid (AMG) type solution strategies to construct efficient preconditioners for the Stokes equation. We integrate AMG in our solver scheme as a preconditioner to the conjugate gradient method (CG) used during the construction of a block triangular preconditioner(BTR) to the Stokes equation, accelerating the convergence rate of the generalized conjugate residual method(GCR). We abbreviate this procedure as BTA-GCR. For our experiments, we use unstructured grids with quadratic finite elements, making the model flexible with respect to geometry and topology and O(h3) accurate. We find that AMG type methods scale linearly (O(n)), with respect to the number of degrees of freedom, n, and scale optimally in parallel for our experiments with up to 100 million degrees of freedom. Furthermore, AMG-type methods are shown to be robust methods that allow us to solve very ill-conditioned systems resulting from strongly varying material properties over short distances in the model interior.

The role of slabs, keels and the asthenosphere for global plate dynamics

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We investigate the impact of slabs, keels and asthenosphere on pressure, velocity and stress patterns in the lithosphere and the upper mantle using the two-dimensional (2-D) finite element code MILAMIN (Dabrowski et al., 2008). Several recent studies have focused on the Pacific domain in order to demonstrate how slabs, keels and plate configuration control the dynamics of this region. O'Driscoll et al. (2009) investigate the effect on mantle-wedge suction of a continental root in the vicinity of a subduction zone. They find that the existence of the keel results into a mantle-wedge suction twice higher compared to the one in a rootless subduction zone, leading to a continental compression up to nearly four times higher. They suggest that this effect is responsible for rapid mountain building associated with subduction, for example the Andes, and that it also affects the net rotation of the lithosphere. From a different perspective, Husson et al. (2008) argue that the gravitational potential energy differences produced by the contemporary Andean topography are large enough to generate the westward drift of the Pacific Ocean basin. In another study, Nagel et al. (2008) invoke the asymmetric configuration of the Pacific plate to explain the absolute trench-normal motions of the surrounding slabs. They compute the asthenospheric flux across the trench boundary, assume that the slabs are anchored into the mantle and that their absolute motion replicates the one of the asthenosphere. Their findings show that even if an asymmetric ridge position leads to differential retreat velocities of the trenches on the sides of the plate, a strong asymmetry is required to induce a net motion in one direction. We generate two-dimensional (2-D) models in order to quantitatively test these hypotheses. While focusing on comparing the different effects, we also explore the influence of the viscosity of the asthenosphere on the results.

Continental deformation along the Chilean margin : Thermomechanical models of subduction

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Numerical models of the upper 300 km of a subduction zone typical to the Chilean margin are presented. They incorporate slab-pull and upper plate convergence and calculate the development of stress and strain over a typical period of 4 Myr. The models test the effects of subduction interface strength, arc and fore-arc crust rheology, and arc temperature, on the development of superficial near-surface faulting as well as viscous shear-zones in the mantle. Deformation geometries are controlled by the intersection of the subduction interface with continental rheological heterogeneities. Upper plate shortening and trench advance are both correlated, and favored to a first order by upper plate weakness, and to a second order by interface strength. In cases of a strong interface, a weak forearc crust is dragged downward by "tectonic erosion", a scenario for which indications are found along the Chilean margin. In contrast for a resistant forearc, the slab-pull force transmits to the surface and produces topographic subsidence. This process may explain the persistence of a Central Depression. Specific conditions for northern Chile produce a shear zone that propagates from the subduction zone in the mantle, through the Altiplano lower crust into the Subandean crust, as proposed by previous studies. Models with a weak interface in turn, allow buoyant subducted material to rise into the continental arc. In case of cessation of the slab-pull, this buoyant material may rise enough to change the stress state in the continental crust, and lead to back-arc opening. In a case of young and hydrated oceanic plate forced by the slab-pull to subduct under a resistant continent, the slab os deviated and indented by the continental mantle, and stretches horizontally at ~100 km depth. This situation might explain the flat Wadati-Benioff zone of Central Chile.

Forthcoming textbook: Introduction to Numerical Geodynamic Modelling (Cambridge University Press)

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Have you ever thought that modelling of geodynamic processes is an exciting topic but too difficult to enter because there is no introductory textbook on this subject? Yes? Then come the good news! Here is the textbook written for graduate students to learn numerical geodynamic modelling from scratch (Cambridge University Press, on sale from February 2010). It does not require any preliminary knowledge besides simple linear algebra and derivatives. It provides a consistent basic background in continuum mechanics, partial differential equations, numerical methods and geodynamic modelling. It is illustrated with 47 practical exercises and 67 MATLAB examples as successive and successful stages on a learning path. In addition, several state-of-the-art, well-commented visco-elasto-plastic codes are provided to allow numerical modelling in two-dimensions of several key geodynamic processes such as subduction, lithospheric extension, collision, slab breakoff, intrusion emplacement, mantle convection and planetary core formation. Below is the book content.

INTRODUCTION Theory: What is this book? What this book is not? Get started. Seven golden rules for learning the subject. Short history of geodynamics and numerical geodynamic modelling. Few words about programming and visualization. Nine programming rules. Acknowledgements. Exercises: Starting with MATLAB. Visualization exercise.
CHAPTER 1: THE CONTINUITY EQUATION Theory: Definition of a geological media as a continuum. Field variables used for the representation of a continuum. Methods for definition of the field variables. Eulerian and Lagrangian points of view. Continuity equation in Eulerian and Lagrangian forms and their derivation. Advective transport term. Continuity equation for an incompressible fluid. Exercises: Computing the divergence of velocity field in 2D.
CHAPTER 2: DENSITY AND GRAVITY Theory: Density of rocks and minerals. Thermal expansion and compressibility. Dependence of density on pressure and temperature. Equations of state. Poisson equation for gravitational potential and its derivation. Exercises: Computing and visualising density, thermal expansion and compressibility.
CHAPTER 3: NUMERICAL SOLUTIONS OF PARTIAL DIFFERENTIAL EQUATIONS Theory: Analytical and numerical methods for solving partial differential equations. Using finite-differences to compute various derivatives. Eulerian and Lagrangian approaches. Transition from partial differential equations to systems of linear equations. Methods of solving large systems of linear equations: iterative methods (Jacobi iteration, Gauss-Seidel iteration), direct methods (Gaussian elimination). Indexing of unknowns in 1D and 2D. Exercises: Numerical solutions of Poisson equation in 1D and 2D.
CHAPTER 4: STRESS AND STRAIN Theory: Deformation and stresses. Definition of stress, strain and strain-rate tensors. Deviatoric stresses. Mean stress as a dynamic (non-lithostatic) pressure. Orientation of stress axes. Stress and strain rate invariants. Exercises: Computing the strain rate tensor components in 2D from the material velocity fields.
CHAPTER 5: THE MOMENTUM EQUATION Theory: Momentum equation. Viscosity and Newtonian law of viscous friction. Navier-Stokes equation for the motion of a viscous fluid. Stokes equation of slow laminar flow of highly viscous incompressible fluid and its application to geodynamics. Simplification of the Stokes equation in case of constant viscosity and its relation to the Poisson equation. Analytical example for channel flow. Stream function approach. Exercises: Solving continuity and momentum equations for the case of constant viscosity with a stream function approach.
CHAPTER 6: VISCOUS RHEOLOGY OF ROCKS Theory: Solid-state creep of minerals and rocks as the major mechanism of deformation of the Earth's interior. Dislocation and diffusion creep mechanisms. Rheological equations for minerals and rocks. Effective viscosity and it's dependence on temperature, pressure, and strain rate. Formulation of the effective viscosity from empirical flow laws. Exercises: Programming viscous rheological equations for computing effective viscosities from empirical flow laws.
CHAPTER 7: NUMERICAL SOLUTION OF THE MOMENTUM AND CONTINUITY EQUATIONS Theory: Types of numerical grids and their applicability for different differential equations. Staggered, half-staggered and non-staggered grids in one, two and three dimensions. Discretisation of the continuity and Stokes equations on a rectangular grid. Conservative and non-conservative discretisation schemes for Stokes equations. Mechanical boundary conditions and their numerical implementation. No slip and free slip conditions. Exercises: Programming different mechanical boundary conditions. Solving continuity and momentum equations for the case of variable viscosity.
CHAPTER 8: THE ADVECTION EQUATION AND MARKER-IN-CELL METHOD Theory: Advection equation. Solution methods for continuous and discontinuous variables. Eulerian

schemes: upwind differences, higher order schemes, flux corrected transport (FCT). Lagrangian schemes: marker-in-cell method. Runge-Kutta advection schemes. Numerical interpolation schemes between markers and nodes. Exercises: Programming of various advection schemes and markers

CHAPTER 9: HEAT CONSERVATION EQUATION Theory: Fourier's law of heat conduction. Heat conservation equation and its derivation. Radioactive, viscous and adiabatic heating and their relative importance. Heat conservation equation for the case of a constant thermal conductivity and its relation to the Poisson equation. Analytical examples: steady and non-steady temperature profiles in case of channel flow. Exercises: Computing shear heating and adiabatic heating distribution for buoyancy driven flow.

CHAPTER 10: NUMERICAL SOLUTION OF THE HEAT CONSERVATION EQUATION Theory: Discretisation of the heat conservation equation with finite differences. Conservative and non-conservative discretisation schemes. Explicit and implicit solution schemes of the heat conservation equation. Advective terms: upwind differences, numerical diffusion. Advection of temperature with markers. Subgrid diffusion. Thermal boundary conditions: constant temperature, constant heat flow, combined boundary conditions. Numerical implementation of thermal boundary conditions. Exercises: Programming various thermal boundary conditions. Solving the heat conservation equation in the case of constant and variable thermal conductivity with explicit and implicit solution schemes. Advecting temperature with Eulerian schemes and markers.

CHAPTER 11: 2D THERMO-MECHANICAL CODE STRUCTURE Theory: Principal steps of a coupled thermo-mechanical solution with finite differences and marker-in-cell techniques. Organisation of a thermo-mechanical code for the case of viscous, multi-component flows. Adding self-gravity. Handling free planetary surfaces with weak layer approach. Exercises: Building a 2D thermo-mechanical code.

CHAPTER 12: ELASTICITY AND PLASTICITY Theory: Elastic rheology. Maxwell visco-elastic rheology. Rotation of stresses during advection. Plastic rheology. Plastic yielding criterion. Plastic flow potential. Plastic flow rule. Exercises: Stress buildup/relaxation with a visco-elastic Maxwell rheology.

CHAPTER 13: 2-D IMPLEMENTATION OF VISCO-,,ELASTO-PLASTICITY Theory: Numerical implementation of visco-elasto-plastic rheology. Organisation of a thermo-mechanical code in case of 2D, visco-elasto-plastic, multi-phase flows. Exercises: Programming a 2D thermo-mechanical code with a visco-elasto-plastic rheology.

CHAPTER 14: THE MULTIGRID METHOD Theory: Principles of multigrid method. Multigrid method for solving the Poisson equation in 2D. Coupled solving of momentum and continuity equations in 2D with multigrid for the cases with constant and variable viscosity. Exercises: Programming of multigrid methods for solving Poisson equation and coupled solving of momentum and continuity equations in 2D. *CHAPTER 15: PROGRAMMING OF 3-D PROBLEMS* Theory: Formulation of thermo-mechanical problems in 3-D and its numerical implementation. Multigrid method for solving temperature, Poisson, momentum and continuity equations in 3-D Exercises: Programming of multigrid methods for temperature and Poisson equations and coupled solving of momentum and continuity equations in 3D.

CHAPTER 16: NUMERICAL BENCHMARKS Theory: Numerical benchmarks: testing of numerical codes for various problems. Examples of thermo-mechanical benchmarks. Exercises: Programming of models for various numerical benchmarks. *CHAPTER 17: DESIGN OF 2-D NUMERICAL GEODYNAMIC MODELS* Theory: Warning message! What numerical modeling is about? Rock properties for numerical geodynamic models. Designing of numerical models for different geodynamic processes: visco-elasto-plastic slab bending, retreating subduction, lithospheric extension, collision, slab detachment, intrusion

emplacement, core formation. Comparison with natural examples. Exercises: Designing numerical model for extension of the continental lithosphere.
EPILOGUE: OUTLOOK Theory: Where are we now? Where to go further? Current and future directions of numerical geodynamic modelling development: 3D, MPI, OpenMp, PETSC, AMR, FEM, FVM, GPU/Cell-based computing, interactive computing, realistic physics, visualization challenges etc. Exercises: No more exercises and home works!

Effect of lateral viscosity variations on mantle flow and the geoid

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We address the long-standing question of how lateral viscosity variations in the mantle, such as due to presence of stiff slabs, affect the geoid. The long wavelength geoid is known to be very sensitive to the radial viscosity distribution within the Earth. However, effects of lateral viscosity variations on the geoid are still not clearly understood. We are motivated by the findings of Zhong & Davies (1999) who found that introducing stiff slabs in the lower mantle degrades the fit to the Earths long wavelength geoid compared to a model with only radial viscosity variations. This would indicate that slabs in the lower mantle are of the same strength as the ambient mantle, which is somewhat contrary to expectations. Moucha et al. (2007), however, argued that lateral viscosity variations inferred from seismic tomography have a minor effect on the geoid. We re-investigate the problem by computing the geoid in the presence of rheological complexity using the high resolution finite element mantle convection code, CitcomS. We test different slab viscosities and compute the correlation with the observed geoid. We substantiate that the geoid calculated from tomography is hardly affected by the presence of LVVs, whereas the geoid computed from global slab models yield a poor fit to the observed geoid when LVVs are considered. However, this degradation of fit only occurs for the very long wavelengths (degrees 2 and 3). For degrees 4 and above (the wavelengths that are most affected by slabs), the geoid remains almost unchanged in presence or absence of LVV, reconciling the findings for slab and tomography models. We also investigate the effects on the geoid from other causes of LVVs, such as weak plate boundaries, strong continental keels and a recently suggested low viscosity in the D layer due to post-perovskite. In addition to the geoid, we also attempt to match plate motions with a circulation model that has prescribed weak zones at plate boundaries. Motions are matched well and, taking into account LVVs, the geoid with appropriate surface velocity boundary conditions can match the observed geoid as well as for free slip cases, unlike what has been suggested before.

Quantifying the uncertainty of 3-D backward mantle convection model

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Reconstructing the past thermal evolution of Earth's mantle from present-day mantle heterogeneity[1] is one of the most numerically challenging tasks in geodynamics. A successful reconstruction of the time-dependent, 3-D mantle convective structure in the geological past provides invaluable insight into the origin and evolution of a number of fundamental surface processes that include epeirogeny[2], eustatic sea level change [3,4], state of stress in the lithosphere then true polar wander and Milankovitch Theory of Climate Change[5]. A critical question is: what are the limitations of backward mantle convection simulations and, most importantly, can we quantify the uncertainties inherent in such time-reversed models [6,7]?

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Signatures of downgoing plate-buoyancy driven subduction in Cenozoic plate motions

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Although subduction is one of the key processes in plate tectonics, the dominant forces controlling subduction parameters have remained elusive. To shed more light on this, we analyze relations between subduction motions and dips for the major subduction zones from the Cenozoic compilation by Sdrolias & Müller (2006), and compare them with the relations predicted by a fully dynamic model for subduction driven solely by downgoing plate buoyancy while resisted passively by the mantle and upper plate.

The data show that: Around 90% of Cenozoic plate convergence is achieved by advance of the downgoing plate towards the trench. Present-day sinking velocities, and downgoing-plate motions throughout the Cenozoic are mostly within the range of upper-mantle slab Stokes velocities. And average present-day dips are steep and display trends with age ranging from positive to negative.

When compared with the models, these trends of motions and morphology of the downgoing plate indicate that downgoing plate motion during the Cenozoic is mainly driven by upper-mantle slab buoyancy, for about 75% of the trench segments through time. The high contribution of plate advance to convergence and the steep dips are compatible with low asthenospheric drag below the plates (as for a viscosity 10^{-2} to 10^{-3} times the upper mantle average), and efficient transmission of ridge push. Steep dips and correlations between dip and radius of curvature indicate a relatively weak resistance to plate bending (such that bending contributes < 20% to overall dissipation). The variable dip-age trends are evidence of a non-linear and possibly bifurcating rheological plate response to bending stress.

Observed trench motions are mostly small, and often highly oblique to motion of the downgoing plate, with an average angle of 73°. This implies that trench motion is not dominantly driven by downgoing-plate pull. The component of trench motion in the direction of plate pull displays correlations with downgoing plate motions ranging from strongly positive to strongly negative, possibly indicative of regionally variable resistance to trench motion. Thus emerges a picture of (upper-mantle) slab pull driven, relatively free, subduction, where motion partitioning and slab geometry adjust to external constraints on trench motions.

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Towards self-consistent modelling of the Martian dichotomy: Coupled models of simultaneous core and crust formation

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One of the most striking surface features on Mars is the crustal dichotomy, a large difference in elevation and crustal thickness between the southern highlands and the northern lowlands. The dichotomy is among the oldest geological features on Mars and was formed more than 4.1 Ga ago [Solomon et al., 2005, Nimmo and Tanaka, 2005, Frey, 2006] owing to either exogenic [e.g. Nimmo et al., 2008, Marinova et al., 2008] or endogenic processes [e.g. Harder and Christensen, 1996, Zhong and Zuber, 2001, Roberts and Zhong, 2006, Keller and Tackley, 2009]. In order to find an internal origin of the crustal dichotomy, located within a maximum of 400 Ma of planetary differentiation, the thermal state of the planet resulting from core formation needs to be considered. Based on the geochemical analysis of SNC meteorites it was suggested that a primordial crust with up to 45 km thickness can be formed already during the Martian core formation [Norman, 1999]. Therefore we suggest that the sinking of iron diapirs delivered by pre-differentiated impactors induced shear heating-related temperature anomalies in the mantle, which fostered the formation of early Martian crust. In this study, we examine parameter sets that will likely cause an onset of hemispherical low-degree mantle convection directly after, and coupled to, an already hemispherically asymmetrical core formation. To test this hypothesis we use a numerical model, where we self-consistently couple the formation of the Martian iron core to the onset of mantle convection. Peridotite melting is enabled to track melting and crust formation caused by heat released from core formation and radioactive heating. We perform 2D spherical simulations using the code I2ELVIS applying the recently developed "spherical-Cartesian" methodology [Gerya and Yuen, 2007]. It combines finite differences on a fully staggered rectangular Eulerian grid with Lagrangian marker-in-cell technique to solve momentum, continuity and temperature equations as well as the Poisson equation for gravity potential in a self-gravitating planetary body. In our model setup, the planet is surrounded by a low viscosity, massless fluid ("sticky air") to simulate a free surface [Schmeling et al., 2008]. We apply a temperature- and stress-dependent viscoplastic rheology inside a Mars-sized planet. Radioactive and shear-heating as well as consumption of latent heat by silicate melting are taken into account. The depth of neutral buoyancy of silicate melt with respect to solid silicates is determined by the difference in compressibility of the liquid and solid phase. To self-consistently simulate the silicate phase changes expected inside a Mars-sized body, we employ the thermodynamical Perple_X database [Connolly, 2005]. As initial condition, we employ randomly distributed iron diapirs with 75 km radius inside the planet, representing the cores of stochastically distributed impactors characteristic for the late accretion stage of terrestrial planets [e.g. Chambers, 2004, Rubie et al., 2007]. Additionally, we explore the effect of one giant impactor core on the planetary evolution. Results indicate that the presence of a large impactor core induces hemispherically asymmetrical core formation. Furthermore, the amplitude of shear heating anomalies generally well exceeds the solidus of primitive mantle material. The formation of a considerable amount of silicate melt is observed. Some of the generated melt segregates to the surface to form primordial crust, whereas negatively buoyant melt from deeper sources sinks to the CMB. The hemispherical asymmetry in temperature induced by a giant impactor works in favour of an onset of low-degree mantle convection after core formation. Such a hemispherical convection geometry might subsequently be sustained by phase-dependent viscosity [Keller and Tackley, 2009], and thus harbour an early development of a dichotomous crustal thickness distribution.

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Mantle convection, topography and geoid on Mars and Venus

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The internal evolution of planetary bodies often include solid-state convection. This phenomenon may have a large impact on the various interfaces of these bodies (dynamic topography occurs). It also affects their gravity field (and the geoid). Since both geoid and topography can be observed by a spacecraft, and are therefore available for several planetary bodies (while seismological measurements are still lacking for all of them but the Moon and the Earth), these are of the first interest for the study of internal structures and processes. While a classical approach now is to combine gravity and altimetry measurements to infer the internal structure of a planet [1], we propose to complement it by the reverse problem, I.e., producing synthetic geoid and dynamic topography from numerical models of convection. The analysis of spectral characteristics of these data (power spectrum, admittance ans correlation) will be studied in a systematic way in order to establish their relationship with the mantle dynamics (rheology, vigour of the convection, geometry of the layer). These procedure first include a simple evaluation of the surface topography and geoid from the viscous flow obtained by the 3D numerical tool OEDIPUS [2] modeling convection in a spherical shell. A visco-elastic layer will then be considered and coupled to the viscous model – one question being whether the (visco-) elastic shell shall be included on top of the convective domain or within it, in the cold lithospheric outer region... What I will present in this workshop corresponds to one of the first step of this work : the comparison of the response functions of the topography and the geoid obtained from the 3D convection program to the results evaluated by a spectral method handling radial variations of viscosity [3] – the filtering effect of an elastic lithosphere will be discussed.

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The effect of different geometries on the numerical models of the thermal mantle convection

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A major tool for understanding thermal convection in the Earth's mantle is numerical modelling. The Boussinesq approximation has been used to formulate the partial differential equation system of the thermal convection. The equations were solved by a finite element method. The flexibility of the method allowed modelling of the thermal convection not only in rectangular domain, but in other geometries, too. The results obtained in rectangular coordinate system were compared with the benchmark study of Blankenbach et al. [1] and the agreement was within 1% error.

The simulations have been carried out in two dimensional rectangular, cylindrical, and in a "mantle-like"cylindrical-shell domain. The Rayleigh number (Ra) varied in the range of 10^4–10^7. It was found that relationships between surface heat flow (Nu) and Ra (Nu ~ Ra $^{1/3}$), and root-mean-square velocity (v_{rms}) and Ra (v_{rms} ~ Ra $^{2/3}$), originally derived from the thermal boundary layer theory for 2D rectangular domain, are valid in the other studied geometries, too. Obviously, for a given Rayleigh number, Nu, v_{rms} and the mean temperature of the convection cell depend on the geometry: the highest values were obtained in case of rectangular model domain. The significance of the cylindrical geometry is that for a given *rms* velocity the surface heat flow is the highest. In that sense the most effective heat transport occurs in cylindrical shape convection systems. The dimensionless mean cell temperature was 0.5 in case of symmetric rectangular domain, and it was lower in cylindrical and cylindrical shell domains. The lower mean cell temperature derives from the asymmetry of the flow regimes determined by these geometries. In case of cylindrical convection the surface of the hot upwelling plume in the centre is smaller than the surface of the cold downwelling flow at the rim of the cylinder. In case of cylindrical- shell geometry the outer cold surface of the domain is larger than the inner heated surface resulting in low cell temperature.

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Anisotropic mobility during two-phase flow

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During coupled flow of viscous mantle matrix and magma, deformation of the matrix leads to the formation of melt films perpendicular to the axes of tensile stress. Frictional resistance at the melt-matrix interface is greatly modified due to the establishment of such an anisotropic network of melt films. A derivation for total frictional resistance due to the formation of melt films in an originally interconnected network of melt tubules is presented. Anisotropy of the resistance is controlled by the parameter β, the resistance enhancement factor. The inverse of the resistance tensor, mobility, is similar to permeability of the aggregate. In a spherically symmetric plume flow, a small value of β renders the mobility extremely anisotropic and focuses melt near the conduit of the plume. Finally, comparsion between different modes of deformation indicate that the magnitude of the anisotropy of melt mobility varies between different modes of deformation. For the parameter range considered within this study, more than an order of magnitude enhancement of mobility is predicted during tension tests.

Radiogenic heating in the lower lithosphere and its effect on geotherm, seismic velocities, and heat flow

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Continental heat flow is strongly dominated by the distribution of radioactive elements in the crust. The concentration of radioactive elements in the lithosphere is much lower and generally does not contribute much to the surface heat flow. Despite the low concentrations, heat generation in the lithosphere can have a significant effect on the deep lithospheric part of the geotherm, especially in regions of thick lithosphere. We illustrate this effect with two sets of results. 1) Seismic tomographic models of the Tornquist Zone between Sweden and Denmark show a sharp velocity contrast at depths between 100-250~km which is interpreted as the boundary between thick Proterozoic lithosphere to the north and younger, thinner terranes to the south. In an earlier study (Hieronymus et al., EPSL, 2007), it was shown that seismic and heat flow data can be fit with a simple model of convection beneath a lithosphere of variable thickness. Recent magnetotelluric data indicate, however, that the predicted temperature contrast is too high. Placing significant but reasonable quantities of radioactive elements into the lower lithosphere allows an excellent simultaneous fit of seismic, magnetotelluric and heat flow data with the dynamic model. 2) In a second set of models, we

investigate in more detail the concept of non-uniform distributions of radioactive elements at depth. We test a number of simple, tectonically plausible models which result in different distributions of radiogenic heating: ancient, stalled subduction zones, ancient continental collision zones, juxtaposed lithospheres with different shallow and deep composition. We show results in terms of temperature and seismic velocities. We find that temperature and composition often work in unison to effect large variations in seismic velocity. Surface heat flow is seen to be very insensitive to deep heat generation.

Rheological insights obtained from postseismic GPS data of the Sumatra-Andaman Earthquake 2004

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Subduction earthquakes break locked parts of the connection between oceanic and continental crust. The stresses produced by the coseismic deformation induce relaxation processes in the viscous asthenosphere below, which in turn can be seen in GPS time series at the surface. We use a coseismic slip model of the Mw=9.3 Sumatra-Andaman earthquake of 2004 [Hoechner et al.2008] as starting point for modeling of the postseismic GPS response in a layered viscoelastic half space [Wang et al. 2006] using different rheologies. Maxwell type rheology is not able to fit the observed time- and amplitude behaviour at the same time [Paul et al. 2007], a problem which can be overcome using Burger rheology. We get the best match of the postseismic behaviour for a thickness of the elastic lithosphere of 40 km, which coincides well with the maximum depth of significant slip inferred in the coseismic model and which corresponds to the locking depth of the subducting slab. Using the rheological model obtained, we try to further improve fit to the data by inverting coseismic slip to jointly fit co- and postseismic deformation, and thus minimizing the need of postseismic slip.

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Impact of the Hapagea surpercontinental aggregation on American Cordilleras and the seafloor age distribution

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The ongoing aggregation of Africa, Arabia, India and Australia onto Eurasia is forming a supercontinent that we refer to as Hapagea. Although not as large as the older Pangea and Rodinia, Hapagea is nevertheless large enough to profoundly modify Cenozoic plate kinematics as it gradually becomes a hub apart from which American continents spread. The continuation of Atlantic spreading is carried out at the expense of the Pacific Ocean, forcing the Farallon / Nazca plates down into eastern Pacific subduction zones, despite the fact that this seafloor is theoretically too young and too buoyant to subduct efficiently. This process occurred later for South America, where the subduction of the Tethys buffered the impact of the Atlantic expansion, and earlier for North America where this configuration was never met. Global geodynamic implications of the current plate tectonics are multiple and include (i) increased compression on the western coasts of the Americas, leading to Cordillera formation in North America (Sevier and Laramide) and later in South America (Andean), (ii) the transition from a rectangular distribution of seafloor ages to a triangular distribution as westward progress of the Americas engulfs young Farallon/Nazca seafloor, and (iii) a decrease in the convective efficiency of mantle flow that results in decreased rates of lithospheric production at ridges, a situation that is cyclically met during the Wilson cycle and diminishes both mantle heat flow and sea level. These results imply that mantle drag causes the Atlantic spread and dominates the force balance of the Earth's lithospheric shell.

Reconciling surface plate motions and a three-dimensional mantle flow field in the southern Alaska subduction-transform system

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Global models find a good correlation between the direction of plate motion and directions of mantle flow field predicted from seismic anisotropy suggesting coupling between the mantle flow field and the surface plates. However, the fit is typically poor at subduction zones [1], [2]. In addition, regional observations of seismic anisotropy used to track the flow direction in the mantle suggest in many subduction zones the direction of mantle flow is non-parallel to plate motions [3], [4], [5], [6], [7]. This implies that near subduction zones, the mantle flow field is partially decoupled from the motion of the surface plates [3]. We construct regional three-dimensional numerical models of the subduction-transform plate system in southern

Alaska that include the overriding North American plate, subducting Pacific plate, and underlying mantle. The models show that with the incorporation of the strain-rate dependent rheology and a realistic plate geometry, plate velocities are produced that are consistent with plate motions and a complex three-dimensional flow field in the mantle is produced that is consistent with observations from seismic anisotropy. The incorporation of the effects of the dislocation-creep mechanism results in low viscosities in the mantle in regions of high-strain rate, and this low viscosity enables the complex mantle flow field to decouple from the motion of the surface plates. Close to the subduction zone, where mantle viscosities are low, the flow velocities in the mantle are on the order of 10 times plate motions. With distance from the subduction zone, mantle viscosities increase, and mantle flow velocities decrease to magnitudes compatible with plate motions and are in a direction closer to that of plate motions. By incorporating the effects of the dislocation-creep mechanism in a three-dimensional numerical model, the plate motions, mantle flow field, and seismic anisotropy observations are met in a self-consistent way.

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Lithosphere thickness on Mars: results from geoid and topography inversion

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We present a global model of crust and elastic lithosphere thickness variations on Mars based on inversion of the geoid and topography data. In the first step, to avoid computational difficulties associated with treating a viscous or elastic shell model of uneven thickness, we use a Gaussian-weighted moving-window and we solve a series of traditional inversions in order to determine regional values of crust and lithosphere thickness in equally spaced grid points. These regional inversions are carried out in spectral domain under the assumption that the thickness of the crust (or elastic lithosphere) in the far zone is the same as in the region investigated. In practice, we divide Martian surface into several areas. In each area we search for an optimal depth of compensation (based on the Airy isostasy hypothesis) and for an optimal elastic lithosphere thickness (based on the elastic flexure hypothesis). Using the Gaussian window we filter off in spatial domain the topography and gravity outside the selected area. Then we invert the filtered geoid and topography in spectral domain in order to determine a single ("global") value of the crust and elastic lithosphere thickness. These values differ from area to area and all together compose our global model of the crust and elastic lithosphere thickness variations. This model may however be biased since we neglect the effects of a variable elastic lithosphere thickness in the far zone on the elastic flexure in the region investigated. That is why, in the second step, we check the validity of our model by performing a finite-element computation of the deformation of a spherical elastic shell with the thickness variations predicted in the first step. The shell is loaded by the observed topography and the agreement of the predicted geoid with the observed one is evaluated. The resultant model is discussed in the light of present-day concepts of the Mars evolution.

Numerical modelling of subducting slabs with trench migration

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We are developing numerical models of mantle convection in order to study the formation and the dynamic behaviors of stagnant slabs, based on our three-dimensional code formulated with primitive variables. A time-dependent thermal convection of Boussinesq fluid in a rectangular box of 1320 km height and 7920 km width is considered. We have included both the exothermic olivine to spinel and the endothermic post-spinel phase transitions at around 410 and 660 km depths from the top surface, respectively. The viscosity of mantle material is assumed to be exponentially dependent on temperature and pressure (or depth). We also take into account the effects of the sudden increase in viscosity at the 660km depth. The computational domain is divided into the ``oceanic and ``continental regions on the left-hand and right-hand sides, respectively. The plate subduction is imposed by applying different kinematic boundary conditions to the top surface of the ``oceanic and ``continental sides. The convergent motion of ``oceanic plate is driven by a fixed velocity along the top surface. In addition, we take into account the effect of trench migration, by extending the two-dimensional approach by van Hunen et al. (2000) to a three-dimensional one. Here we assume the subduction below an actively overriding continent which moves oceanward at a given rate with respect to the deep mantle. We also included a thin layer of weak ``lubricating material along the top surface of the ``oceanic plate in order to accommodate a strong shear deformation along the ``plate boundary. The lubrication at the plate boundary is modeled by applying maximum yield strength in the regions with the weak materials which are advected along with the subduction of ``oceanic plate. We have employed non-uniform mesh divisions between the ``oceanic and ``continental sides and between the upper and lower mantle, in order to resolve the dynamic behavior of subducted slabs as much as possible. We have conducted preliminary two-dimensional calculations by ignoring the variations of subducting behavior in the direction of trench axis. In these calculations we have studied the influences on the slab dynamics of (a) the trench retreat, and the discontinuous changes in (b) viscosity and (c) density associated with the phase transition at the 660km depth. Our calculations show that the motion of overriding plate is of the primary importance on the formation of stagnant slabs: For a sufficiently fast trench retreat, the subducting slab tends to stagnate near the 660km depth. We also found that the stagnant slabs ``floating above the 660km depth are hardly formed solely by the effect of viscosity jump at the discontinuity. This indicates that the slab stagnation of the Earth mainly comes from an interplay between the surface motions and the phase transition at the 660km depth. In future we will further explore the truly three-dimensional dynamics of stagnant slabs, by expanding our models in the along-axis direction.

Two-phase solitary wave solutions and numerical benchmark

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It has long been recognized that the arc volcanism was directly related to the slab dehydration and water is necessary to explain the low temperature melting of the mantle wedge and possibly of the subducting oceanic crust and the composition of arc magma. To better understand the dynamics of geophysical fluid (water, melts) in the mantle wedge related to subduction zone, we have developed a two-phase flow numerical model which takes into account the effects of compaction of the matrix. In order to benchmark our code, we have looked for solitary wave solution and derived analytical solutions for the one-dimensional problem along with a method to compute their shapes. Implementing them as initial conditions allows us to test our numerical code and further investigate the properties of the solitary waves (speed of propagation as a function of amplitude and background porosity).

Analytical and numerical models of the dynamics of subducting slabs

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Subduction zone dynamics has been extensively studied with laboratory models in which a dense, high viscosity slab sinks into a less dense and less viscous mantle. The resulting slab shapes appear realistic compared to, e.g., the shapes that are imaged by seismic tomography, and subduction models have therefore been compared with various observables such as trench motion, subduction angle and subduction speed. If a similar setup (viscous slab in viscous mantle) is modeled in an Eulerian numerical code, however, a very different behavior is observed: Instead of bending and subducting, the slab 'drips off' in a Rayleigh-Taylor like instability. Since this result does not appear very natural, many workers have introduced a Byerlee-type, plastic yielding rheology in the slab, or added a low-viscosity 'crust' on top of the subducting slab. If the parameters (in particular the effective friction angle) are tuned accordingly results appear indeed similar to laboratory models. A direct comparison of such models with laboratory experiments, however, remains incomplete since the rheology and/or geometry is different. In addition, no scaling law exists that predicts slab velocity (or slab behavior) as a function of slab thickness, slab/mantle viscosity ratio and slab/mantle density difference. Existing scaling laws, such as the approach of Conrad and Hager [1999, JGR], rely on knowing the radius of curvature of subducting slabs, which is a parameter that is typically known only after an experiment has been performed. Before applying results to nature, where complicating factors such as depth-dependent nonlinear viscosities may play a role, it is important to have a more thorough (and quantitative) understanding of the fluid dynamics of a single, freelysubducting viscous slab in a viscous mantle. Ideally, such understanding should come from rigorously comparing numerical experiments with analytical and numerical models. As a first step in this direction, Schmeling et al. [PEPI, 2008] performed a benchmark study that addressed the effects of the upper boundary condition on slab dynamics. The results show that models in which the upper boundary condition is a true free surface, or in which a 'sticky-air' layer is employed, are indeed capable of reproducing laboratory experiments, as long as sufficiently fine numerical resolutions are employed. Here, we build on this work and perform a much more extensive analysis on the effect of numerical settings (resolution, time step), initial geometry (slab tip length and angle), and rheology on subduction dynamics. For this purpose, we use the most efficient code from the benchmark study, a 2D adaptive FEM code (MILAMIN) capable of modeling both slab and mantle in a single computational domain in the presence of a free surface. Results confirm earlier findings that slab dynamics is to a large extent controlled by the effective viscosity contrast between slab and mantle. Two main deformation modes exist as a function of viscosity contrast: the 'drip' or 'Rayleigh-Taylor' mode occurs for viscosity contrasts smaller than ~100, and is dominated by slab-stretching and non-constant horizontal plate velocities (which are significantly larger towards the trench). The 'plate' mode, on the other hand, occurs for viscosity contrasts larger than ~500 and is characterized by slabs that do not change their initial length during subduction. Horizontal plate velocities are homogeneous along the slab and bending occurs in the trench area, with a bending radius that depends on viscosity contrast and slab thickness. In the plate mode, the initial slab tip length and angle have a significant effect on the initial subduction rate. After the slab tip reaches a depth of several hundreds of km, however, subduction rates are largely independent on the initial geometry. A visual analysis indicates that this is the stage when slab bending at the trench is well established. If an increase in viscosity at 670 km depth is taken into account, the numerical models reproduce a range of observed slab dynamics in laboratory experiments, including forward trench motion, slab folding at the 660 and stagnant slabs. In particular, the results of Enns et al. [GJI, 2005] are confirmed for purely viscous behavior. Moreover, since our numerical simulations do not incorporate surface tension and are only mildly sensitive to the mantle-air density difference, this suggests that the effects of surface tension in laboratory experiments are unlikely to be of first-order importance. The numerical models have been used to derive scaling laws for slab sinking velocities as a function of geometrical and material parameters. The scaling laws are combined with equations that describe the behavior of thin viscous sheets, to give a semi-analytical model of slab subduction versus time. Excellent agreement exists between the semi-analytical and numerical models, which yields further insights in slab dynamics on Earth.

Modelling mantle dynamics and crust formation on Mars

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In order to explain the origin of the Martian crustal dichotomy, a number of recent papers have examined the effect of layered viscosity on the evolution of degree-1 mantle convection. It was found that a mid-mantle viscosity jump, combined with highly temperature- and depth-dependent rheology, are effective in developing a degree-1 convection within a short timescale. Such a layered viscosity profile could be justified by Martian mineralogy. However, the effect of a degree-1 convective planform on the crustal thickness distribution has not yet been demonstrated. It is not obvious whether a thinner crust, due to sub-lithospheric erosion and crustal thinning, or a thicker crust, due to enhanced crustal production, would form above the hemisphere of mantle upwelling. Also, the general shape of the dichotomy, which is not strictly hemispherical, has not yet been fully investigated.

Here we propose a model of the crustal patterns produced by 3D spherical numerical simulations of Martian mantle convection, using the finite-volume multigrid code StagYY [1]. A self-consistent treatment of melting, crustal formation and chemical differentiation has been added to models of three-dimensional thermal convection. This allows us to obtain global maps of the crustal thickness distribution as it evolves with time. The obtained results demonstrate that it is indeed possible to form a crustal dichotomy as a consequence of near degree-1 mantle convection early in Mars history. We find that some of the observed patterns show intriguing first order similarities to the elliptical shape of the Martian dichotomy. In all models, the region of thick crust is located over the region of mantle upwelling, which itself is a ridge-like structure spread over roughly one half of the planet, a planform we describe as 'one-ridge convection' [2].

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Edge-driven convection in 3D spherical convection

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I examine a series of 3D spherical incompressible convection calculations with strong temperature-dependent rheology and a step increase in viscosity in the lithosphere over one hemisphere. The calculations start from a uniformly hot mantle and the flow is followed over 500 million to one billion years. There is a significant difference in the convective plan form of the two hemispheres. The thick hemisphere has a simple upwelling plume structure while the thinner hemisphere has time-dependent short-wavelength structure below the lithosphere. In contrast to the stable plume model, with a low-viscosity channel below the lithosphere small-scale convection develops along the lithospheric step within the first 100 million years. I will map out the parameters necessary for this mode of edge driven convection (i.e., how large of a lithospheric step and what conditions on the low viscosity channel are nec-essary). Then, I will address over what time scale this mode of convection is stable and whether this mode of convection can generate enough melt to produce the Tharsis volcanic province. There are several possible explanations for why only part of the dichotomy boundary had extensive volcanism. The mantle may have had an anomalously hot region beneath the area that becomes the Tharsis swell. Alternatively, the geometry of the dichotomy may have favored that region over others. Finally, there may have been anomalous lithospheric structure that favored edge driven convection beneath Tharsis. These ideas will be explored with further computational experiments.

Multigrid and Krylov subspace solvers for the Stokes system

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Viscosity in the Earth's mantle varies by several orders of magnitude, dependent on temperature, pressure, grain size and phase transformations. Modeling these variations realistically in three-dimensional mantle convection simulations has been a long-standing problem.

We present various approaches to increase the robustness of the solution process in a two-dimensional Cartesian domain as well as in a spherical shell. Emphasis is on the finite-element discretization and on the iterative solution of the Stokes equations, which are the central part in the high-viscosity convection calculations. The accuracy of the finite-element discretization is estimated and the influence of inf-sup stability on the reliability of the solution and the convergence of the iterative solver is examined.

Convergence results for the Uzawa and MINRES methods will be compared, with special attention to the multigrid algorithm, which is used as solver resp. preconditioner for the momentum equation in both cases. Furthermore, the influence of the convergence tolerance for the steady-state Stokes solution on time stepping is examined to give an appropriate stopping criterion for the iterative solver. Finite-element discretization and solution methods are parallelized with MPI and domain decomposition.

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Upper mantle convective instability causes San Andreas Fault to creep

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The San Andreas Fault in California is composed of a 150 km long creeping segment between the northern and southern locked sections. We propose that the Pliocene removal of the southern Sierra Nevada mantle lithosphere drives a local crustal scale flexure anomaly responsible for this creeping behavior.

Along the border of the Sierra Nevada micro-plate (SN), the SAF is comprised of three segments. Two segments (to the north and south) are locked and support large earthquakes (e.g. the M 7.7 1906 San Francisco and M 7.8 1857, Fort Tejon earthquakes) while one in the center, from Parkfield (Pkd) to San Juan Bautista (SJB), is creeping at rate similar to plate motion (28-32mm/yr). What factor controls the contrasting seismic behavior along the SAF?

A mechanism must be found that reduces the fault's strength solely along its creeping segment. As faults are expected to be strongest between depth of 8 to 15 km, we suspect that at this depth range that the static friction should be reduced for the SAF to creep.

The recent discovery of a small amount (< 2%) of talc in the center part of SAF at 3,319–3,350 m depth (*1*) potentially can explain the creep of the SAF. However, there are three significant problems with this hypothesis. (i) Serpentinized ultramafic bodies of the Franciscan complex are dispersed along both creeping and non-creeping segments and individual bodies are not as large as the 150 km length scale of the creeping segment; (ii) laboratory experiments on natural fault gouges show that the static friction is only sufficiently low when the clay contents reach 30-40% weight (*2*), a much larger proportion than observed; (iii) geophysical data show that the serpentinized body drilled at Parkfield extends only to 4-5 km depth (*3*), not the 8-15 km required to make the fault creep.

Here, we propose an alternative hypothesis in which the regional geodynamics has modified the stress field along the central creeping segment of the SAF. Geomorphic, geophysical and geochemical observations, interpreted in terms of mechanical models suggest that the Southern Sierra Nevada is undergoing local convective instability within the mantle. The foundering of the crustal and lithospheric root of the southern Sierra flexurally bends the lithosphere and allows the maintenance of a stress field that is close to lithostatic at 8-15 km depth only along the creeping segment.

To quantitatively constrain our model, we use a 2D plane stress flexural formulation of the lithosphere coupled with 2D plane strain thermo-mechanical numerical simulations at upper mantle scale and we show that mantle convection coupled to an elastic-brittle lithosphere can influence the seismic behaviour of faults.

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Relationship between variations in spreading rate of the Pacific plate and time-dependent subducting slab dynamics

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Quantitative analysis of oceanic spreading rates is important for understanding of mantle dynamics, earth's heat budget and tectonic history. Evaluation of magnetic isochrons shows that spreading rates of oceanic plates during the last 180 My have been nearly constant. However, unlike the Atlantic and Indian plates, the Pacific plate experienced pulses – increases in spreading rate – from late Jurassic (~ 150 Ma) to early Cretaceous (~ 120 Ma) and during Cenozoic (from ~ 55 Ma to present). The following hypotheses have been proposed to explain variable plate velocities: 1) a superplume beneath the Pacific plate and 2) increases in mantle temperature up to 50 K. Both of these hypotheses focus the increased production rate of oceanic plate but, the role of subducting slab on the spreading rate rarely has been evaluated. In contrast to the Atlantic and Indian plates, the Pacific plate which has extensive subduction zones implies a relationship between spreading rate and subducting slab evolution. To evaluate the relationship, a dynamic subduction model where subduction is controlled by slab buoyancy, mantle viscosity structures and phase transitions has been formulated. The initial oceanic plate is prescribed as 5780 km long and ~ 130 My old by using the half-space cooling model. The trench and overlying continental lithosphere are fixed. Composite viscosity using diffusion and dislocation creep is used for the upper mantle rheology and diffusion creep is used for the lower mantle rheology. Our preliminary results show that cyclic spreading (subducting) rates are similar to the pulses of the Pacific plate, and the varying rates are related to slab evolution; the rate decreases, dip of the slab becomes shallower and vice versa. Using different mantle viscosity and Clapeyron's slopes of phase transitions (410 and 660 km depths) affect the style of cyclic spreading (subducting) rates and fate of the slab. Further, introduction of the mantle compressibility which makes the model more realistic will be considered in the future research.

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Investigating the physical properties of mantle plumes in 3D using an automatic plume detection routine

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Numerical calculations have been carried out to investigate the physical properties of mantle plumes in highly viscous thermal convection depending on the Rayleigh number (*Ra*). Boussinesq approximation was applied in a three-dimensional Cartesian domain filled with isoviscous, purely bottom-heated fluid with infinite Prandtl number. In order to monitor the dynamical behavior of plumes an automatic plume detecting routine (PDR) was developed based on the temperature between the plume and its surroundings.

It was established that as the convection becomes more vigorous with increasing Rayleigh number the average cross-sectional area of an individual plume decreases (appr. $\sim Ra^{-2/3}$), the vertical velocity in plumes increases ($\sim Ra^{2/3}$), while the average temperature in plumes is independent of *Ra*. It means that the volume and the heat transport in an individual plume is independent of the Rayleigh number. The number of plumes forming in the box increases ($\sim Ra^{1/3}$) which is in accordance with the scale analysis using the energy balance and the conservation of momentum. Furthermore, the Rayleigh number influences the temporal behavior of the average surface heat flow (Nusselt number – $Nu_0(t)$) and the heat advected by plumes ($Tw_p(t)$). The characteristic frequencies of $Nu_0(t)$ and $Tw_p(t)$ increase by $\sim Ra^{2/3}$ in agreement with the rate of increase of the vertical velocity in plumes. The characteristic frequencies of $Nu_0(t)$ and $Tw_p(t)$ are between the frequency corresponding to the time necessary for a plume to rise from the bottom to the top of the layer and the frequency of a whole convective cycle. The time series of $Tw_p(t)$ contain larger amplitudes and higher frequencies than $Nu_0(t)$. It was assumed that the heat in the top thermal boundary layer (TBL) propagates by conduction and using $Tw_p(t)$ as an input at the bottom of the top TBL the amplitude and the frequency of the heat flow series on the surface was calculated. It corresponds very well to the amplitude and the frequency of the observed $Nu_0(t)$. The correlation analysis between the time series of the surface Nusselt number and the heat advected by hot plumes showed that the time delay between the time series is equal to the time of the heat propagation by conduction through the TBL. The correlation between time series $Tw_p(t)$ at different depths demonstrated well that the main heat transfer mechanism in plumes is advection.

Subducting slab : a jellyfish in the Earth aquarium

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It is now widely accepted that some subducting slabs may cross the lower/upper mantle boundary to ground below the 660 km discontinuity. Indeed, geophysical data underline long and narrow traces of fast materials, associated with subducting slabs, from the upper mantle transition zone to mid-mantle depths that are visible beneath North and South America and southern Asia (Li et al, 2008). Furthermore, seismic tomography data (Van der Hilst et al., 1997, Karason and van der Hilst, 2000, 2001) show a large variety of slab geometries and of mantle flow patterns around subducting plate boundaries. However, seismic tomography does not elucidate the temporal evolution of the slab behaviour and geometry during its descent through the upper and lower mantle. In this work, we therefore propose to study the deformation of a thin plate (slab) falling in a viscous fluid (mantle). The combination of both analogue and numerical experiments provides important insights into the shape and attitude evolution of subducting slabs. Models bring information into the controls exerted by the rheology of the slab and the mantle and on the rate at which this deformation takes place. We show that in function of a viscosity ratio between the plate and the surrounding fluid, the plate will acquire a characteristic shape. For the low viscous case, the plate shape tends toward a bubble with long tails: a “jellyfish” form. The time necessary for the plate to acquire this shape is a function of the viscosity between the slab and the mantle but also as function of the slab width and mantle viscosity stratification.

Geodynamical models of the rotation and extension of Alcapa and Tisza blocks in the Pannonian basin of central Europe

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The two major crustal blocks of the Pannonian basin, Alcapa (Alpine-Carpathian-Pannonian) and Tisza, underwent a complex process of rotation and extension of variable magnitude during the Tertiary. The northward push of the Adriatic Block initiated the eastward displacement and rotation of both the Alcapa and Tisza blocks. Emplacement was accompanied by substantial strike-slip movements, together with shortening and possible extension across the Mid-Hungarian Line, which now separates the two domains. Anti-clockwise rotations of variable amplitude occurred during the Early Miocene in the Alcapa unit, and clockwise rotations of the Tisza block occurred between Late Cretaceous and Late Miocene. The opposite rotations of the two plates led to NW-SE convergence and NE-SW extension in the space between the two Intra-Carpathian terranes. Subsequently both domains underwent extension dominantly in the NE-SW direction. We have constructed geodynamical models of the rotation and extension of the two Pannonian blocks. We decompose this complex process into two stages. We aim to show how the two plates deformed under the influence of a NW push by the Adriatic block, a NE pull from a retreating subduction zone on the eastern Carpathians, and the internal buoyancy forces arising from crustal thickness variations. We consider only 2D aspects of the problem, using an idealised thin viscous sheet model of the continental lithosphere. The deformation of the lithosphere is described by a non-linear viscous constitutive relationship. Our approach is based on the finite element method, and we consider several distinct models of initial geometry, boundary conditions, and constitutive parameters. Rotation and distortion vary across both blocks, with clockwise rotation occurring in the Alcapa plate, and anticlockwise rotation in the Tisza block. For a fixed exponent in the non-linear stress vs strain-rate law, increasing the viscosity coefficients of the blocks relative to the surrounding domain has a distinct impact on the distribution of rotation and deformation within the two blocks.

The influence of evolving plate boundaries in 3D mantle convection simulations

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A variety of mantle convection simulations featuring model plates suggest that plate-like surface motion strongly influences underlying convection patterns, surface heat flux, system temperature and plume stability. However, a number of the conclusions have been made based on modelling in which plate boundaries remains fixed. However, plate boundaries move at comparable speeds to the velocities associated with convection driven flow in the mantle, therefore the shapes and sizes of the tectonic plates change considerably in just one mantle transit time. In order to properly assess the influence of plate-like surface motion on mantle convection, we investigate convection in systems featuring evolving plate geometries. In the calculations presented we investigate the behaviour of systems featuring both evolving plate velocities and shapes. Plate velocities in our study evolve so that the shear stress on the base of each of the finite thickness high viscosity plates sums to zero at all times, to ensure that the plates neither drive nor resist the convection. We compare the evolution of the surface and basal heat flow and changes in convection planform in two sets of calculations in which simple plate geometries change with time while plate velocity responds dynamically to the evolving driving forces in the plate-mantle system. The models feature either 4 or 9 polygon-shaped plates resulting in a surface characterised by piece-wise continuous uniform velocities corresponding to each plate interior. In the first study we compare the difference in evolution of a pair of models featuring 9 plates in a 6x6x1 system. In one calculation the plate boundaries are held fixed and in the second the plate boundaries evolve dynamically in response to motion of the plate geometry triple junctions. In addition to thermal evolution we compare the time-dependence of the plate velocities in these models. In a second set of calculations using 4x4x1 solution domains we prescribe the evolution of four plates, rotating the initial plate geometry through 90 degrees at a constant rate in each experiment. The influence of the plate boundary motion on the convective planform is compared in models featuring different viscosity profiles.

Numerical modeling on craton destruction

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Archean cratons are characterized by a cold, thick, stable lithosphere keel. The North China Craton(NCC),however, is an anomaly. The eastern NCC experienced significant lithospheric thinning in the Late Mesozoic to Cenozoic. In order to understand the mechanisms of lithospheric thinning, we performed a set of geodynamic experiments using MILAMIN_VEP, which is based on the finite element method.

The setup involves a flat homogeneous lithosphere with a thickness of 190km. The influences of (a) lithosphere extension, (b) upper mantle convection and (c) thermal anomaly beneath lithosphere are investigated separately or simultaneously. In the cases of (a), a push velocity is imposed to extend the lithosphere while the end of lithosphere is replaced by material with low viscosity. In the cases of (b), thermal anomalies at the bottom of the model are used to start the convection. In cases of (c), high temperature anomalies are imposed just beneath the lithosphere.

We conclude from our initial experiments that: (A) simple extension can thin the whole lithosphere homogeneously at the beginning and break the lithosphere by a normal fault finally, (B) downwellings dominate convection after about 10Myrs, independent of the initial magnitude of the temperature anomaly. The bottom of lithosphere can be partly destroyed at certain places where stable downwelling forms, (C) a simple high temperature anomaly beneath lithosphere has little influence to the lithosphere thinning. It is thus suggested that upper mantle convection is the main mechanism of destroying a craton.

Thermomechanical modeling of the channel flow dynamics and metamorphism

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We investigate the indentation of a tectonic plunger into a thick and hot crustal root and consequent flow of a hot orogenic lower crust over the basement promontory. Such a scenario was proposed for the eastern margin of the Bohemian Massif where the Brunia basement promontory indented the thickened crustal root of the Variscan orogen. However, some general conclusions are valid for other orogenic systems too. Three critical model parameters are tested: the thermal structure of the root, lithology stratification and the velocity of the basement promontory. We examine characteristic properties of the channel flow process and PT paths of the exhumed orogenic lower crust and discuss their dependence on the critical parameters. The thermomechanical model of the indentation process was developed using the open source finite element software for multiphysical problems Elmer (http://www.csc.fi/english/pages/elmer). The modeled 2D Cartesian domain represents a vertical cross section through the deformed orogenic root. We assume viscoplastic rheology of the crustal material and prescribed rheological parameters correspond to the expected composition of the Brunia basement and of the Variscan orogenic root at the eastern part of the Bohemian Massif. In order to model the compositional convection, we implemented active markers. An arbitrary Lagrangian-Eulerian method (ALE) is used to treat the upper moving boundary of the model which represents the free surface of the Earth. We also discuss the role of erosion and isostasy. Both of these effects strongly influence pressure and temperature conditions in the system and their inclusion is thus important for proper prediction of geological observables.

The role of Tehuantepec ridge subduction on mantle hydration and young volcanism in Southern Mexico

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The origin of El Chichón volcano is poorly understood, and we attempt in this study to demonstrate that the Tehuantepec Ridge (TR), a major tectonic discontinuity on the Cocos plate, plays a key role in determining the location of the volcano by enhancing the slab dehydration budget beneath it. Using marine magnetic anomalies we show that the upper mantle beneath TR undergoes strong serpentinization, carrying significant amounts of water into subduction. Another key aspect of the magnetic anomaly over southern Mexico is a long-wavelength (~ 150 km) high amplitude (~ 500 nT) magnetic anomaly located between the trench and the coast. Using a 2D joint magnetic-gravity forward model, constrained by the subduction P–T structure, slab geometry and seismicity, we find a highly magnetic and low-density source located at 40–80 km depth that we interpret as a partially serpentinized mantle wedge formed by fluids expelled from the subducting Cocos plate. Using phase diagrams for sediments, basalt and peridotite, and the thermal structure of the subduction zone beneath El Chichón we find that ~ 40% of sediments and basalt dehydrate at depths corresponding with the location of the serpentinized mantle wedge, whereas the serpentinized root beneath TR strongly dehydrates (~90%) at depths of 180-200 km comparable with the slab depths beneath El Chichón (200-220 km). We conclude that this strong deserpentinization pulse of mantle lithosphere beneath TR at great depths is responsible for the unusual location, singularity and, probably, the geochemically distinct signature (adakitic-like) of El Chichón volcano.

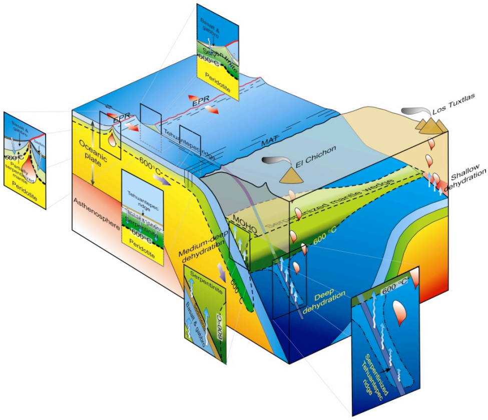

Figure. Tectonic model for southern Mexican subduction zone showing where serpentinization–deserpentinization processes might occur. Large red and blue arrows indicate relative plate motion. Vertical light blue arrows depict fluid access or discharge. Red drops represent magma. Black lines along EPR, TR and MAT show the presumably location of fractures which cut deep into the oceanic lithosphere. The serpentinized oceanic lithosphere beneath TR carries water into subduction zone and releases it at greater depths of 180–200 km (deep dehydration). Sediments and oceanic crust participate with fluids to serpentinize the mantle wedge (medium-deep dehydration).

3D modeling of flat slab subduction and detachment beneath Central Mexico

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Recent tomographic images beneath Central Mexico revealed a perfectly flat slab segment extending several hundreds of km inland [Perez-Campos et al., 2008]. Also, the flat slab in not in direct contact with the overlying crust, and a low velocity layer decouples the two plates. Here we present a 3D geodynamic model tailored to realistic paleoreconstruction back to 35 Ma. Using a tracer technique described in details by Manea and Gurnis [2007], the models incorporate a low viscosity wedge and channel down to 300 km. Time-dependent dynamic models are solved using the finite element package CitcomS from CIG. The computations are performed within a spherical domain (r=1300 km, θ,= 57°, φ,=57°). The position of plate boundaries is imposed and set using the G-Plates software. The modeling results show that the subduction system in Central Mexico entered into flat slab regime at ~15 Ma. Later, at ~10 Ma, the slab started to break off and by ~5 Ma is completely detached. In Central Mexico the propagation of slab detachment is expressed by a short (2–3 m.y.), eastward-migrating pulse of mafic volcanism that took place from ca. 11.5 to ca. 5 Ma to the North of the present Trans-Mexican Volcanic Belt [Ferrari, 2004]. The onset of flat slab (from volcanic rock dating, Ferrari et al., 1999) took place 17-12 Ma. Our models predict both, the onset of flat slab around 15 Ma and the slab detachment at ~10 Ma.

Core mantle boundary topography as a constraint on large scale mantle models

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Several dynamic hypotheses have been proposed to explain the nature of large scale mantle convection and the cause of the large, low shear velocity provinces (LLSPs) observed in tomography beneath Africa and the Pacific. Here, we explore whether the topography of the core mantle boundary (CMB) may act as a constraint upon these hypotheses. We examine 2 conceptual mantle models, long-lived thermochemical piles and plume clusters. We find that each model predicts a unique characteristic style of CMB topography. Beneath thermochemical piles, CMB topography is relatively flat and positive, with a ridge of more elevated topography along the margins. In the plume cluster model, CMB topography is elevated beneath individual upwellings, producing a spoke-like network of topographic ridges. In both models, CMB topography is depressed beneath subduction regions. Each model produces a unique, characteristic pattern of CMB topography that could be discernable provided adequate seismic observations exist.

Generation of intermediate to deep earthquakes by self-localizing thermal runaway: insights from petrological and numerical studies

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The causes of intermediate-depth earthquakes (50-300 km) in convergent plate-margins are, in the absence of high fluid pressures, difficult to explain because the high confining pressure makes brittle failure, typical of shallow earthquakes, unlikely. An alternative failure mechanism is thermal runaway of ductile shear zones [1-3]. Irreversible ductile deformation dissipates mechanical work into heat that can lead to thermal softening and failure by progressively self-localizing thermal runaway (SLTR)[1]. To test this alternative we have studied pseudotachylytes, remnants of intermediate-depth earthquakes, from an eclogite-facies gabbro that contains parallel non-seismic shear zones and co-seismic pseudotachylytes. Clear signs of interactions with external fluids suggest that, besides thermal softening, weakening by hydration also plays a key role in shear zone formation and ultimately seismic failure. These observations are in good agreement with the predictions from fully coupled thermo-viscoelastic numerical simulations. The numerical simulations demonstrate that SLTR occurs at differential stresses lower than the brittle yield stress, is facilitated by hydration weakening, and results in the same brittle and ductile deformation patterns that are observed in natural examples. More elaborate simulations that include continuous stress loading and weakening due to fluid infiltration or low temperature plasticity at high confining pressures could significantly lower the stress required to initiate SLTR. Our simulations provide an explanation for the observed coexistence of ductile deformation (shear zones) and brittle-like

catastrophic failure (pseudotachylyte veins) with seismogenic strain rates and active melting at the deep-earth conditions.

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Strength of Dead-Sea-Transform Fault: Constrained by thin-shell thermo-mechanical model

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We use the thin-shell neotectonic modelling method [1, 2] to study at large scales the parameters controlling the dynamic of the Dead Sea Transform (DST). The DST is the left-lateral strike-slip system of faults that accommodates about 105 km of the relative motion between the African and Arabian plates during the last 15-20 Ma [3] (see Fig. 1, left). The slip rate at the southern part of DST is between 0.3-0.6 cm/year.

A key question related to the Dead Sea Transform Fault is: What should the rheological properties of the lithosphere beneath the DST be, to allow it to work as a transform plate boundary with the slip rate of few millimeters per year? This study is aimed at addressing the above question using a thermo-mechanical model in an extended 2-D approximation (thin-shell approach) focused on the deformation processes in scale of several thousand of kilometers, although at the Middle East scale.

The slip rate at the DST is controlled by far-field plate motions, thickness of the lithosphere beneath the fault and friction coefficient at the fault. The far field plate motions are provided by plate tectonics model [3]. The thickness of the lithosphere directly beneath the DST is not well constrained by seismic data, but thermo-mechanical modelling study [4] suggests that thickness of mantle lithosphere beneath the DST can be as low as 20-30 km. The fault friction coefficient has not been extensively examined at this region yet. In this work we compute a two-parameter suite of models with different fault friction coefficient and different mantle lithosphere thickness beneath the DST to find out the range of parameters compatible with the slip rates at the DST of 0.3-0.6 cm/yr.

We use regional elevation data and available deep seismic and surface heat flow data to estimate the lithosphere structure and thermal regime under the assumptions of steady state and Airy isostasy.

A variety of models were tested with different fault friction coefficient values (varying from 0.05 up to 0.40) and different mantle lithosphere thickness values (varying from 20 km to 40 km) beneath the Dead Sea Transform. We also analyze the effect of the shape of fault by considering (i) a large segment of DST extending from the Gulf of Aqaba through Dead Sea and the Lebanon Mountain Belt until East Anatolian Fault and (ii) a short segment without considering the bending northern part, which comprises the region from the Lebanon Mountain Belt until the East Anatolian Fault.

Based on the plate velocity field, which is one of model's predictions, we conclude on possible rheology in terms of the trade-off between fault friction coefficient and lithosphere thickness.

The observed slip rate of 0.3-0.6 cm/year at the DST can be achieved only if the average friction coefficient at DST is lower than 0.10 (see Fig. 1, right). Hence, the friction at DST appears to be as low as for the world's weakest transform fault, the San Andreas Fault in California [5]. The reason why such low friction is required at the DST to allow observed slip rates is the irregular shape of the DST, especially its bending in the northern part. Without its bending northern segment, DST would allow observed slip rates even being much stronger. Model results also suggest that mantle lithosphere below DST must be thinner than 30 km, in accord with prediction of the thermo-mechanical model [4].

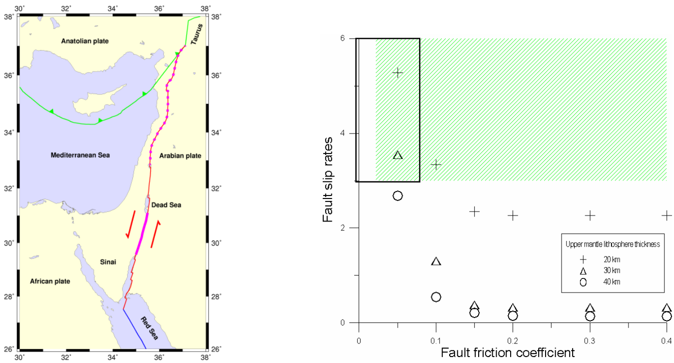

Fig. 1: (Left) *area of interest. DST is depicted with red line, extending from the Gulf of Aqaba through Dead Sea and the Lebanon Mountain Belt until the East Anatolian Fault. Northern bending part of DST is highlighted with pink dots. (Right) fault slip rate versus fault friction coefficient when considering the whole segment of the DST. Green rectangular represents the area of observed fault slip rates. Different symbols represent different mantle lithosphere thicknesses.*

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Adaptive wavelet methods for computational geodynamics

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Calculation of phase diagrams for the Earth's materials exerts a growing impact in studying of core and mantle dynamics. Recently, the method for calculation of phase diagrams and related in situ properties of rocks (e.g. density, enthalpy, seismic velocity, etc.) in space of two variables (P, T) by using second generation 2D wavelets was proposed (Vasilyev et al., EPSL, 2004). Here we present further generalization of this approach to three dimensions. We employ combination of adaptive wavelet-based meshing technology and efficient ''phase diagram function'' designed as a Gibbs free energy minimization. The proposed automated strategy allows one to obtain equilibrium phase assemblages and related physical properties depending on three arbitrary variables (e.g. P, T, water activity). The use of this strategy captures very small details of phase diagram morphology allowing both acceleration of the calculations and efficient compression of the results. Compressed phase diagrams can be efficiently used in geodynamic numerical modeling studies of tectonic processes on the basis of coupled petrological-thermomechanical modeling approach.

Repeated ridge jumps associated with plume-ridge interaction and melt migration

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Observations at ridges migrating away from hotspots such as the Mid-Atlantic Ridge at Iceland and the Galapagos Spreading Center display repeat jumps of the axis toward the hotspot. The mechanisms that control the initiation of jumps and repeat jumps are poorly understood, but likely include the effects of off-axis plume-lithosphere interaction and lithospheric heating caused by magma penetration. We use the CITCOM finite-element code to examine new 2D (cross section) models of ridge jumps associated with a near-ridge plume-like upwelling in a visco-plastic mantle and magmatic heating of the lithosphere controlled by melting and melt migration. Melting of the mantle is calculated assuming an anhydrous peridotite solidus with a mantle productivity that produces 6-7 km of crust at a normal ridge. Melt is assumed to travel vertically through the mantle to the solidus, just below the lithosphere, and then to be transported along the solidus according to a simplified version of two-phase flow. In locations along the solidus with large porosities (melt pressure) and/or damage associated with previous magmatism, a narrow zone of magma penetration and heating weakens the lithosphere promoting (for off-axis locations) ridge jumps. Calculations predict ridge jumps to be promoted on younger, slower moving plates and the time to initiate a jump to decrease with smaller plume-ridge separation distances and larger heating rates. Additionally, in cases including ridge migration, our results predict jumps to be promoted for migration rates similar to the half-spreading rate. A migration rate much greater than the half-spreading rate results in the plume and ridge separating without a jump because the plate rapidly crosses the plume melting zone decreasing the time available to heat a given portion of lithosphere. Large heating rates tend to "capture" the ridge without a jump. Finally, heating rates predicted to initiate jumps to ~3-5 Myr old lithosphere in fixed cases, successfully predict repeat ridge jumps. The primary process involved in initiating repeat jumps is the dependence of magmatic heating on melt transport which causes a discrete shift (instead of a smooth migration) of the heating zone from the current ridge to a new off-axis location.

3D models of shear and extensional deformation of the lithosphere

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We will show some of our recent work on the 3D deformation of the continental lithosphere in which we examine the interaction of shear bands with conflicting initial orientations.

Possibility of hot anomaly in the sub-slab mantle at northeast Japan subduction zone

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Recently a couple of seismological studies confirmed the existence of low seismic velocity anomaly in the sub-slab mantle of the northeast Japan subduction zone around the 410 km discontinuity and argued that it is mainly due to the high temperature anomaly whose magnitude is around 200 K. In this presentation, in order to investigate the origin of this anomaly and to understand the dynamics of sub-slab mantle based on the mantle convection theory, two types of models are considered.

First, as a possibility of hot anomaly coming from elsewhere, the model in which a past hot anomaly was entrained there (Honda et al., 2007) is reconsidered. Their model has two problems; They do not consider the effects of the thermal structure inside the subducting/overlying plate and the effects of slab deformation such as a stagnation around the 660 km discontinuity. Thus, we have constructed a new model that takes into account these effects and re-evaluated the results of Honda et al. (2007). It is found that they underestimated the effects of the thermal structure inside the slab and the plate, and hot anomaly cools faster than their models show. Thus, their suggestion that the past Pacific superplume activity may be the cause of the low seismic velocity anomaly observed at present may not be likely, as far as their assumed plume size, magnitude of hot anomaly, plate geometry and plate velocity are appropriate.

Second, as a possibility of hot anomaly emerging in-situ, the model that takes into account the effects of radiogenic heat production, adiabatic heating, latent heat and viscous heating are considered. It is found that the magnitude of high temperature anomaly is O(200 K) for the earth-like cases. However, the position of high temperature anomaly is in the lower mantle, and, thus, it is unlikely that these heat sources can explain the observed anomaly, unless there are any mechanisms to shift the hot anomaly to the upper mantle.

Finally, by combining two types of models as described above, we suggest and discuss briefly another possibility that may explain the existence of hot anomaly adjacent to slabs.

In the future, besides improving the models, global observations of sub-slab mantle will be helpful to limit the possibilities, because some possibilities are local in nature. This kind of studies is also important to understand the dynamics of the sub-slab mantle and the subduction processes.

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Towards a robust TERRA

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The simulation of mantle convection with the code TERRA is investigated from a numerical point of view. Theoretical analysis as well as practical tests are performed. The stability criteria for the numerical formulation of the physical model will be made clear. For the incompressible case and the Terra specific treatment of the anelastic approximation, two inf-sup stable grid modifications are presented, which are both compatible with hanging nodes. For the element pair a simple numeric test is introduced to prove the stability for any given grid. For the element pair and 1-regular refinements with hangig nodes an existing general proof can be adopted. The influence of the slip boundary condition is found to be destabilizing. For the incompressible case a cure can be adopted from the literature. The necessary conditions for the expansion of the stability results to the anelastic approximation will be pointed out. A numerical framework is developed in order to measure the effect of different numerical approaches to improve the handling of strongly varying viscosity. The framework is applied to investigate how block smoothers with different block sizes, combination of different block smoothers, different prolongation schemes and semi coarsening influence the multi-grid performance.

Length-scale of compressible mantle convection with the plate-like behavior

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Numerical simulations of compressible mantle convection including all major phase transitions with the plate-like behavior are used to find out whether the rheology inducing the plate-like behavior is dominated or not. Several combinations of yield stress and activation enthaphy including iso-viscous case are tested here. For surface to mid-lower mantle, the flow-scale is dominated as degree 1 to 2 of spherical harmonics but, in the lowermost mantle, shorter length-scale of convection is expected because of existence of post-perovskite phase transition. Detail analyses on flow-scale will be shown in the poster.

Subduction dynamics and magmatic arc growth: Numerical modeling of isotopic features

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Convergent margins are the sites of a substantial mass transfer, where the Earth's crust material is recycled back to the mantle, which in turn induces a new crust formation. Several aspects of magmatic arc formation are consequently discussed in literature but still poorly understood. Among these are (i) influence of subduction dynamics on the crust growth, (ii) slab and mantle contributions to the crust formation, (iii) dynamics of mantle partial melting, and (iv) the way of material transport to the surface (fluid or melt). We have developed a coupled geochemical-petrological-thermomechanical 2D numerical model of retreating subduction, which includes spontaneous initiation of subduction, slab retreat and bending, aqueous fluid release and transport, melting of slab and mantle, and resulting magmatic arc formation. This model allowed us to investigate the dynamics of subduction, mantle wedge plumes development and magmatic arc growth and displacement. Our numerical experiments showed that subduction rate varies strongly with time and plays a crucial role in a rate of crustal growth and composition of newly formed crust. The goal of the present work is to combine numerical modeling method with geochemical approaches. Geochemical features of each process are tracked by markers in the model, which includes element partitioning between minerals and fluid and/or melt. Particularly we study 231Pa-235U and 238U - 230Th - 226Ra systems, which are known as good tracers to constrain both melt and fluid contribution and sources of a new crust material.

Super-size Earth: Influence of an inner stagnant lid on the plate tectonic behaviour of super-Earths

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Due to new technologies the number of terrestrial exoplanets found in the past few years increased very fast. Some of them have masses in the range of 2 to 10 Earth masses, and the habitability of these planets is a widely discussed topic of the last years. Many scientists believe that life depends on (or at least benefits of) plate tectonics [1] and hence the question if plate tectonic behaviour (including subduction) could occur on Super-Earths like on Earth is of great importance for determining their habitability.

Parameterization models of terrestrial planets as well as convection models have been adapted to this problem by various scientists leading to two different conclusions. [2] investigated up-scaled versions of the Earth and concluded that plate tectonics is not possible for such planets larger than Earth. [3] on the other hand found that plate tectonics will develop easier on Super-Earths, since the upper lid will be thinner and hence easier to break.

Both models used many simplifications, which influence the results strongly. In the present study we investigate planets of Earth-like composition with masses ranging from 1 to 10 Earth masses. Physical parameters like gravity and ratio of core to planet radius have been rescaled using the parameterizations of [4]. To obtain more realistic results, the viscosity was calculated using the Arrhenius law not only with temperature-dependence, but with pressure-dependence as well, which has been neglected in the earlier studies [2, 3]. The activation volume is taken to be Earth-like and is considered to be constant or depth-dependent for comparison issues.

In a previous work using a 3D convection model of the mantle [6] and a 1D parameterization model [5], we already showed that pressure has a strong influence on convection and hence on the thermal evolution of an Earth-size planet. This effect will be stronger for Super-Earths, since the pressure and its influence on the viscosity increase.

In this paper, we investigate the influence of increasing planetary mass and hence increasing pressure on the emerging stagnant low-lid at the core-mantle boundary and its influence on the convection and plate tectonics behaviour.

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The effects of glacial loading on lithospheric instabilities

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Vertical motion of the Earth's surface couples tectonics and climate. Post- glacial rebound, for example, is driven by climate-generated perturbations of the lithosphere-mantle system. Vertical motions of the Earth's surface in turn alter climate through topographically induced changes of surface temperatures and precipitation patterns. Previously, tectonically induced perturbations to the lithosphere-mantle system have been suggested to generate lithospheric in- stabilities, these instabilities result in surface uplift [Houseman and Molnar, 1997]. We propose glacially-induced perturbations to the lithosphere-mantle system may induce lithospheric instabilities, and seek to determine if associated uplift may produce climate feedbacks. Ultimately, by studying the relationship between lithospheric in- stabilities and glacial loading, we will explore the possible long term coupling between tectonics and climate on Earth.

Modeling transform plate boundary in 3D: Dead Sea Transform Fault from the Red Sea to Lebanon Mountains

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Dead Sea Transform (DST) fault system is a part of the Syrian-African rift system and it extends from the divergent plate boundary of Red Sea rift at the south to the convergent plate boundary in the Taurus Mountains at the north. The DST itself is a left-lateral transform fault, accommodating differential motion between the African and Arabian plates. The morphology of the DST fault system is expressed by several linear stretches separated by a number of pull-apart basins, where the Dead Sea basin is a largest. Our previous models (Sobolev et al. 2005, Petrunin and Sobolev, 2006, 2008) have been focused at two main topics: (1) major controls of the fault localization in strike slip settings and (2) major controls of the structure and evolution of pull-apart basins located at strike- slip faults. To do so, we modeled lithospheric deformations using 2D and 3D FEM techniques with realistic elasto-visco-plastic temperature and stress dependent rheology. However, limitation of our models was their relatively small size, which did not allow including the source of the strike-slip motion in the region (opening of the Red Sea Rift), and major obstacle for the propagating fault resulting in its bending in Lebanon. In present work we extend the model to the larger region. The new model domain includes north-western part of the Red Sea and extends to the Lebanon Mountains in the north where deformation becomes more complicated and large part of the strike-slip motion becomes distributed. Because of the large size of the domain, we made an improvement in the modeling technique taking into account sphericity of the Earth surface.

Here we present a model aimed at revealing controls of initiation and positioning of the DST fault. We also consider the discrepancy between present day surface heat flow (about 50mW/m2, consistent with the thickness of the lithosphere of more than 120 km) and observed thickness of the lithosphere at the DST area of 70-80 km according to seismic data (Mohsen et al. 2005). This discrepancy means that lithosphere around DST was thinned in the past and related high heat flow had not enough time to reach the surface.

As an initial setup we use simplified geometry of the lithosphere-asthenosphere boundary and lithospheric structure corresponding to continental margin conditions. The lithospheric thickness is reduced by 50 km at some time, which is considered as a model parameter to fit observations. In contrast to previous models, where kinematic boundary conditions were used (constant velocities at the side boundaries), in this model we apply a constant force at a right boundary of the modeling domain (fig.1), which is also considered as model parameter.

The model shows evolution of strain distribution during the Red Sea opening. As the Red Sea basin spreads, the strain is first accumulated in broad zone along the DST during several millions years (fig 1,A). The strike-slip rate and displacements at this stage are low, less than 20% of their present-day values. After thinning of the lithosphere by about 50 km the strike-slip strain localizes at the region of minimum strength controlled by crustal thickness and thermal structure of the lithosphere (fig 1 B-D).

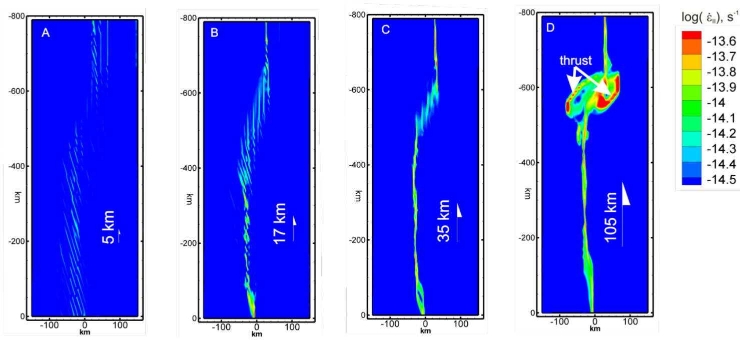

Fig. 1. Evolution of the DST. Strain rate distribution before (A) and after (B-D) the thermal erosion of the lithosphere.

From our model we conclude that to localize the strike slip deformation at DST in the cold lithosphere (surface heat flow lower than 50mW/m2) the following conditions had to be met: (i) large force (about $1.6x10^{13}$N/m) applied by the Arabian plate, (ii) relatively low strength of mantle lithosphere, (iii) thermal erosion of the lithosphere that triggered the DST localization.

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The problem of using Frank Kamenetskii approximation for the viscosity law in thermal evolution models

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Mantle convection in terrestrial planets is strongly influenced by the temperature dependence of its viscosity. This temperature dependence is described by the so called Arrhenius law. Applying the temperature dependent viscosity to model the mantle dynamics shows basically three different regimes depending on the viscosity contrast in the mantle: a mobile lid regime, a transitional regime and a stagnant lid regime. In the first two regimes, surface material can move and is incorporated in the mantle convection, whereas in the third regime a stagnant lid forms on top of the convecting mantle. For realistic rheological mantle parameters all terrestrial planets are actually in the stagnant lid regime unless the lid is prone to break. This latter process can for instance be simulated with a visco-plastic rheology.

For numerical reasons, an approximation of the viscosity is commonly used to model the mantle convection, i.e. the Frank-Kamenetskii approximation. This linearization assumes that the Arrhenius law can be approximated by an exponential law suggesting a viscosity which is many orders of magnitude smaller at the surface. The approximation has been shown to represent only the stagnant lid regime correctly but it is widely used in the literature also for the other regimes.

Here, we present a comparison of the mantle convection for stagnant lid cases with either Arrhenius law or Frank-Kamenetskii approximation with a 3D spherical code, GAIA [1], [2]. The results confirm earlier studies that the Frank Kamenetskii approximation can be used in the stagnant lid regime for a fixed Rayleigh number. However the Frank Kamenetskii approximation is not appropriate to model the thermal evolution of a planet in the stagnant lid regime.

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3D modeling of continental transform faults: case study San Andreas Fault System

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The continental transform faults are difficult to model on geological time scale. The lithosphere rarely encounters pure strike-slip deformation around a fault zone, but rather always include transpression (transtension) component. This fact makes it necessary to conduct the modeling in the 3D formulation. The present state of code development in geodynamic community shows a lack of software for simulating 3D lithospheric deformation with brittle-ductile transition, free surface and strain localization, which are the other absolute requirements for successful modeling of continental transform faults. Recently we have published the tool that is intended to fill this gap (Popov and Sobolev, 2008. PEPI, 171: 55-75). In this work we demonstrate some details of the method as well as application to the Neogene tectonic history of the San Andreas Fault System in central and northern California. In particular we show a few insights on the simultaneous activity of the sub-parallel faults in the system and the overall landward migration of the plate boundary between the North America and Pacific plates. The results show that the landward migration of the plate boundary is most likely caused by the capture of small fragments of the ancient Farallon plate (microplates) by Pacific plate, rather then by colling and accretion of uprising asthenosphere. Our models also confirm the importance of the slip-related weakening and the low strength of major faults in the San Andreas Fault System.

What drives plates? What drives plates? A new approach by combining the two torque balance methods.

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The way in which lithospheric plates are connected to the underlying mantle is still debated. The contentious `chicken and egg problem (does the plate drive the underlying mantle convection or does the mantle drag the plate?) has hampered global earth science since the plate tectonics revolution. In this project, we propose to investigate the past plate-mantle coupling system by styding the paleo stress regimes. There have been two major approaches to model forces that act on plates numerically. The first one requires the classical characterisation of forces acting regionally on a plate, as slab pull/suction, ridge push,mantle drag used by Forsyth and Uyeda (1975) and Chapple and Tullis (1977). The second approach is a torque balancing procedure which depends on the flow-induced stress generated by the internal mantle flow and the flow associated with the pre-defined plates (e.g., Ricard and Vigny, 1989, Monnereau and Quere, 2001, Quere and Forte, 2006). The model developed by Quere and colleagues is the only 3-D spherical code with dynamically coupled plates. This method, which ensures the retrieval of the main global observables at the Earths surface (mean plate velocity, global heat flux and potential temperature under oceanic ridges), is unique and is treated on the global scale. Due to its parameterization, this method can be used either with imposed plate motions (e.g., past or present-day) or with freely moving plates in response to buoyancy driven mantle flow. These two methods present their own advantages/disadvantages. One advantage of the regional approach is that direct interactions between plates are taken into account, which is not the case for the global approach. One main disadvantage on the regional approach is that coupling to the underlying mantle is done via a coupling coefficient. The drag coefficient of any one plate is treated independently of that of the other plates. This parameterization ignores that the motion of a plate is coupled to viscous stresses that will also affect the motions of all the other plates. On the contrary, on the global scale, the formalism explicitly determines the viscous stresses which are an integral of the buoyancy forces generated at all locations and at all depths in the mantle, not just at the surface. In this project, we propose to combine the two alance methods. In a first step, we will extract the shear stress field induced by the imposition of past plate motions (Lausannes reconstruction) on top of a 3-D convective code where plates are coupled dynamically. For the first time, an output 3-D convective flow obtained after a model simulation having spanned the Earths history will become an input flow for the prediction of intra-plate stress fields. The interpretation and comparisons with basin extension and orogenesis observations will provide new clues to oil exploration teams.

The influence of surface boundary conditions on subduction zone dynamics

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Numerical models of subduction have a choice of surface boundary conditions: free-slip (“roller”), prescribed velocities (kinematic) or entirely free. A free-slip surface boundary condition has zero vertical velocities, while the horizontal velocity is calculated. Particles at the surface of the model domain can therefore only migrate horizontally. This potentially increases the horizontal velocities at the surface, which may influence the dynamics of the subduction system. Han and Gurnis (1999) showed that subduction dynamics are not influenced when horizontal velocities determined from a free-slip model are imposed as prescribed velocities. However, Čižková et al. (2002) showed that trench migration velocities may. In the case of a free surface boundary condition, both horizontal and vertical velocities are solved for and surface shear stress is zero. This implies that a vertical deformation of the surface is possible, introducing topography into the model.

We aim to characterise the influence of the top boundary condition on subduction zone dynamics. To this purpose we use Sulec, a 2D ALE, finite element code developed by Susanne Buiter and Susan Ellis. Sulec uses a particle-in-cell scheme to solve for large deformations using a viscoelastic-plastic rheology. Our study focuses on the effects of a free-slip surface boundary condition versus a free surface on trench migration velocities and subduction sinking velocities.

We use two subduction model set-ups. First, we investigate the effects of the top boundary condition on free (gravitational) subduction of an oceanic plate without an overriding plate. The subducting oceanic plate is defined as a dense layered slab consisting of a thin brittle crustal layer overlying a Newtonian viscous lithosphere. The slab subducts into a light Newtonian viscous mantle. This model set-up is then extended to include an overriding oceanic plate of similar properties as the subducting slab.

A thin layer of weak and light Newtonian viscous material ("funny air") has previously been used as a substitute for a free surface boundary condition (e.g., Schmeling et al. 2008). We attempt to derive the rheological parameters for the "funny air" layer that best mimic a free surface condition.

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The role of fluids in the subduction channel: towards a new thermomechanical model

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Subduction channel is one of the key elements in the subduction process and has been thoroughly studied by many authors in the last years. Its mechanical properties are highly determined by the friction coeffi,cient, which works as a proxy for many factors that are usually not included in the models. Despite of being a few kilometers wide, and small compared to the subduction picture, its eff,ects propagate far away from the trench. For example, that was demonstrated by Sobolev and Babeyko (2005) by means of a numerical model focused at the evolution of the Central Andean Subduction Zone. The model was based on a fi,nite-element / fi,nite-diff,erence explicit code called LAPEX-2D (Babeyko et al., 2002). We present a new and enhanced 2-D thermomechanical model developed to study this type of tectonic setting. The main ideas of the technical implementation are based on the work published by Popov and Sobolev (2008). The domain is modeled by means of the Finite Elements Method with an implicit approach. The rheology is considered to be elasto-visco-plastic and the viscosity is temperature- and stress-dependent. Diff,usion, Dislocation and Peierls types of creep and Mohr-Coulomb plasticity are included. Topography evolution is naturally tracked by a Lagrangian mesh. A particle technique similar to the particle-in-cell method was used to minimize diff,usion during re-meshing. Compared to previous models, we include here the capability to handle a non-uniform mesh to describe the domain, which allows two main benefi,ts. First, the study of specifi,ed regions of interest with more detail by means of the concentration of elements (like subduction channel), and second, the possibility to defi,ne more realistic and smooth interfaces between diff,erent materials without distorsions related to mesh orientation. Remeshing is also improved by basic automatic tracking of specifi,ed parts of the domain where a denser mesh is usually employed. Another implementation improvement is related to the use of parallel-solvers that allow us to refi,ne signifi,cantly the studied domain, obtaining more precise results. Finally, a porous fl,ow model is coupled to the mechanical one in order to model more precisely the eff,ects of the fl,uid presence in the subduction channel.

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Stress - strength relationship in the lithosphere during continental collision and plateau formation: Implications for occurrence of deep Earthquakes

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Our understanding of the thermo-mechanical processes forming mountain ranges and plateaus, such as the Tibetan Plateau, is still incomplete. Therefore, the interpretations of the same geophysical observations with respect to lithospheric processes in general and lithospheric rheology in particular vary often significantly. This is, for example, the case for interpretations of the lithospheric rheology based on the relative scarcity of earthquakes in the sub-Moho continental mantle. Lithospheric strength profiles generally predict excessively high differential stresses in the sub-Moho continental mantle, which seems inconsistent with the relative scarcity of earthquakes at this depth. This inconsistency was put forward as evidence for weak lithospheric mantle rheology. However, this argumentation implicitly assumes that strength envelopes are valid in actively deforming lithospheric regions. We test this assumption on two end-member lithospheres with (1) a weak lower crust and strong mantle and (2) a strong lower crust and weak mantle. For this purpose, we compare 1D models with 2D visco-elasto-plastic numerical models of continental shortening. Both 2D models show that strongly heterogeneous deformation typically follows initially homogeneous deformation. Lithospheric-scale buckle folds and shear zones result in strain rate variations of up to three orders of magnitude. Differential stresses in the upper crust are close to yield, as predicted by 1D models. Stresses in deeper lithospheric regions, however, are significantly smaller than in 1D models, especially in actively deforming regions. Systematic numerical simulations as a function of temperature and deformation rate reveal that 1D models are reliable in hot and/or slowly deforming lithospheres only. The relative scarcity of earthquakes at mantle levels should thus be interpreted as an intrinsic consequence of strong lithospheric deformation rather than as evidence for a weak upper mantle rheology.

Postglacial rebound with spatially varying lithospheric thickness

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We ran a number of GIA (glacial isostatic adjustment) models to test the effect of a sloping lithosphere-asthenosphere boundary. The models were run using the commercial finite-element software ABAQUS and the implementation described by Wu (Geophys. J. Int., 2004, 158, 401-408). However, based on a 2-D pre-study, we modified the implementation to use spring-elements rather than Winkler foundations as the latter do not act in the direction of the gravitational acceleration at an inclined interface. The models are regional models covering northern Europe, where the lithospheric thickness is known to be increase going from west (of the coast of Norway) to east (Finland). We use a dynamic ice-model not previously tested in GIA-modeling and evaluate the results against GPS and relative sea level (RSL) data. A good fit with GPS velocity data in both the vertical and horizontal components is achieved for the simplest models using horizontal layers in the lithosphere and a uniform mantle. The predicted present-day uplift rates are observed to be dependent on both the viscosity structure of the mantle as well as the presence of density contrasts, whilst a lesser dependence is observed on the lithospheric structure. The models with variable lithosphere thickness show a worse fit to the GPS data. The deterioration of the fit manifests itself in a westward shift of the center of present-day uplift and an increase in the velocity magnitudes, especially in the horizontal components. The deterioration in the fit for the models with a laterally varying lithospheric thickness is probably due to the horizontal-layer Earth model that was used in constructing the ice-model, as ice model and Earth model are not independent of each other. The model comparison with RSL data is only a preliminary attempt. Assuming a eustatic sea-level rise of 2 mm/yr yields a reasonable data fit in some areas, while in other regions the model predictions are too high. The poor fit is not surprising since the present, simple approach does not account for regional variations nor the adjustment of the geoid. A more accurate method would be to calculate the model sea level curve from the sea-level equation instead of assuming a constant eustatic sea-level change. Overall, the best-fitting model uses a 100 km thick lithosphere on top of a uniform mantle with a viscosity of 1 x 1021 Pa s.

Initiation of the modern style of subduction in the precambrian: insights from numerical experiments

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Plate tectonics is a self-organizing global system driven by the negative buoyancy of the thermal boundary layer resulting in subduction. Although the signature of plate tectonics is recognized with some confidence in the Phanerozoic geological record on continents, evidence for plate tectonics is less certain further back in time. To improve our understanding of plate tectonics on the Earth during the Precambrian, we have to combine knowledge derived from the geological record with results from realistic numerical modeling. In a series of experiments using a 2D petrological–thermomechanical numerical model of oceanic-continental subduction we have systematically investigated the dependence of tectono-metamorphic and magmatic regimes at an active continental margin on upper-mantle temperature, crustal radiogenic heat production, degree of lithospheric weakening as well as other physical parameters. The model includes spontaneous slab bending, dehydration of subducted crust, aqueous fluid transport, mantle wedge melting, and melt extraction from the mantle resulting in crustal growth. We have identified a first-order transition from a "no-subduction" tectonic regime through a "pre-subduction" tectonic regime to the modern style of subduction. The first transition is gradual and occurs at upper-mantle temperatures between 250-200 K above present-day values, whereas the second transition is more abrupt and occurs at 175-160 K. The link between geological observations and model results suggests that the transition to the modern plate tectonics regime might have occurred during the Mesoarchean–Neoarchean time (ca. 3.2–2.5 Ga). In the case of a "pre-subduction" tectonic regime (upper-mantle temperature 175–250 K above present) the plates are weakened by intense percolation of melts derived from the underlying hot melt-bearing sub-lithospheric mantle. In such cases, convergence does not produce self-sustaining one-sided subduction, but rather results in shallow underthrusting of the oceanic plate under the continental plate. A further increase in the upper-mantle temperature (> 250 K above present) induces a transition to a "no-subduction" regime where horizontal movements of small deformable plate fragments are accommodated by internal strain and even under imposed convergence shallow underthrusts do not form. To better understand the underlying physics of these models we performed an additional series of experiments using similar 2D petrological–thermomechanical numerical model but without hydration, melting and extraction procedures. In these models, we have obtained a similarly abrupt transition from the modern style of subduction to the "no-subduction" regime at the upper-mantle temperature 160-180 K above the present-day values. This temperature is approximately the same as determined in the first set of experiments. The "no-subduction" regime is characterized by 'dripping-off' of the plate tips, most likely because of the small effective viscosity constrast between subducting slab and surrounding mantle. Indeed we do not observe a transitional "pre-subduction" tectonic regime with underthrusting of the oceanic plate in these sets of models. This implies critical role of rheological weakening by sublithospheric melts in defining how transition between ancient "no-subduction" stage and modern plate tectonic regime occurred in the Earth's history.

Vertical motions of passive margins of Greenland: influence of ice sheet, glacial erosion, and sediment transport

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The sub-ice topography of Greenland is characterized by a central depression below the sea level and by elevated (in some places significantly) margins. Whereas the central depression may be explained by significant load of the Greenland ice sheet, the origin of the peripheral relief remains unclear. We analyze the influence of formation of the ice sheet and carving by glacial erosion on the evolution of topography along the margins of Greenland. Our analysis shows that: (1) The heavy ice loading in the central part of Greenland and consecutive peripheral bulging has a negligible effect on amplitude of the uplifted Greenland margins. (2) First order estimates of uplift due to isostatic readjustment caused by glacial erosion and unloading in the fjord systems is up to 1.1 km. (3) The increase of accuracy of topographic data (comparing several data sets of resolution with grid size from 5 km to 50 m) results in increase of the isostatic response in the model. (4) The analysis of mass redistribution during erosion-sedimentation process and data on age of offshore sediments allows us to estimate the timing of erosion along the margins of Greenland. This ongoing analysis, however, requires careful account for the link between sources (localized glacial erosion) and sinks (offshore sedimentary basins around Greenland).

Distinct styles of subduction and implications for Earth's evolution

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Using a 3-D numerical model of a single, fully dynamic subducting plate, we describe a total of 5 different styles of subduction that can possibly occur. Each distinct style is distinguished by its upper mantle slab morphology resulting from the sinking kinematics. We provide movies to illustrate the different styles and their progressive time-evolution. In each regime, subduction is accommodated by a combination of plate advance and slab rollback, with associated motions of forward plate velocity and trench retreat, respectively. Although only 2 of these styles presently operate on Earth, the possibility exists that other modes may have been the predominant mode of recycling the lithosphere in the past. Subduction dynamics within the upper mantle are responsible for producing the particular type of subduction mode and resultant partitioning of plate motions. In particular, the preferred subduction mode depends upon two essential controlling factors: 1) the buoyancy of the downgoing plate and 2) the strength of plate in resisting bending at the hinge. Based on these models, we propose that the lithosphere is the primary factor in describing key elements of the plate tectonics system over time, and not the convecting mantle. Thus, secular changes in Earthís tectonic behavior are driven by changes in the nature of the lithosphere. The progression from strong plates in the past to weak plates (present day) has had the most profound influence on controlling transitions between geologic Eons. We propose that during the Archean, very strong plates favored pure trench retreat, which allowed cratons to stabilize as they remained nearly stationary. Throughout the Proterozoic, the mode of subduction switched to one entirely driven by plate advance, which allowed cratons to aggregate into continents. Interestingly, both the pure retreat and pure advance modes result in entirely flat-lying slabs atop the lower mantle, which has implications for geochemical stratification. Finally, the modern-day type of plate tectonics emerged (i.e. the Wilson Cycle) allowing for both plate advance and trench retreat to occur simultaneously.

A benchmark study of mantle convection models with plates

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Previous studies have shown that changes in parameters controlling mantle convection (e.g. variable viscosity, Rayleigh number or mode of internal heating) strongly affect the surface expression. The surface expression can range from a stagnant lid mode of convection to plate mobilisation (e.g. [1], [2]). As a consequence of a heat build-up around a downwelling, intermittent behaviour has also been observed which is characterised by changes in plate direction [3]. Our aim here is to investigate the interplay of the pressure dependence of the viscosity and internal heating rate on the convective flow and to analyse the resulting surface conditions utilizing different model approaches. For this benchmark study we consider thermally driven convection of an incompressible fluid with infinite Prandtl number and variable viscosity in a 2D Cartesian geometry. We use a yield-stress criterion in the one model and in the other model dynamic plates are incorporated by using the force-balance method where the shear stress on the base of each of the finite thickness high viscosity plates sums to zero at all times. In this way we ensure that plates neither drive nor resist the convection (cf. [2] and [3]). We pay special attention to internal heating by considering convection models with purely internal heating and ones with mixed-mode heating. Our results reveal a great difference between these two modes of heating which has large implications for the thermal history of planets and consequently their surface expression. Purely internally heated systems are characterised by a cooler interior so that it is more difficult to sustain a stagnant lid in these systems.

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The quest for dynamic topography: What can we learn from a combined regional and spectral approach?

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One of the most important outcomes of mantle flow models is the prediction of surface uplift and subsidence over time on a large scale. Dynamic topography influences which regions are below sea level, and therefore where sediments and related natural resources may form. The strength of the lithosphere controls the amount of deflection that can develop under heavy surface or buoyant mantle loads, directly influencing the development of topography.

Dynamic topography is computed here from a mantle flow model with density variations inferred from seismic tomography and only radial mantle viscosity variations. Globally, modelled dynamic surface topography and the "residual topography" (computed by substracting topography due to crustal thickness variations and sea floor age) do not agree well, with correlations typically not exceeding 0.5 and dynamic topography typically too high by a factor 1-2.

In an attempt to narrow down the causes for this discrepancies we compute here dynamic vs. residual topography correlations and ratios (1) regionally in caps of 30 degrees of arc and (2) spectrally, as a function of spherical harmonic degree (wavelength). We first only consider seismic velocity variations below 220 km depth: We find large regional variations, with particularly high correlations in a band reaching from North Africa through Europe and the North Atlantic to North America (Fig. 1). Ratios tend to be lower in continental than in oceanic regions indicating that coupling between lithosphere and mantle beneath continents is stronger than modelled here. Dynamic/residual ratio tends to decrease with increasing spherical harmonic degree, which is probably in part because only density variations below 220 km are considered for computing dynamic topography. We aim here at keeping this ratio as a function of degree close to 1 by including some density variations in the upper 220 km based on (1) various tomography models, both whole-mantle and surface wave models, but (2) leaving out density anomalies in regions that are interpreted as thick, neutrally buoyant lithosphere.

We focus in on some intracratonic basins in North and Central Africa, given that our model appears to work comparatively well there. For these basins, we find that coupling our model with a more realistic lithosphere model does not lead to strong lithosphere deformation, with uplift and subsidence remaining similar to the simple mantle model, which we therefore consider appropriate for these regions. We use backward-advection of density in combination with African absolute plate motion to tentatively model uplift or subsidence in these basins for the last few 10s of Myrs.

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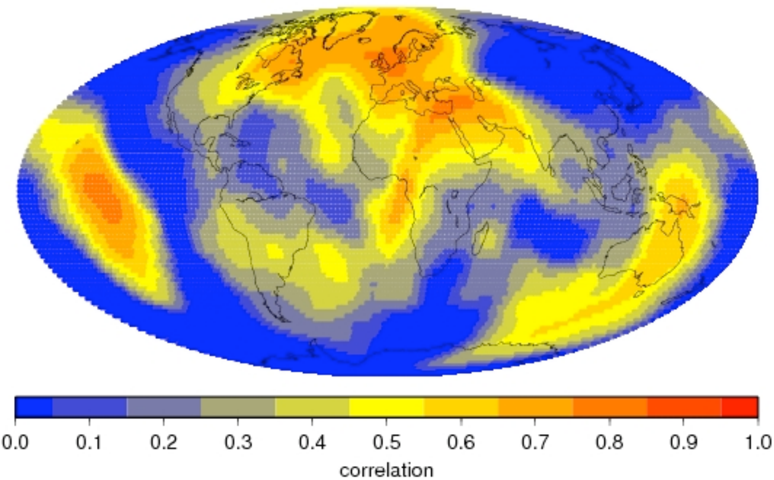

Figure: Correlation of predicted dynamic and observed residual topography. They are computed for each point in a spherical cap of 30 degrees around that point and in the spherical harmonic degree range 1-31. Dynamic topography is computed from density anomalies inferred from seismic velocity variations of the *smean* tomography model [1] below 220 km depth and a radial viscosity structure that is consistent with mineral physics, geoid and heat flux constraints.

Predicting the seismic signature of thermo-chemical mantle plumes

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Over the past few years, there has been considerable debate surrounding the role of mantle plumes in mantle convection, and whether or not such features might be detected seismically. Where seismic anomalies are observed below hotspot locations there are arguments about whether they are the result of plumes, and if so, whether they are simply hot and (or) also anomalous in composition.
To settle this debate we need a greater understanding of what the morphologies of physically realistic thermal and thermo-chemical plumes in the mantle and their likely geophysical expression (especially in terms of seismic velocity anomalies) might be. To investigate this, we convert a range of thermal and thermo-chemical whole mantle dynamic plume models, with Earth-like characteristics, into synthetic seismic signatures. We analyse how well such signatures can reflect the physical differences, and to what extent these might be imaged.
Before converting the plumes, we first provide an updated analysis of the sensitivity of seismic velocities and densities to changes in temperature and plausible compositional variations throughout the mantle. Into this we incorporate the large uncertainties in density and elastic parameters of the constituent minerals and in anelasticity, from several recent data bases.
This analysis is then used to determine what the most likely compositional heterogeneity carried by whole mantle plumes might be. Previous work we have carried out on the one-dimensional background seismic signature of the mantle implies that it likely to be biased by large scale three-dimensional chemical heterogeneity. In the lower mantle, this bias is probably predominantly the result of the two large low-shear velocity piles imaged below Africa and the central Pacific. Our sensitivity analysis, and comparisons with seismic constraints, suggests that these piles are most likely hot and rich in basaltic components. This is compatible with recent models suggesting that subducted slabs may penetrate into the lower mantle where they pile up on top of the core-mantle boundary.
Assuming that this composition (and associated change in density) is partly or wholly sampled by plumes that initiate at these depths, we then convert selected thermal and thermo-chemical dynamic plume models into synthetic seismic structure. Such models can then be compared with global and/or regional seismic data at hotspots on Earth to test hypothesized plume sources.

The thermal structure and the surface manifestation of mantle plumes in three-dimensional models

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Thermal convection has been modeled in a 3-D model box, in order to study the thermal structure (temperature anomaly and diameter) of whole mantle plumes and their topographic and geoid anomalies at the surface. The aim of the study is the systematic analysis of the effects of the following parameters: the Rayleigh number, the depth-dependent viscosity and the temperature dependency of the viscosity.

In the simplest models the viscosity is assumed simply exponential increasing with depth by a factor 1of 10 and 100. The typical viscosity layers (lithosphere, asthenosphere, D'' layes) were added to this basic viscosity profile. The effect of one viscosity layer was systematically analyzed by varying the width and the amplitude of the viscosity jump.

The interior of the convective cell had a lower temperature in the case of higher viscosity contrast. Therefore, the temperature anomaly of the plume became higher. In the topographic anomalies, there were no significant differences between the models of different viscosity contrast. The addition of low viscosity layer (asthenosphere) decreases the geoid and topographic anomalies. The lithosphere (high viscosity layer at the top) makes higher the temperature of the interior of the convective cell. The low viscosity layer at the CMB (D'' layer) has no significant effect on the topography, but the interior of the convective cell will be warmer.

The effect of the temperature dependent viscosity was studied by using a simple exponential viscosity law. The viscosity increases exponentially from the top to the bottom by a factor of 10 or 100, as in the previous models. The additional exponential temperature dependency has a factor of 2 – 1000.

The temperature anomaly of the plume becomes lower by the addition of temperature dependency. The lower viscosity of the hot material can not support so high topography, that's why the topography radically decreases by applying stronger temperature dependence.

Modelling the thermo-chemical evolution of planets in a 3-D spherical shell with large viscosity contrasts using the yin-yang grid

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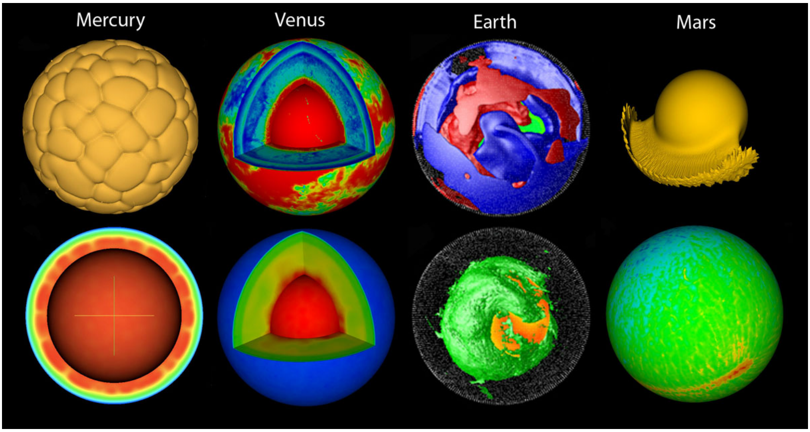

Figure 1. Planetary models using StagYY: Mercury, Venus (by M. Armann & P. Tackley), Earth (by T. Nakagawa and P. Tackley [5]) and Mars (by T. Keller and P. Tackley [6]).

Here I report the latest version of the 3-D finite volume multigrid code Stag3D [1], adapted to spherical geometry using the "yin-yang" grid introduced by [2] and renamed StagYY [3]. This grid allows the orthogonal staggered-grid primitive-variable discretization to be retained, as well as other features of the original code, including: the compressible anelastic approximation, tracking of composition using tracers (marker-in-cell), multiple phase changes including both olivine and pyroxene-garnet systems, and a nonlinear visco-plastic rheology. A single input switch selects different geometries including spherical-shell, spherical patch, 2D spherical annulus [4], or Cartesian. A multigrid solver allows efficient solution of large problems on only modest-sized beowulf clusters (e.g., $>10^9$ degrees of freedom on 64 CPUs). An improvement to the multigrid scheme allows large viscosity variations to be modelled, e.g., factor 10^{13} globally with factor 10^8 between adjacent points- enough to use 'laboratory' activation energies. Recently, a self-consistent mineralogical treatment was added [5], as was calculation of the geoid including self gravitation. The code is being applied to study the dynamics and evolution of Mercury, Venus, Earth, Mars, Io and super-Earths, as well as regional-scale problems.

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Linking CitcomS with SPECFEM3D

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The mantle is heterogeneous, as evidenced by the complex waveforms and arrival times of various seismic phases. A major goal of mantle convection model is to understand and explain the generation, preservation and distribution of the seismic heterogeneity. Here, we present a set of tools toward the goal.

CitcomS [1][1] is a mantle convection code in 3D spherical geometry that can compute thermo-chemical convection of compressible material. We extend CitcomS by incorporating mineral physics models to convert the temperature and composition fields into seismic velocities in the post-processing stage. The code is open source and can be downloaded from this link [2].

SPECFEM3D_GLOBE [3] is a seismic wave propagation code in 3D spherical geometry that can simulate synthetic seismograms from complex Earth structure. We build a web portal on which users can launch SPECFEM3D_GLOBE on TeraGrid machines from web browsers without installing any software. The web portal is flexible and can handle arbitrary earthquake sources and seismic stations. Users can upload their own custom Earth structure as well. The web portal is also open to public [4].

Combining the two pieces of codes together, one can run CitcomS to get a mantle convection model, convert it to seismic velocity model, and then upload the velocity model to the SPECFEM3D web portal to generate synthetic seismograms. This tool chain is a step toward understanding the origins of the seismic heterogeneity in the Earth.

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Geodynamic modeling of terrane accretion

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Accretion, subduction, or collision of allochthonous terranes occurs in most, if not all, subduction zones during their existence and may have a profound effect on the behavior of subduction zones. Specifically, terrane-continent subduction can produce crustal growth through accretion, affect subduction polarity, cause trench jumping, or break off the down-going slab.

Two representative examples of crustal growth through terrane accretion are the North American Cordillera and the Mediterranean subduction zone. The North American Cordillera represents an ancient plate boundary that has been subjected to episodic accretion from the Paleozoic through the Cenozoic, punctuated by several orogenic events. Various tectonic models have inferred slab-break off and subduction zone jumping, as a result of terrane-continent collision. Unfortunately, the main problem with deciphering the subduction and accretion history of the North American Cordillera is that much of the geologic evidence has been eroded or overprinted and the subducting slabs have long been removed. Looking to the present, the Mediterranean region is an example of an active subducting plate boundary that has accreted many terranes of oceanic and continental affinity. In the Aegean, nappes of oceanic and continental crust have been accreted onto Europe since the Jurassic without terminating subduction or causing the subduction zone to jump. Geodynamic modeling of terrane-continent collision can help decipher the parameters in terrane accretion that lead to slab break off, subduction zone jumping, or delamination and continuous subduction that is observed in these regions.

We will examine basic models of terrane-continent subduction to determine the controlling factors in accretion, subduction, or collision of terranes. An important first-order controlling factor is buoyancy of the colliding block, which is coupled to terrane rheology and size. For simplicity we focus on three types of allochthonous terranes: oceanic arc, continental arc, and extinct ridge, to understand how size and lithology affect subduction. Other factors in terrane-continent subduction we plan to investigate are delamination of the terrane crust, plate contact, subduction velocity, and tectonic stress. We will employ the Arbitrary Lagrangian-Eulerian finite element method code SULEC, developed by Susan Ellis and Susanne Buiter, to investigate terrane accretion in subduction zones. SULEC is a 2-D linear visco-elasto-plastic code with the ability to assume a free surface. We will present basic models of ocean-continent subduction followed by terrane-continent collision, initially focusing on size and lithology of allochthonous terranes.

Geodynamically consistent cross-sections through active mountainbelts

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Cross sections though active mountainbelts are usually constrained by a range of geophysical and geological data, but the resulting interpretations are not necessarily geodynamically consistent. To better understand the thermomechanical behaviour of such collision zones it is of major importance to combine knowledge about the geometrical, the density and the inferred viscosity structure of those zones. Constraints on the geometry can be obtained by reflection seismics, refraction seismics or seismic tomography. Constraints on the density come from gravimetrical methods. Effective rheological parameters of the lithosphere, however, are much less known. Laboratory experiments on creep of rocks, extrapolated to natural conditions, yield several orders of magnitude variation in the effective viscosity. Better constraining the effective viscosity of the lithosphere is however crucial, since variations in these parameters might result in drastically different lithospheric dynamics. For this reason, we here develop and test an approach that employs 2D thermomechanical viscoplastic geodynamics codes. Rather than studying the long-term deformation of the lithosphere, as is typically done with such codes, we here focus on the present-day structure of the lithosphere. Before applying this approach to real date it is necessary to study the theoretical power of the methodology. We therefore apply the method to snapshots obtained from synthetic (million-year timescale) forward runs.

High-resolution two-dimensional lithospheric simulations

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We present a new two-dimensional Finite Element ALE code called FANTOM. It is designed to investigate viscoplastic Stokes flows within a model of large lithospheric deformation, and can be run in a sequential or parallel mode. Throughout the code, allocated memory is kept to a minimum in order to allow the direct solver to deal with the large system sizes which arise from the high grid resolutions on which the calculations are performed. Ultimately, this will allow a bridging of length scales : from kilometric tectonic processes to metric localised faults and surface processes. We present standard Fluid Dynamics as well as Geomod benchmarks results.

Longitude: Linking Earths ancient surface to its deep interior

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Earth scientists have had no direct way of calculating longitudes for times before those of the oldest hotspot track eruption sites in the Cretaceous. For earlier times palaeomagnetic data constrain only ancient latitudes and continental rotations. We have recently devised a hybrid plate motion reference frame that permits the calculation of longitude back to Pangean assembly at ca. 320 Ma. This reference frame, here also corrected for True Polar Wander (TPW), places most reconstructed Large Igneous Provinces (LIPs) of the past 300 Myr radially above the edges of the Large Low Shear wave Velocity Provinces (LLSVPs) in Earths lowermost mantle. This remarkable correlation between surface and deep mantle features, which is also discernible for all hotspots with a deep-plume origin, provides a new way of reconstructing the original positions of LIP sites, and therefore the position of continents whose longitudes have hitherto been unknown. As an example, we place the 258 Ma Emeishan LIP eruption of South China at 4N and 140E, in that way for the first time constraining the width and the geometry of the Palaeotethys Ocean during the Late Permian. If LLSVPs have remained stable for even longer and TPW has been small, we can, under these assumptions, also restore Siberia and Gondwana longitudinally for Late Devonian and Late Cambrian times. Knowing ancient longitudes is important and in many cases critical for improving understanding in fields as diverse as palaeogeography, palaeobiology, long-term environmental evolution, tectonics, mantle dynamics and Earth history on the grandest scale. Fundamental questions that we have addressed that now need further analysis include: (1) are all LIPs derived from deep sources? (2) why do reconstructed LIPs form a ring on the LLSVP edges? (3) how do plumes develop?, and (4) were deep mantle heterogeneities initiated as a result of Pangea assembly or are they older? The stability of the LLSVPs also implies long-lasting heat-flux variations across the core-mantle-boundary, and this opens up new research opportunities concerning secular cooling of our planet and the geody

Subducted slabs and lateral viscosity variations: effects on the long-wavelength geoid

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The characteristic broad local maxima exhibited by the long-wavelength geoid over subduction zones are investigated with a numerical model of mantle flow. A synthetic model of subduction is used to test the effects on the geoid caused by the depth of penetration of the subducted lithosphere into the mantle, by the viscosity stratification and by lateral viscosity

variations (LVV) in the lithosphere, upper and lower mantle. The presence of anomalous slab density in the lower mantle guarantees geoid amplitudes comparable with the observations, favoring the picture of slabs that penetrate the transition zone and sink into the deep mantle. The viscosity of the lower mantle controls the long-wavelength geoid to the first order, ensuring a clear positive signal when it is at least 30-times greater than the upper mantle viscosity. The presence of LVV in the lithosphere, in the form of weak plate margins, helps to increase the contribution of the surface dynamic topography, causing a pronounced reduction of the geoid. Localized LVV associated with the cold slab play a secondary role if they are confined in the upper mantle. On the other hand, highly viscous slabs in the lower mantle exert a large influence on the geoid. They cause its amplitude to increase dramatically, way beyond the values typically observed over subduction zones, suggesting that slabs may be weakened in the lower mantle or that they retain their high viscosity while other mechanisms act to lower the geoid. It is shown that a phase change from perovskite to postperovskite above the core-mantle boundary can cause the geoid to reduce significantly, thereby helping to reconcile models and observations.

On the different ways to define a thermal plume and look at mantle entrainment

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As they bring deep mantle material to the surface, mantle plumes offer an unique opportunity to probe the planets deep interior. But deciphering their geochemical message requires to understand quantitatively plume dynamics and sampling. For several decades, much effort has been devoted to understand plume dynamics and to provide scalings for plume ascent velocity or for plume growth by entrainment of ambient fluid. However, different studies have often proposed different scalings. Besides the differences in experimental set ups, another reason is that the "plume" definition often depends on the visualization technique which is used. We present an experimental study of the dynamics of a plume generated from a small heat source in sugar syrup, a high Prandtl number fluid whose viscosity depends strongly on temperature. Areas sampled by the plume were visualized using neutrally buoyant dye. The velocity field was determined with particle image velocimetry (PIV), while the temperature field was measured using differential interferometry (DI) and thermochromic liquid crystals (TLCs). The combination of these different techniques run simultaneously allow us to quantify the differences arising from different possible definitions of a thermal plume, to identify the different stages of plume development, and to characterize mantle entrainment and sampling by the plume.

Transitions in tectonic mode based on calculations of self-consistent plate tectonics in a 3D spherical shell

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In the past decade, several studies have documented the effectiveness of plastic yielding in causing a basic approximation of plate tectonic behavior in mantle convection models with strongly temperature dependent viscosity, strong enough to form a rigid lid in the absence of yielding. The vast majority of such research to date has been in either two-dimensional, or three-dimensional cartesian geometry. Also, scalings for mixed internally and bottom heated convection are not well established. In our previous study (van Heck and Tackley, 2008), mantle convection calculations were performed to investigate the planforms of self consistent tectonic plates in three-dimensional spherical geometry. We found, for internally heated convection and fixed Rayleigh number, that when yield stress of the lithosphere is low a "great circle"-subduction zone forms. At low-intermediate yield stresses plates, spreading centers and subduction zones formed and were destroyed over time. At high-intermediate yield stresses two plates form, separated by a great circle boundary that is a spreading centre on one side and a subduction zone on the other side. At high yield stresses a rigid lid was observed. Here, the planforms found by van Heck and Tackley (2008) are investigated further, leading to a more general understanding of how different parameters determine which planform prevails. New calculations are performed to investigate the effect of varying Rayleigh number and different internal/bottom heating ratios. Cases with zero internal heating are compared to cases which have both internal heating and bottom heating. The results are compared to analytical scalings for boundary regimes as well as scalings for heat flux. This allows us to scale to different planets of different sizes and can be applied to the evolution of Earth, Mars and Venus as well as terrestrial extra-solar planets. Also, we can study the tectonic evolution of a cooling planet. As radioactive heat production decreases over time the tectonic mode (e.g. changes in plate size, rigid lid convection to tectonic plates, smoothly evolving plates to more episodic, time dependent, tectonics) is likely to change. The results show that with decreasing internal heating rate the transition from rigid to mobile lid occurs at higher lithospheric yield stress, meaning that for a cooling planet it becomes more likely to have active plate tectonics over time. Grigné et al. (2005) showed that surface heat flux depends on the wavelength of convection so the scalings for heat flux will not only depend on the internal/bottom heating ratio but also on the planform since the wavelength of convection (i.e. plate size) changes for different planforms (van Heck and Tackley, 2008).

Dynamics of continental collision

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Continental collision is part of the Wilson cycle and has occurred frequently during the Earth history. Even though the process itself is relatively short-lived compared to the preceding oceanic subduction, its remnanbts are often preserved, and probably provides a valuable window into the plate tectonic process during the Proterozoic and perhaps the Archaean. We performed 2-D and 3-D numerical models to gain insight in the dynamics of the continent collision, with an emphasis on the process of slab detachment. In general, our 2-D results reinforce previous findings. We show the relationship between detachment timescales and detachment depth and crustal buoyancy. We also discuss implications for the occurrence of ultra-high pressure metamorphism. Preliminary 3-D results provide insight in the process of slab tearing, and future comparison with observations should provide valuable insight in the rheology of subducting slabs. These results will have implications for the dynamics of slab detachment in the hotter mantle of the early Earth.

Exploring parameter space of rift induced delamination

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The extreme elevation of Rwenzori Mountains, a horst situated inside a rift zone, motivates our search for their geodynamic driving mechanism. Testing several hypotheses favours RID due to some first successful numerical models. RID is the hypothesis of rift induced delamination of mantle lithosphere and uplift of crust. It is based on the propagation of the rift tips feeded by upwelling asthenosphere, surrounding stiff old lithosphere, thereby triggering the delamination of cold and dense mantle lithosphere root by reducing viscosity and strength of the undermost lower crust. This unloading induces pop-up of the less dense crustal block along steep inclining faults.

Viscous flow of 2D models is approximated by Finite Difference Method in an Eulerian formulation. Equations of conservation of mass, momentum and energy are solved for a multi component system. Based on laboratory data of appropriate samples a temperature, pressure and stress dependent rheology is assumed.

We try to establish RID and learn about the process by exploring the parameter space with model families. Aim is to identify relvant factors controlling the delamination. Investigation candidates are parameters describing the initial pertubation such as excess temperature and geometry and its distance between bounding rifts. Further candidates include rheological properties such as the power laws of mantle, upper and lower crust (LC) and the limiting yield stress and its depth dependence and after all the background geotherme. The range of variation and sensitivity of the individual quantities are presented. Because some values are highly sensitive physical and numerical outcome must be distinguished carefully.

The system answer to “When occurs delamination?” is a bifurcation, either the anomaly cools down (C) or the central mantle lithosphere detatches and sinks down (D).

Delamination takes place only in a determined parameter range, which additionally depends on the converging numerical resolution. For a resolution of 101^2 grid points and a gaussian shaped anomaly width is optimal at b = 15 ±5 km, the central distance at a = 45 (+20/-15) km. The heigth cutting nearly the whole LC has only a small range of h = 97-100 km. The pore fluid pressure factor in LC tops 1.4%. "Weak" power law parameter in the mantle favours delamination. Increasing temperature level supports delamination, but decrease soon impeeds it. The velocity of lateral intrusion of hot material from the anomaly's top into LC relative to thermal diffusion is of vital importance for the decision to D or C.

The actually used model is 2D and simple as possible to test under which conditions the hypothesis is basically working. Earth naturally is more complex as new observations around Rwenzoris suggest. A first step would be an asymmetric model leading to 3D. If RID is true for the very special situation of the Rwenzoris and by now sole example, one ought to generalize it and check wether similar situations are detectable. The limits found here provide a search pattern.

Influence of mantle dynamics on global patterns of mid-ocean ridge bathymetry

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Global observations of mid-ocean ridge (MOR) bathymetry reveal a correlation between changes in the axial depth across ridge offsets and the direction or ridge migration (Carbotte et al 2004). Segments leading with respect to the direction of ridge migration typically have a shallower bathymetry than the trailing segments. We use 3D numerical models of non-Newtonian mantle flow and thermal structure beneath a migrating MOR to address these observations. Our models show that migration of the mid-ocean ridge leads to a perturbation of the typical upwelling flow regime beneath ridges. The characteristics of this perturbation are controlled by the shape of the lithosphere-asthenosphere boundary. The perturbation flow leads to an asymmetry of upwelling with more beneath the leading plate and less beneath the trailing plate. Parameterized melting and melt migration is used to map the perturbation in mantle flow to a predicted asymmetry across transform offsets. The predicted asymmetry is consistent with global observations. We also investigate how melt migration leads to along-axis variation in melt supply to the base of the crust. These results build on work with a 2D model (Katz et al 2004) but differ in that they capture the three dimensional flow dynamics and lithospheric geometry near transform faults.

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Influence of surrounding plates on 3D subduction dynamics

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The important role of the third dimension in subduction dynamics has already been demonstrated and a variety of models has been proposed using physical, semi-analytical and numerical methods to study the dynamics of subduction zones in 3D. At the Earth's surface tectonic plates form a complete shell. In spite of which most of those studies consider only a subducting plate isolated in the mantle and consequently, the influence of surrounding plates (lateral and overriding) is often neglected.

In order to test the influence of these surrounding plates on subduction dynamics, we have used the 3D code DOUAR. Our results show that presence of lithospheric plates around a subducting plate has a first-order influence on subduction dynamics:

The presence of an overriding plate modifies the flow generated by the subducting slab (poloïdal flow). Consequently, neglecting overriding plate leads to overestimates of trench retreat velocities by a factor 2 or 5 and underestimates of slab dips at depth.

The presence of a lateral plate prevents lateral shortening observed in many experiments where the subducting plate is implicitly assumed in isolation. To prevent such an undesirable effect several models include more complex and somewhat ad-hoc rheologies that our study reveals unnecessary for the presence of lateral plates is sufficient to prevent unrealistic trench perpendicular dynamics.

Our results suggest that not only the subducting plate affect subduction kinematics, and therefore surrounding plates must be included in modeling-based studies, where the effects of many parameters characterizing a subduction system are explored (e.g. thickness of the lithosphere, viscosity and density ratios, friction between plates, etc…).

Role of phase transitions at 410 and 660 km depths on upper mantle flow beneath continental rifts and mid-oceanic ridges

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The seismic discontinuities at 410 and 660 km depths are widely accepted to result from the Olivine-Spinel and Spinel-post Spinel phase transitions in the upper mantle. Most previous work focused on the interaction of seismic discontinuities with a cold descending slab or a hot up welling plume. Less attention has been paid to the effect of the phase transitions on passive flow resulting from plate motion in an extensional regime. Here, plane-strain thermo-mechanical finite element model experiments are used to investigate the role of exothermic and endothermic phase changes at 410 and 660 km depths on the pattern of upper mantle flow beneath continental rifts and mid-oceanic ridges. Consequences of upper mantle viscosity structure, dehydration strengthening, variation in Clapeyron slope and magnitude of density jump on the pattern of flow are explored. The results are tested for varying spreading rates and their sensitivity on the time history of top driven extension.

Small-scale thermal-chemical convection in 3-D mantle wedge

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Our 3-D thermal-chemical models with I3ELVIS code (Gerya, 2009) have shown three types of Rayleigh-Taylor instabilities propagating atop the subducting slab: 1) finger-like plumes that grow atop sheet-like trench-parallel structure, 2) Ridge-like structures perpendicular to the trench, 3) periodic wave-like structures propagating upwards along the upper surface of the slab that form zig-zag patterns parallel to the trench. Hydrated mantle and partially molten peridotite are main components of these instabilities triggered by the dehydration of the slab and hydration of upper mantle atop the slab. Lower viscosity of the partially molten rocks facilitates the Rayleigh-Taylor instabilities at small wavelengths. With an effective viscosity around 1018 Pa s, the spacing of the finger-like plumes is approximately 30-45 km, the spacing of the trench-normal ridges is about 15-25 km, the wavelength of the wave-like plumes is about 70-100 km. However, with a larger effective viscosity of ~1020 Pa s the ridge spacing increases to about 50-100 km. From the streamlines in the mantle wedge, time-dependent small-scale convection is easy to occur in the subduction zone, which may provide one explanation for seismic heterogeneity in the mantle wedge, consistent with 2-D results (Faccenda et al., 2008). The computed spatial and temporal pattern of melt generation intensity above the slab is compared to the distribution and ages of volcanoes in the northeast Japan (Zhu, et.al., 2009). The similarity of the patterns indicates that the growth dynamics of 3-D thermal-chemical plumes may explain the source and the path of volcanoes along the arc in NE Japan.

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International Workshop on Mantle Convection & Lithospheric Dynamics

The workshop on Modeling of Mantle Convection and Lithospheric Dynamics is held every two years at various locations all around Europe. This international event is generally regarded as the main conference in geodynamics in Europe. The main goals of this workshop are to:

- *Provide a forum for in-depth discussion on scientific and technical issues in geodynamic modelling.*
- *Provide a forum for in-depth discussion on the integration of results from geodynamical modelling to other fields in Earth sciences.*
- *Introduce students and postdocs to the breadth of current research in geodynamics.*
- *Trigger interdisciplinary and international collaborations.*

The 11th workshop of this series is held from June 28th to July 3rd 2009 in Braunwald, Switzerland, and includes discussion of the differentiation of terrestrial planets, the evolution of Earth and planetary mantles, new seismological constraints on the deep mantle, the origin and consequences of chemical heterogeneities in the mantle, modelling of lithospheric dynamics, plate tectonics, transform faults and subduction zones, two-phase flow modelling, and recent advances in numerical tools.

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