Submitted abstracts (in alphabetical order)

FE modeling of post glacial rebound with complex viscosity structure

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The response of the Earth to the late Pleistocene ice sheets melting, is usually modeled by spherically symmetric models. In this work we approach the GIA problem by FE modeling in two stages. In the first we compute the post-glacial displacements for a 2D axis-symmetric Earth model including a lithospheric thickening (craton), which constitutes the simplest departure from the 1D spherical symmetry. These computations are a necessary step to understand the first order role of lithospheric depth variations and to perform benchmark comparisons with solutions provided by other research groups which employ spectral approaches. The effects of the craton on the displacement field are mainly evident during the relaxation following the ice melting, as confirmed by previous findings. In the second stage we present the preliminary results of our FE 3D models, where we employ a realistic ice distribution and we account for lateral variations of the lithospheric thickness and mantle viscosity constrained by the ocean-continent distribution. The relative sealevel curves for sites close to the margins of the ice load, such as New York, exhibit the larger sensitivity to the presence of lateral viscosity variations, as it occurs in the 2D case. The direction of horizontal rates of displacement, which are currently monitored by geodetic surveys, are affected by the presence of lateral viscosity variations on large spatial scales.

Effect of slab dehydration on the mantle wedge dynamics in subduction zones

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In oceanic subduction zones, dehydration of slab's minerals might partly explain back-arc spreading and its initiation within the volcanic arc. While the slab enters the asthenosphere, it releases water which hydrates the asthenosphere and might significantly decrease its viscosity. This should develop the corner flow, and warm the overriding lithosphere. If the induced thermal erosion lasts, an extensive stress will locally appear.

In our dehydration modelling, the released water comes from the oceanic crust, and the altered peridotite of the slab. This peridotite is believed to be serpentinized at the mid-ocean ridge and along normal faults during bending near the trench, and can be 5 to 20 km thick. We use accurate phase diagrams for H_2O-satured mantle peridotite and a gabbroic crust to determine at each time step the amount of water released or absorbed by each unit of rock. Transition phases are supposed to be not metastable. We assume that the rock viscosity decrease depends on the concentration in water. The viscosity of a H_2O-satured asthenospheric rock is at least 100 times less than that of a dry one, at a pressure of 3 kbars (Hirth and Kohlstedt, 1996).

For cold subductions, simulations show a three-step dehydration of the subducting lithosphere. The crust releases its water at 74 km (blue schists destabilisation) and the top part of peridotite at 150 km (chlorite destablisation). In the bottom peridotite part serpentine transforms into phase A at 200 km whitout losing water. As P-T-t paths remain quite cold, only a small amount of water is liberated. However this water seems to be sufficient to hydrate the overlapping lithosphere over a significant volume (about 100 km wide and 50 km high) and increases the mantle corner concentration in water. Introducing a decrease in viscosity associated to the hydrated corner, the viscosity contrast visco(dry)/visco(wet) must be at least equal to 50 to obtain a developed thermal erosion. In these cases, the overlapping lithosphere is eroded on a wide region (between 151 and 271 km of the trench) and deeply (about 50 km of eroded materials). This specific position corresponding to the back-arc region, with longer simulations it wouldn't be impossible to observe back-arc spreading in some cases of subduction.

Effect of frictional and viscous softening in the crust on the lithospheric-scale deformation in Central Andes

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The Altiplano plateau in the Central Andes is the second greatest plateau in the world after Tibet with an average elevation of about 4 km formed as a result of ocean-continent collision between subducting Nasca plate on the west and Brazilian shield on the east. According to the classical Isacks (1988) scenario, the Cenozoic evolution of the plateau started ca. 30 Ma in response to the retreat of the flat-subducted Nasca plate. Astenospheric material, which replaced the retreated plate, thermally thinned and softened the overlying lithosphere. Continuing relative westwards motion of the cold Brazilian shield was first accomodated by distributed shortening of the softened lithosphere of the present-day plateau (pure-shear mode of shortening). However, at ca. 8–10 Ma deformation style abruptly changed into a simple-shear mode. Upper crustal shortening was ceased at the plateau and migrated eastwards, onto the margin of the Brazilian shield, while the plateau itself continued to grow due to the continuing shortening of its lower crust.

We employ numerical 2D thermomechanical modelling to test the above scenario and to evaluate key parameters, which account for the transition from pure- to simple-shear style of the lithosphere-scale deformation under pure-shear boundary condition. As numerical tool we use explicit finite element lagrangian code that originates from well-known PARAVOZ. Material and historical properties are tracked by markers. The code is parallelized for sheared-memory machines (OMP), MPI-paralellization is in progress.

The starting model is composed of rheologically different layers representing sediments, felsic and mafic crust, lithospheric mantle, and astenosphere. Rheological laws are Mohr-Coloumb elasto-plastic and Maxwell visco-elastic with nonlinear power-law creep. Both plastic and viscous softening is implemented. Initial and boundary conditions simulate thermal activation of the Altiplano lithosphere by upwelling astenosphere as well as its westward pushing by the cold Brazilian shield with constant velocity.

We found that model shortening always occurs in a pure-shear mode unless the uppermost crust of the margin of Brazilian shield becomes during the deformation considerably weaker than the Altiplano upper crust (drop of friction coefficient down to 0.05–0.1). Viscous softening in the middle and lower crust of the plateau is not strictly required, but its presence gives more "clear" simple-shear mode. The weakening in the uppermost part of the Brazilian shield may be attributed to pronounce plastic softening in the thick layer of Paleozoic sediments covering the shield. The physical mechanism of the abrupt and strong plastic softening in sediments remains an open question. One explanation could be fluid overpressure due to hydrocarbon generation.

2.5-D thermomechanical modelling of the Dead Sea transform

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The Dead Sea transform system (DST) is the boundary between the Arabian and African plates, where left-lateral transform motion has largely accommodated the opening of the Red Sea basin during the last 15–20 My. General geometry of the system is, to a first approximation, two and half dimensional, i.e., variations along the strike are much smaller than that across the transform. Taking this into account, we extent the well-known two-dimensional explicit finite-element code PARAVOZ to 2.5-D. We solve the full 3-D system of conservation equations (momentum, mass, energy) assuming no variations along the third axis (d/dz = 0). This simplification allows us to perform calculations on a 2D-grid. Explicit calculation scheme allows us to operate with realistic visco-elasto-plastic rheology of lithosphere without any predefined faults. Faults are generated in a self-consistent way due to the strain localization process associated with the strain softening in plastic deformation mode. Material and history properties are tracked by markers. The algorithm was parallelized for sheared-memory machines (OMP), MPI-paralellization is in progress.

Modelling results suggest that the DST lithospheric structure is controlled by the plate-scale transform displacement within a relatively cold lithosphere. In such a lithosphere, shear strain is localized in a narrow (20–40 km wide) vertical decoupling zone, which crosses the entire lithosphere. In the upper crust the deformation localizes at one or two major faults located at the top of this zone. The location of the vertical decoupling zone is controlled by the temperature of the uppermost mantle prior to the transform motion. The lithospheric structure imaged along the DESERT seismic line is consistent with the 105 km transform motion combined with less than 4 km transform-perpendicular extension. Uplift of the Arabian Shield adjacent to the DST can be explained by young (< 20 Ma) thinning of the lithosphere at and east of the plate boundary. Such lithospheric thinning is consistent with seismological observations as well as with low present-day surface heat flow and with high temperatures derived from mantle xenoliths brought up by Neogene-Quaternary basalts. The modelling suggests that the lithospheric thinning in the southern part of the DST have enabled transform motion at the DST by lowering the strength of the otherwise too strong Arabian lithosphere.

Constraints on the mechanics of the southern San Andreas fault system from velocity and stress observations

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We use GPS and stress-orientation observations to study the distribution of slip on the system of faults comprising the southern California plate boundary region. Of particular interest is how slip is partitioned between the San Andreas Fault (SAF), the San Jacinto Fault (SJF) and the Eastern California Shear Zone. Some prior work places the majority of slip on the SAF. Other studies, however, find that the SJF accommodates much slip in the south, implying a low slip rate on the San Bernardino segment of the SAF.

Two new data sets are used to address this question. The first is the Southern California Earthquake Center's geodetic velocity field (version 3), which includes much improved coverage over prior models. The second is a regional map of stress field orientations at seismogenic depths, as determined from earthquake focal mechanisms. While GPS data has been used in similar studies, this is the first application of stress field observations to this problem.

We construct a simplified version of the southern California fault system, and model the surface velocities using a block model with elastic strain accumulation, following Meade et al. (2002). Additionally, we model the stress orientations at seismogenic depths, assuming that the stress field results from the loading of active faults. An inversion for fault slip rates is performed to simultaneously fit the GPS and stress observations. The model fit to the data is good in general, indicating that a simple mechanical model can capture both observed interseismic strain and stress accumulation. We evaluate the sensitivity of the slip rate solutions to the different datasets and identify 'anomalous' fault segments with stresses that deviate from our simple loading model.

Global azimuthal anisotropy from Rayleigh waves and flow models

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We model the development of finite strain in three-dimensional mantle-circulation models and compare our model predictions with azimuthal anisotropy as derived from Rayleigh waves. The flow models are simplified; we use a Newtonian viscosity that is only allowed to vary with depth. However, the predicted circulation includes the effect of plate motions and density anomalies as derived from tomography. Flow fields are thus representations of the large-scale upper mantle currents and either steady-state or evolving with time based on tectonic reconstructions of plate boundaries. Differences in the predicted strain for these two cases are small, however, since saturation strains of order unity accumulate in a few Myr at all but the shallowest depths. By using synthetic anisotropy based on the flow calculations as input for the Rayleigh wave inversions, we explore the resolving power of the seismologic data. We establish that structure can be resolved reliably and observed regional patterns are hence stable features of the inversion. The predicted longest axes of the finite-strain ellipsoid (FSE) from our flow models match the observed fast propagation orientations for anisotropy within most oceanic lithosphere and some young continental regions well. We find that alignment of seismically fast axes with the FSE leads to substantially smaller deviations from observed anisotropy than alignment with absolute plate motions, as is commonly assumed. Regions of large misfit might be indicating intraplate deformation for which our geodynamic model does not yet account for. These findings lend support to the hypothesis that seismic anisotropy is due to lattice-preferred orientation (LPO) of olivine crystals due to shearing in nontrivial mantle flow. We further explore how the model predictions are affected when the infinite strain axis (ISA) is considered alongside the FSE. The ISA was proposed by Kaminski & Ribe (2002) as a high-strain, limit-case indicator for LPO as expected for a path-dependent treatment of fabric development that includes dynamic recrystallization. Our models contribute to the verification of theories about anisotropy formation and establish anisotropy as a quantitative indicator of mantle convection.

The mantle transition-zone water filter model

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The chemical distinction between ocean island and mid-ocean ridge basalts (OIB and MORB, respectively) suggests that the mantle contains relatively isolated geochemical reservoirs which are due either to chemical layering or poor mixing. All mantle-reservoir theories, however, introduce various problems of their own, and geochemical constraints are often satisfied at the expense of seismological and geodynamical ones. Here we propose and explore an alternative hypothesis that mantle convection is not layered but instead undergoes a filtering mechanism at the 410km-deep olivine-wadsleyite phase tranformation. We argue that as the broad background of upwelling ambient mantle (forced up by the downward flux of subducting slabs) moves out of the high-water-solubility transition zone (between the 660km and 410km discontinuities) into the low-solubility upper mantle above 410km, it undergoes water supersaturation and partial melting that removes water and filters out incompatible elements; the remaining solid phase continues to ascend and supplies relatively dry and depleted materials to the MORB source region. The residual melt is likely denser than the surrounding solid and is thus trapped at the 410km boundary; however, slab entrainment provides an effective means for recirculating this enriched and hydrated material back into the transition zone and lower mantle. Mass balance ("box-model") calculations predict that sufficient melt is produced at 410km to filter incompatible elements, and the resulting melt layer is of order 1-10km thick. The filtering effect, however, is likely suppressed for hotter mantle plumes, because of lower transition-zone solubility at higher temperature; the plumes would therefore generate more enriched OIBs. The filter mechanism could also have been suppressed globally in the hotter Archaean during peak crustal production, thereby allowing for chemically enriched continental crust. Observations suggesting separate isotopic evolutions of MORB and OIB source regions could be explained by homogenization of mantle isotopic signatures as the ambient upwelling passes through the 410km melt zone, followed by several hundred million years of isolation as the solid-residue material rises slowly across the upper mantle. Although segregation of incompatible elements occurs, bulk elements and heat are transported across the mantle as if in whole-layer circulation, thereby avoiding the geophysical problems with layered convection (such as build up of internal thermal boundary layers and the resulting anomalously strong plumes). Seismic evidence for a melt zone above the 410km discontinuity provides partial support for our hypothesis. Overall, the transition-zone water-filter model explains the chemical variability between ocean islands and mid-ocean ridges, yet avoids the many problems of invoking isolated mantle reservoirs and layering.

Seismic velocity and density anomalies from subducted basalts

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Products of chemical differentiation near the surface, such as oceanic crustal basalts and gabbros, may be transported downward by subduction to give rise to chemical heterogeneity at depth. In the shallow upper mantle, anhydrous metabasalts (e.g., eclogites) should be slightly fast relative to ambient peridotite mantle, with a signature arising primarily from the thermal anomaly rather than composition. Hydrous metabasalts (e.g., lawsonite blueschists, lawsonite eclogites), on the other hand, should be significantly slow in the 100-250 km depth range, becoming faster (e.g., stishovite eclogites) below 250 km. The properties of observed seismic reflectors along the upper surfaces of subducting slabs are consistent with phase relations in hydrothermally altered basalts [Helffrich et al., 1989; Helffrich & Stein, 1993; Peacock, 1993; Hacker, 1996; Helffrich, 1996; Connolly & Kerrick, 2002].

In the lower mantle, anhydrous metabasalts (e.g., perovskitites) should be fast, growing progressively more so with increasing depth. This signature arises from the compositional contrast, as the temperature-dependence of seismic velocities falls with increasing depth in the lower mantle, and the magnitude of temperature anomalies from subducted material should also fall with increasing depth due to thermal assimilation [Bina & Wood, 2000; Mattern et al., 2002; Bina, 2003]. Thus, subducted metabasalts can explain many apparently fast seismic scatterers in the lower mantle, but how can some apparently slow scatterers (e.g., at ∼1115 km) be explained [Kawakatsu & Niu, 1994; Niu & Kawakatsu, 1997; Hedlin et al., 1997; Kaneshima & Helffrich, 1998, 1999; Vinnik et al., 1998, 2001; Castle & Creager, 1999; Kruger et al., 2001; Niu et al., 2003]? Possible causes of such low velocity features include dense hydrous silicate phases and post-stishovite phases of free silica.

If dense hydrous phases persist to such depths, they may decrease the predicted velocity anomaly (as in the case of hydrous metabasalts in the upper mantle). However, dense hydrous silicates are unstable below ∼1200–1300 km depth [Shieh et al., 1998; Ohtani et al., 2001]. Furthermore, the elasticity of these phases appears to depend primarily upon density rather than upon water content, so that any associated slow velocity anomalies should be small [Angel et al., 2001]. Thus, significantly slow seismic anomalies in the lower mantle may be difficult to generate from dense hydrous silicate phases in subducted material.

An unusual shear-mediated phase transition in silica, from rutile-structured stishovite to a $CaCl_2$-structured phase, occurs at high pressures. As a result, the shear modulus of SiO_2 should drop by ∼20 % in the pressure interval ∼40–47 GPa before rising again subsequently [Karki et al., 1997; Shieh et al., 2002]. This transition thus has the potential to generate slow V_S anomalies in the ∼1200–1500 km depth range which are accompanied by positive density anomalies but small V_P anomalies, in accord with recent seismic observations below 1100 km [Niu et al., 2003]. At greater depths, such high-pressure silica phases may be expected to yield fast anomalies. It has recently been suggested, however, that mantle temperatures may possibly depress this transition in silica to greater depths, perhaps ∼1900 km, rendering it unsuitable to explain velocity anomalies at shallower levels [Ono et al., 2002]. Thus, the temperature-dependence of this transition pressure in silica remains an important topic for further study. In summary, slow shear velocity anomalies at ∼1200–1500 km may arise from a post-stishovite phase change in silica (as may large fast anomalies at greater depths) unless dP/dT for the transition proves to be large.

It is important to note that both fast and slow anomalies in material subducted into the lower mantle arise largely from the presence of free silica in metabasaltic mineralogies. Hence, such anomalies depend upon the survival of free silica phases, which are unstable in contact with the surrounding peridotite. In the lower mantle, for example, silica reacts with ferropericlase to form perovskite. Thus, these metabasalt mineralogies (free silica + perovskite) can persist only to the extent that they are preserved as armored relics (with perovskite rinds) from contact with surrounding metaperidotite (perovskite + ferropericlase). Therefore, high temperatures and efficient mixing in the deep mantle may induce decay in such velocity anomalies, due not only to volumetric averaging but also to chemical reaction.

Subducted metagabbro/basalt should remain negatively buoyant (relative to peridotite) throughout the lower mantle [Bina & Wood, 2000; Mattern et al., 2002; Bina, 2003; Mattern, pers. comm. 2003; Ohtani et al., 2003]. While it has been suggested that an abundance of low-density (Ca-ferrite structured) Na-Al phase in sodic compositions may allow for density crossover (to neutral buoyancy) near ∼1500–2000 km [Ono et al., 2001], high-pressure alkali phase behavior remains a complex puzzle for further study [Miyajima et al., 2001].

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Numerical models of the formation of extensional sedimentary basins: sensitivity to rheology and surface processes

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Extensional sedimentary basins are an expression of localisation of crustal deformation during extension of continental lithosphere. The geometry of extensional basins can evolve in a symmetric or asymmetric manner, which in a purely kinematic description would result from pure shear or simple shear, respectively. Here we use dynamic models to study factors controlling the geometrical evolution of extensional sedimentary basins. We focus specifically on the effects of crustal rheology, strain softening of the frictional-plastic crust, and sedimentation and erosion.

For our experiments we use a thermo-mechanical numerical model on a crustal scale. All materials have a viscous-plastic rheology where brittle behaviour is governed by the frictional-plastic Coulomb criterion and viscous flow follows a temperature-dependent creep law for quartz. Variations in crustal strength are obtained by scaling the viscous creep law or through changes in the extension velocity. Shear zones develop dynamically (i.e., are not prescribed) and can weaken through strain softening of the frictional-plastic crustal material. The models are isostatically compensated through flexure of an underlying elastic beam.

Our models show how extension of the continental crust leads to the formation of sedimentary basins bounded by narrow shear zones. An asymmetric basin geometry is promoted by a weak lower crust and frictional-plastic strain softening. Extension of weak crust with a thin frictional-plastic domain is compensated by upwelling of the lower crust. This causes an outward propagation of small half-graben basins. A strong (i.e., frictional-plastic) crust leads to the formation of a deep, initially symmetric, sedimentary basin. In general, we observe that if sedimentation is included basins tend to be narrower and deeper. Our results illustrate that surface processes have the potential to influence crustal tectonics directly.

Benchmark of numerical codes used for subduction modeling

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Modeling of subduction has long been attempted with various numerical codes, each with its own limitation. From the numerical point of view, a self-consistent model of a subducting slab is very challenging. We do not have full knowledge of slab rheology, i.e. the dominance of different creep mechanisms and the role of elasticity. Different assumptions on the controlling factors of lithosphere rheology have resulted in development of different numerical codes. Most of the codes were developed to simulate mantle convection, focusing on sharp viscosity variations and, recently, plasticity. However, the rheology of the lithosphere is different from the mantle. New results have shown the importance of elasticity for modeling lithosphere dynamics.

To document the strength and limitations of different approaches a benchmark comparison was proposed at the Geodynamical Workshop in September 2002 at the ETH Zurich. Here we compare codes comprising commercial packages and university-developed codes. We use a simple geometrical setup published on http://www.Geobench.org. We compare passive subduction of a purely viscous rheology with a prescribed or thermally controlled density field. Four codes were used namely: ELLIPSIS, a particle-in-cell finite element code based closely on the standard finite element method, a finite-volume multigrid code based on the method developed by Trompert and Hansen (1996 [1]), ANSYS/Flotran a fluid-dynamic commercial code (CFD) and ABAQUS Explicit an Arbitrary Lagrangian Eulerian (ALE) commercial code.

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Postglacial rebound with laterally variable viscosity

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We present a new time-domain spectral method to model viscoelastic deformation of spherical Earth with a 3-dimensional (3d) viscosity structure. The method gives stable results for lateral contrasts in viscosity up to 2-3 orders of magnitude. The use of the method is especially efficient for cut-off degree < 100, thus for a low and intermadiate resolution modeling. We apply the method to investigate the effects of viscosity changes associated with lateral variations of the lithospheric thickness. Comparison of relative vertical displacements predicted for various 1d and 3d viscosity models suggests that the postglacial uplift is mainly sensitive to the viscosity profile below the observing site and basically insensitive to the lateral viscosity variations in the remote areas. This indicates that the traditional inversions of the uplift data for 1d viscosity may give correct results provided that the data come from a region of constant lithospheric thickness and they were obtained sufficiently far from the border between the lithospheric blocks of different thickness.

A synthetic fault system in a spherical and viscoelastic Earth model

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In order to improve the knowledge about the fault interaction at long distances due to the postseismic stress transfer, we have developed a synthetic fault system based on a spherical, viscoelastic, selfgravitating Earth model. Though seismicity in our simulation is controlled mainly by tectonic loading, our results highlight the significant role played by postseismic stress transfer in assessing the spatio-temporal pattern of the earthquakes.

A cell model for mixed heating convection

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Solid-state thermal convection in planetary mantles is generated by both volumetric heating (radiogenic elements, secular cooling, tidal heating) and heating from below (cooling of the metallic core). However, the relative importance of plumes emanating from both boundary layers and their interaction is yet poorly understood. A simple scaling can be achieved for fluid layers bounded by rigid horizontal surfaces, based on the observation that the structure of the top cold boundary layer does not depend on the heating distribution but simply on the global amount of heating (internal plus basal). In the case of free-slip boundaries, however, variations of the relative bottom heat flux (0: pure volumetric heating; 1: pure basal heating) induce modifications in the cold boundary layer that may have a significant influence on the geological history of the planet.

The proposed scaling is based on the classical boundary layer theory for a 2D cell structure, modified in order to take into account the heating distribution: the cell's rotation center is shifted toward an upper corner due to an asymmetry of the flow (cold plumes associated with a larger velocity than hot ones when internal heating is present); the heating of plumes during their ascent/descent is also modeled; in addition, the asymmetry due to a different impact of the impinging plume on the boundary layer is also described. The relationships issued from the derivations mentioned above produce an efficient framework to analyze numerical results carried out in a 2D Cartesian geometry.

— INVITED — Convection in the Earth's core from the perspective of a mantle convection modeller

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During the past eight years numerical simulations of the geodynamo found a lot of attention and the field has attracted researchers also from the mantle convection community. The time delay of 25 years in the development of the two fields has several reasons. Most important is that Cowling's theorem does not allow the generation of purely axisymmetric magnetic fields by self-sustained dynamo action. Hence a self-consistent dynamo model must be three-dimensional from the outset. While mantle flow is simply governed by Stokes law, i.e. a balance between buoyancy and viscous friction, the force balance for core flow is much more complex. Inertia cannot be neglected on short time scales although it is not of prime importance. The Coriolis force plays a key role in structuring the flow and is balanced by the electromagnetic Lorentz force to first order. Viscous forces are almost negligible in the core, which creates large problems for the stability of numerical methods. Because of the competing symmetries of buoyancy forces (radial) and Coriolis forces (axial), spherical models are essential. Plane layer dynamo models, which are computationally simpler, miss important aspects. In addition to the familiar (in mantle convection) advection-diffusion equation for temperatur and/or composition, a similar equation must be solved for the magnetic field (i.e. for a vector rather than a scalar). While the fundamental physical laws governing core flow are more complex than those for mantle convection, complexities of the material properties that are very important for mantle rock, such as the strong temperature dependence or nonlinearity of viscosity, are irrelevant in liquid iron.

Mantle convection models can today be calculated at the appropriate parameter values (correct Rayleigh number) even in 3D, but this is not possible for core convection. Key parameters, such as the Ekman number describing the ratio of viscous forces to the Coriolis force or the magnetic Prandtl number, the ratio of viscosity to thermal diffusivity, are off by many orders of magnitude. As a consequence the hierarchy of forces acting on the flow is not necessarily the same in the models as it is in the Earth's core and results must be interpreted with care. Dynamo models have been calculated with two different purposes in mind. One is the fundamental understanding of how magnetic field is generated, in particular the dominant dipole part. Here the helical structure of the convective flow in columns that are aligned with the rotation axis seems to play the key role. Another aim is to reproduce the characteristic structure in space and time of the geomagnetic field as faithfully as possible. Some models are successful to a surprising degree. They create not only a dipole-dominated field of about the right strength but also agree in the characteristic morphology of the multipole components and exhibit stochastic dipole reversals closely resembling to what is known for the Earth from paleomagnetism. Given the discrepancies in model parameters it is not clear if the agreement is fortuitous or if this indicates that the models contain all the essential physics nonetheless.

Mantle flow and core convection meet at the core-mantle boundary. Their interaction is predominantly thermal. The core is the slave and the mantle is the master who imposes a condition of non-uniform heat flow on core convection. Non-zonal differences in heat flow break the axial symmetry of the dynamo and should lead to a longitudinal bias in the statistical properties of the geomagnetic field. The question whether deviations from axisymmetry exist in the time-average geomagnetic field or in the distribution of paths of the virtual geomagnetic pole during reversals is discussed controversally in the paleomagnetic community. Dynamo models, in which the pattern of heat flow is related to seismic velocities anomalies in the lowermost mantle from tomography, predict longitudinal differences in geomagnetic properties in agreement with suggested pattern from paleomagnetic data. If this can be substantiated it would support a thermal rather than a compositional interpretation of seismic velocity anomalies in the D"-layer.

Generation of slab-like downwellings in a layered model with an interface at a depth of 1000 km

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We investigate the stability of hypothetical layered convection in the mantle and the mechanisms how the downwelling structures originating in the lower layer are generated. The stability is studied by means of numerical simulations of the double-diffusive convection in a 2-D spherical model with radially dependent viscosity. We demonstrate that the stability of the layering strongly depends not only on the density contrast between the layers but also on the heating mode and the viscosity profile. In the case of the classical Boussinesq model with an internally heated lower layer, the density contrast of about 4 % between the compositionally different materials is needed for the layered flow to be maintained. The inclusion of the adiabatic heating/cooling in the model reduces the temperature contrast between the two layers and, thus, enhances the stability of the layering. In this case, a density contrast of 2–3 % is sufficient to preserve the layered convection on a time scale of billions of years. The generation of the downvelling structures in the lower layer occurs via mechanical or thermal coupling scenarios. If the viscosity dependent on depth and average temperature at each depth is considered, the low viscosity zone develops at a boundary between the two convecting layers which suppresses mechanical coupling. Then the downvelling structures originating in the lower layer develop beneath upper layer subductions, thus resembling continuous slab-like structures observed by seismic tomography.

— INVITED — Mantle chemical evolution: constraints and models

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Progresses in geochemistry, geophysics and numerical modeling have significantly improved our understanding of mantle convection. Though, the chemical structure and evolution of the mantle still remain puzzling problems. Some geophysical and geochemical data cannot be unambiguously interpreted and the physics of mantle differentiation is not well understood. In this context, several end-member models of mantle dynamics have been proposed and some have been partly tested through numerical models.

Reviewing and criticizing the data is the first step to establish a set of constraints on the evolution of the mantle. The second step is to use modeling to focus on the relevant physics and parameters of the problem. The last step is to look back at the data and to identify future observations needed to better constrain mantle models. Following this procedure shows that, today, the major limitation towards an accurate modeling of mantle chemical evolution is our lack of understanding of early Earth history.

Finite elements modeling of postglacial rebound in North America: the predominance of nonlinear creep

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Several finite elements simulations of postglacial rebound we run, showed how the employment of a composite (linear plus nonlinear) mantle rheology (*Gasperini et al.*, 1992) could reproduce Relative Sea Level (RSL) time histories in North America more accurately than a pure linear rheology. Moreover, the power-law creep component came out to account for 55 % up to 85 % of the total strain-rate during the numerical analysis (Fig. 1). We evaluated models reproduction of RSL sequences through a chi-square analogous statistics (*Wu*, 1999) and we tested fitting improvement significance of composite rheology by the analysis of variance.

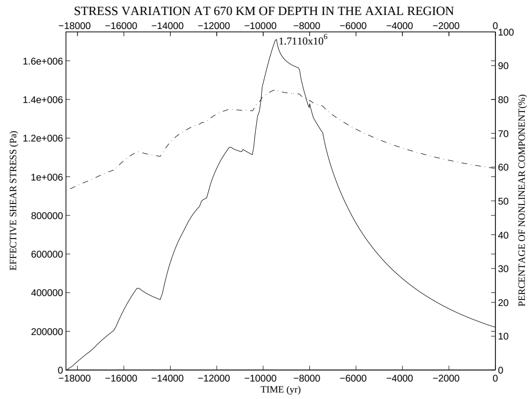

Fig. 1: Stress induced in the mantle by glacial forcing. The solid line represents the effective shear stress produced by glacial forcing during our simulation at the depth of 670 Km; the dash-dotted line, instead, the percentage of nonlinear component we estimated for the model having $\sigma_B = 1.6$ MPa and $\sigma_T = 1.5$ MPa.

The main limit of the whole modeling procedure is the axially symmetric geometry together with the restriction of tested datasets to RSL variations. Thus we are currently implementing 3D flat models having rheological parameters values in ranges which better performed in axisymmetric analysis; at this stage the best-fitting linear model performed strongly better than the corresponding axisymmetric model, while the improvement was much smaller for composite rheology. This difference with respect to the axisymmetric results can be partially ascribed to the fact that local time histories of the glacial model ICE-3G (*Tushingham and Peltier*, 1991, 1992) were deduced under the assumption of a linear mantle rheology and thus the latter could overfit the deglaciation details especially in the periphery of the ice load. Furthermore, we did not explored the full parameter space of composite rheology for the tridimensional case. However, the slightly better fit (Fig. 2) of the composite rheology appears to confirm the findings obtained in axially symmetric geometry.

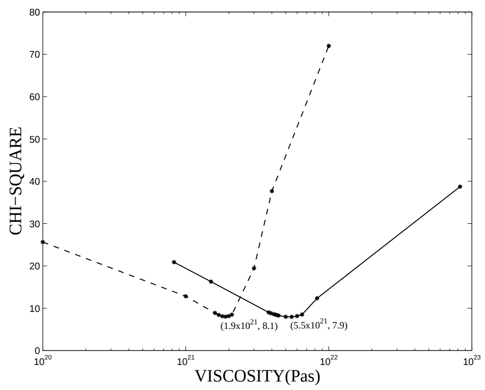

Fig. 2: Chi-square values versus viscosity for linear (dashed line) and composite (solid line) models.

— INVITED —
Experimental investigation of mantle convection and mantle mixing

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The surface of terrestrial planets shows signatures of strongly episodic phenomena such as intense volcanism (e.g. Mars, Venus and Earth), complete resurfacing (Venus), plate tectonics and continental growth (Earth). On the other hand, geochemical and sismological data show that the Earth's mantle is also heterogeneous in composition, density, and viscosity, on a wide range of lengthscales. To explain those phenomena, we therefore need a better understanding of the convective dynamics of a planetary mantle. Thermal convection is known to produce episodicity (e.g. transient 3D cells, plumes), which is further enhanced by the presence of an endothermic phase transition, or when the fluid is heterogeneous. However, strong episodicity, or/and generation of sharp interfaces and fine scale motions are still difficult to study systematically with numerical methods. Hence, laboratory experiments, using analogous fluids such as aqueous polymers and sugar syrups, offer a good complement to numerical and theoretical studies, being a good tool to map and characterize the different regimes of thermal convection and mixing.

Since Plate Tectonics-like convection remains to be produced in a laboratory, this review focuss on the generation of upwellings in a mantle with various initial degree of heterogeneities, and the figures of mixing which can be generated. In a homogeneous mantle, we shall see that the classical image of a plume with a long conduit connecting its source in a bottom thermal boundary layer, to the lithosphere is valid only during a short time compared to the entire life of the plume. Scaling laws further show that the typical lifetime of hotspots produced by such plumes should be under 40–50 Myr. To create fixed, long-lived plumes, a mechanism to anchor them is needed. A fluid initially stratified in density and viscosity is capable of producing such long-lived features, a well as more episodic and dramatic motions, depending on the buoyancy ratio B (ratio of the stabilizing chemical density anomaly to the destabilizing thermal density anomaly). Indeed, two regimes are found: at high B, convection remains stratified and fixed, long-lived thermochemical plumes are generated at the interface; while at low B, hot domes oscillate vertically through the whole tank while thin tubular plumes can rise from their upper surfaces. Under certain conditions, the initial configuration can even be completely reversed. Scaling laws derived from laboratory experiments allow predictions of a number of characteristics of the convective features, such as their geometry, size, thermal structure, and temporal and chemical evolution. Convection acts to destroy the stratification through mechanical entrainment and instabilities. Therefore, both regimes are transient and a given experiment can start in the stratified regime, evolve towards the doming regime, and end in well-mixed classical one-layer convection. In a heterogeneous fluid, figures of mixing are complicated, since convection creates compositional heterogeneities with two different typical size and topology: (a) thin filaments are generated by mechanical entrainment through viscous coupling, either in the thermochemical plumes on top of the domes, or during the doming sequence. The two initial reservoirs therefore quickly become "marble cakes", even though they remain dynamically separated for a long time. (b) domes, and blobs encapsulated in the domes, are generated by instabilities.

Those fluid mechanics results will then be applied to planetary mantle convection, in an attempt to explain 1) the present-day global tomographic images, 2) the episodic generation of intense volcanism, such as hot spots and flood basalts, on Venus, Mars and Earth, and 3) the resurfacing of Venus.

Consequences of different rheologies on numerical models of subduction

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In a subduction process, the collision of two continents may result in one of two different modes; either the subducted slab breaks off and the plate boundary ceases to be active or the plate boundary reorganizes to continue plate convergence. Our aim is to use a 3D numerical model to identify the parameters that act as the switches between the two different modes of collision, and to test them in the Timor region, where continental collision is occurring following subduction of Tethyan oceanic lithosphere. To investigate the subduction process we use finite element models that solves mechanical equilibrium, diffusion and diffusiom-advection heat equations in a Lagrangian domain. The first problem that we address is how different rheologies affect the subduction process. In this preliminary step we investigate a simpler 2D model in which the oceanic thinner lithosphere is subducting under a continental plate. We did that using different rheologies. We put particular attention on the role of the viscosity which is in some cases temperature and stress dependent.

Mantle tomography and its relation to temperature and composition

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A method is provided to constrain lateral variations of temperature and composition in the lower mantle from global tomographic models of shear- and compressional-wave speed. We assume that the lower mantle consists of a mixture of perovskite and magnesio-wüstite, and we used recent mineral physics data together with a careful equation of state modeling to compute sensitivities of velocities to temperature and composition. In a first stage, we directly invert VP- and VS-anomalies for variations of temperature and composition, using the appropriate sensitivities of velocities to temperature and composition. However, uncertainties in the tomographic models and in the sensitivities are such that variations in composition are not robust. At present knowledge, a deterministic determination of lateral variations of temperature and composition seems therefore unfeasable. We then turn to a statistical approach, which allow us to infer some robust features. We compute synthetic histograms of the ratio R of the relative shear-to-compressional velocity anomalies for a large variety of cases, including different combinations of the anomalies of temperature and composition. Comparisons of these complete histograms (not only averages) with those predicted by global tomography show that the origin of seismic anomalies cannot be purely thermal. In the bottom of the mantle, strong anomalies of composition, due to changes in the amount of perovskite and/or iron, are clearly present. The ratio R alone is however unable to resolve all existing trade-offs between anomalies of temperature and composition. An accurate determination of temperature and composition requires knowledge of density variations. We show that anomalies of iron can be resolved from the additional analysis of histograms of the relative shear-velocity to density anomalies. Preliminary comparison with robust observed histograms obtained using a neighbourhood algorithm suggest that iron anomalies $\pm 2\,\%$ at the bottom of the mantle.

Small-scale convection below oceanic lithospheres: scaling laws of onset time, influence of transform faults and 3-D geometry

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Numerical simulations of two-dimensional Rayleigh-Benard convection are designed to study lithospheric cooling above a convective mantle. We model transient lithospheric cooling by imposing a zero temperature at the surface of the mantle with an initially homogeneous temperature. A strongly temperature-dependent viscosity fluid is heated from within, in order to avoid internal temperature drift. For a while the lithosphere cools approximatively as a conductive half-space and lithospheric isotherms remain flat. As instabilities progressively develop at the base of the lithosphere, lithospheric cooling departs from the half-space model.

We propose two different parameterizations of the age of the first dripping instability, using boundary layer marginal stability or quantifying the characteristic timescale of the exponential growth of instabilities as a function of the Rayleigh number and of the viscous temperature scale.Both account very well for our numerical estimates of onset times, within their error bounds. The absolute value of the onset time depends on the amplitude and location of initial temperature perturbations within the box, and on the initial temperature structure of the thermal boundary layer.

Furthermore, thermal perturbations of finite amplitude located within the lithosphere (such as the ones induced by transform faults, for example) strongly reduce the age of the first dripping instability. This study emphasizes the role of the lithospheric isotherms topography on the development of instabilities. To developp our analyse, a work in collaboration with G. Choblet (University of Nantes) is started. We will use a 3-D convection code in order to study the influence of transform faults, and therefore lithospheric isotherms topography, on small-scale convection.

The dynamics of the slab rollback effect

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Subduction influences plate tectonics by modifying the surface area and velocities of plates, and plates connected to slabs move faster than plates without slabs. Most of the subduction zones on Earth show the trench retreat effect, which influences the subduction process and geologic deformation at the surface. To investigate the trench retreat effect we used the 2D finite differences code FDCON (Schmeling & Marquart, 1993). In order to start subduction, we assumed that initially one edge of the subducting plate dips into the mantle. An overriding plate was not included in the models. The models are isotherm and viscous (Stokes flow) with a visco-plastic subducting lithosphere. The plastic rheology of the plate is described by the Byerlee law, mimicking brittle deformation in the shallow lithosphere. The density and viscosity of the mantle and the lithosphere are advected with the tracer approach. We used periodic and reflective free slip boundary conditions. Numerical experiments were done to analyze the relationship between the trench retreat and various subduction parameters using different viscosity structures: (1) homogeneous mantle viscosity and (2) stratified viscosity to model the upper and the lower mantle. The viscosity of the plate and the mantle, the thickness and the length of the lithosphere were varied. We found that the flow in the lower part of the model box for the models with periodic and reflective boundary conditions influences the way in which the slabs are folded. For the trench retreat, we observed that it depends predominantly on the viscosity of the mantle, rather than on the viscosity of the slab. The velocity of trench retreat decreases when the slab touches the boundary between the upper and lower mantle.

Seismic velocity anomalies and anticorrelation in the lowermost mantle: the role of chemical heterogeneities

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Recent seismological observations cannot be explained by thermal anomalies alone, but suggest the existence of chemical heterogeneities in the lowermost mantle. Our objectif is to investigate the dynamics of chemically denser material and to constrain its composition by using seismological observations.

We solve the equations governing convection of a compressible viscous fluid, and use active tracers to model chemically denser heterogeneities. We consider a two phases mantle: (Fe,Mg)SiO_3 perovskite + (Fe,Mg)O magnesiowustite and assume that the reference mantle has a pyrolitic composition. For the denser material we investigate a plausible range of mineralogical compositions by varying: (i) the silica molar ratio, (ii) the iron molar ratio, (iii) the iron-magnesium partition coefficient between perovskite and magnesiowustite.

The calculated seismic velocity anomalies for P- and S waves and for the bulk sound speed are compared with seismic observations. Moreover, the obtained anticorrelation between bulk sound speed and S wave velocity shows that anticorrelation is associated with upwelling regions, while we find almost no anticorrelation in subducting areas, in good agreement with recent observations. We also show that in order to satisfy both geodynamical and seismological constraints, the (1–2 %) denser material in the lowermost mantle may result from a simultaneous enrichment in Fe and Si, with respect to a pyrolitic composition. A decrease of the iron-magnesium partition coefficient, due to a pressure increase and to the presence of Al-perovskite, would reduce the required Fe and Si enrichment.

— INVITED —
Phase transitions and mantle dynamics

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In studies of mantle convection, phase transition zones, in particular those at 670km depth have been considered either as a barrier between upper and lower mantle, as the site for lateral mass anomalies hampering the flow or merely as areas of potential increase in viscosity as function of depth, without much impact on mantle dynamics. The possibility of a petrological change through the phase transition zone was invoked in some ancient studies but is rarely proposed since seismological studies have shown the slabs to penetrate in the lower mantle. Here, we shall attempt to discuss various mechanisms linked with phase transitions and able either to affect the vigor of mantle convection or to induce compositional variations as function of depth.

The most widely studied mechanism through which phase transitions can affect mantle dynamics is the potential effect of a negative Clapeyron slope at 670km depth. The global buoyancy of colder material around 670km depth will depend strongly upon the phase changes in the non olivine components of the mantle (i.e. upon the Majorite-garnet towards perovskite phase change). The 'Effective Clapeyron slope' will depend upon the background mantle temperature and upon details of the phase diagram which are not perfectly known but it is unlikely to be so negative that the avalanche regime prevails.

Two types of compositional variations associated with the 670km phase transition have been proposed: a denser (iron rich) lower mantle has been invoked. Ringwood suggested that the crustal and non crustal components of the mantle had their relative densities varying as a function depth, the crustal material being less dense in a thin layer below 670km. He inferred that crustal material may remain trapped above the 670km discontinuity. Tests of these ideas using convection models show that phase transitions may indeed induce segregation as function of depth in the mantle. A negative Clapeyron tends to segregate the denser crustal material in the lower mantle, but a difference in depth of the phase changes of the olivine vs pyroxene (crustal) components tends to induce accumulation of crust above and of depleted material below the 670km depth discontinuity.

Kinetic effects induce a delay in the phase transformations. This corresponds to deflections of the phase transition zones and therefore to lateral density variations hampering the flow. The release of latent heat is at the origin of one of these kinetic effects. It may hinder convection whatever the sign of the Clapeyron slope but can play a significant role in mantle dynamics only for thin transition zones (ringwoodite to perovskite plus magnesio-wustite at 670km depth?). A phase transition implies a change of volume which will occur only if it is accompanied by creep. This is true both on a global scale and on a local scale. This introduces a delay in phase transitions inversely proportional to the viscosity in the zone of phase change. If there is no 'transformation plasticity', this effect linked to the volume change at the 670km phase change could significantly hamper convection. On a macroscopic scale, the grain growth of the newly formed phase can also be delayed because of the creep necessary to accommodate the volume change. As most mantle phase changes are divariant, the diffusion of elements {Fe, Al}can also be a cause of kinetic delay but the diffusion coefficients are poorly known. This mechanism is however important for preventing short term, small amplitude variations of the love numbers.

Is-there a viscosity reduction in the zones of phase transition? These low viscosities could affect the flow, both directly and also because they would strongly trigger petrological segregation. The viscosity reduction may be linked either to internal stresses because of inhomogeneous change of volume on a microscopic scale or to grain size reduction. Experimental investigations concerning these viscosity reduction mechanisms are difficult: The phase changes occur within a few minutes in the lab (usually in specimens with micron grain sizes), but over 1Ma in nature.

In summary, several processes linked with phase transitions can potentially hamper mantle convection and also induce major elements variations as function of depth. Geoid data seem indeed to favor models involving mass anomalies hampering convection in the transition zone. There are presently uncertainties in the values of the physical parameters involved in each of the processes described above. Seismological studies, bringing constraints on the thickness and velocity jump across phase transitions, more sophisticated numerical models of mantle convection and also more data from high pressure physics (phase diagram for non olivine phases, diffusion coefficients of Fe, Al, grain size as function of speed of reaction...) should improve our understanding of the dynamic and petrologic effect of phase transitions.

Contemporary changes in the geoid about Greenland: predictions relevant to gravity space missions

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Contempory spatial and temporal changes in the geoid about Greenland are the sum of several contributions. We have examined those from glacial-isostatic adjustment. These may be divided into changes in ice loading occuring outside of Greenland, particularly North America, following the last glacial period, and those resulting from the Greenland Ice Sheet (GIS). Concerning the GIS's contribution, this may be further divided into past and current changes in the ice sheet. The spatial variability in the GIS's present-day mass balance affects the geoid power spectrum significantly and results in a signal that may be better resolved by measurements from gravity space missions than has been proposed by other authors.

Stagnant lid convection with an ice rheology

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Numerical investigations of thermal convection with strongly temperature dependent Newtonian viscosity (diffusion creep) and extremely large viscosity contrasts have demonstrated the existence of three convective regimes. These are the small viscosity contrast regime, transitional regime and the stagnant lid regime. The strong temperature dependence of water ice suggests that convection operating within the mantle of an icy satellite should be within the stagnant lid regime. We study the evolution into the stagnant lid regime with a water ice rheology by solving the equations of thermal convection for a creeping fluid with the Boussinesq approximation and infinite Prandtl number. The viscosity is non-Newtonian (dislocation creep). We fix the Rayleigh number at the base (Ra_1) to be 1×10^4 and systematically increase the viscosity contrast (as determined by ΔT) over the region from $\Delta\eta = 1$ to 10^{14}. The transition to the stagnant lid regime occurs at a viscosity contrast greater than 10^4 for Newtonian viscosity convection, whilst non-Newtonian viscosity convection accommodates the stagnant lid regime at larger viscosity contrasts. For a stress exponent, n, equal to 3, the stagnant lid regime is achieved at a viscosity contrast greater than 10^8. Dislocation creep of water ice is characterized by a larger stress dependence ($n = 4$) than silicates ($n = 3$), and with this water ice rheology, the stagnant lid regime is attained at a viscosity contrast greater than 10^{10}.

Role of lateral mantle flow in the evolution of subduction system: insights from laboratory experiments

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Subduction zones are complex 3-dimensional (3-D) structures. They vary both in lateral and depth extent and have irregular vertical and horizontal geometry. Nevertheless these geodynamic structures have been always interpreted on the basis of laboratory and numerical models bearing a fundamental 2-dimensional (2-D) geometry. We present here the first systematic laboratory setup that focuses on the feedback of mantle flow and slab dynamics as constrained by 3-D boundary conditions. These experiments are conducted with a composite silicone-honey system. The velocity of the incoming plate is varied with the aim of exploring the widest field of conditions in the subduction system. We find that the behavior of the slab during the fall into a stratified mantle is always characterized by three distinct phases, independently by applied boundary conditions: 1) the fall of the slab into the upper mantle; 2) the dynamic interaction phase with the 660 km discontinuity; 3) the final phase of steady state when the slab lies flat on the upper/lower mantle transition zone. Forces active into the system, whose distribution is influenced by the choice of the adopted boundary conditions, govern the nature of these phases Nevertheless our results highlight also that the highly dynamic behavior of subduction is strongly function of the effects of slab-mantle interactions and of the possible mantle flow restrictions both vertically and horizontally.

The number of hotspots in numerical models of mantle convection

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Numerical calculations have been carried out to study the effect of the Rayleigh number, viscosity distribution and internal heating on the areal density of upwellings in three-dimensional Cartesian models of mantle convection. Model domain with large aspect ratio (661) has been applied to ensure a robust upwelling statistics and to minimize the distorting effect of the sides of the box. Model parameters were chosen to simulate physical processes occurring in the Earths mantle according to available computational resources. The Rayleigh number varied in the domain of $Ra = 10^5$–$5 \cdot 10^7$, the viscosity increased exponentially with depth by a factor of γ =1, 10, 30 or 100, additionally a mantle-like depth-dependent viscosity profile has been studied. The value of internal heating corresponds to the chondritic abundance of radioactive elements, nondimensional internal heating was $H = 10$. Horizontal boundaries were isothermal and stress-free, vertical boundaries had mirror symmetry.

It was found that by increasing the Rayleigh number the flow velocity becomes faster ($\nu \sim Ra^{2/3}$), convective cooling intensifies, thus the surface heat flow increases ($Nu \sim Ra^{1/3}$), the characteristic length of the horizontal and vertical boundary layers decreases ($\delta \sim Ra^{-1/3}$). Obtained exponents are in accordance with results from scaling analysis [Solomatov 1995]. By increasing the viscosity contrast between the bottom and the top of the box the flow slows down especially in the lower regions resulting in the decrease of the heat transport and causing the strengthening (in thermal sense) of the bottom boundary layer. Therefore, the symmetry of the convective pattern deforms, upwellings are represented as axisymmetric ascending currents (plumes), while downwellings have slab-like feature.

On the basis of the numerical investigation of the areal density of upwellings the number of plumes increases with growing Rayleigh number [Parmentier and Sotin 2000], but decreases with the increase of the viscosity contrast (Fig. 1). It has been established, that the number of upwellings is related to the thickness of the bottom boundary layer as its inverse proportion, $N \sim \delta_1^{-1}$ (Fig. 2). It is supported by both numerical models and scale analysis.

In the presence of internal heating the form of the convection modifies substantially. The average temperature in the model domain increases leading to the strengthening of the upper and the weakening of the bottom thermal boundary layer. As a consequence, downwellings will appear as cold plumes, upwellings as passively ascending diffuse, hot zones. However, by increasing the Rayleigh number the model domain cools, temperature difference across the bottom boundary layer increases. Increasing viscosity contrast decreases more the average temperature of the box making stronger the bottom thermal boundary layer. The high Rayleigh number and the viscosity increasing with depth results in the main forms of convective motion as upwelling plumes and downwelling slabs. Since the internal heating weakens the bottom boundary layer, thus increases the number of plumes (Fig. 3). On the basis of flow parameters calculated from numerical models (average surface heat flux, velocity of the lithosphere, thickness of lithosphere and D” zone, diameter of plumes) mantle convection occurs rather in one- than two-layered form. The type of the convective flow system (one- or two-layered) can be inferred from the relation between the areal density of upwellings and surface hotspots, as well. If the convection occurs in one-layered form, the density of plumes beneath hotspots will be about 2–3 (using the depth of the mantle as a unit) [Steinberger 2000]. However, if the flow system were two-layered separated by the phase boundary at the depth of 660 km, it would yield the density of upwellings of 0.04–0.06 in the upper mantle (using the depth of the upper mantle as a unit). Whereas the areal density of plumes obtained from our realest numerical models lies in the domain of 0.8–1, which is between the two values, a coexisting one- and two-layered flow regime is supported. This form of the mantle convection is not a new hypothesis, such a flow system has been suggested by both geochemical investigations of extrusive basalts and numerical models including mineral phase transition at 660 km [Cserepes and Yuen 1997].

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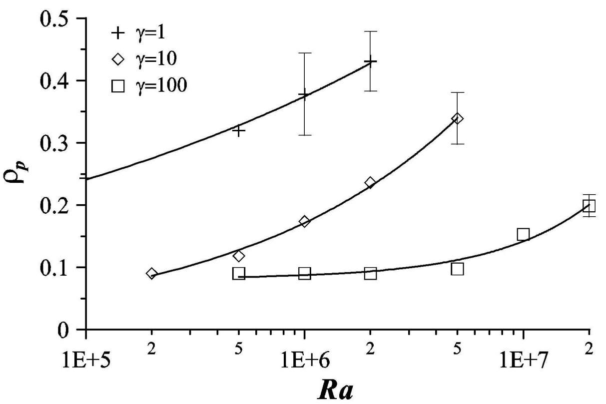

Fig. 1. The areal density of upwellings as a function of the Rayleigh number and the viscosity exponentially increasing with depth in a model box of 661 in the absence of internal heating ($H = 0$). At high Ra the average density of upwellings is indicated with its standard deviation. Viscosity contrast is marked in the figure by symbols.

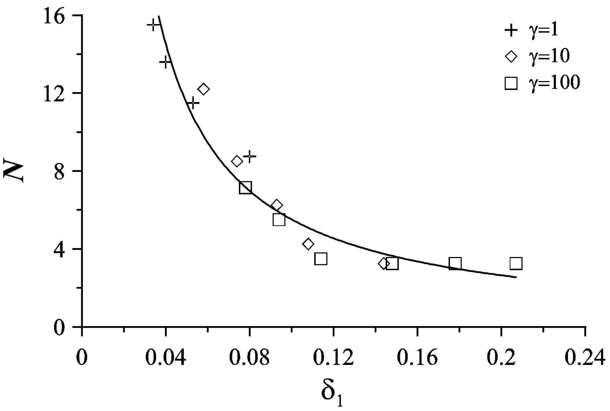

Fig. 2. The number of upwellings in a model box of 661 plotted against the thickness of the bottom boundary layer, $H = 0$. The fitted curve: $N = 0.48 \cdot \delta_1^{-1.06}$.

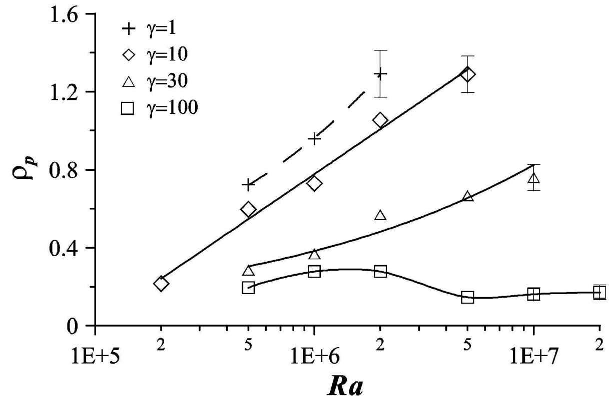

Fig. 3. The areal density of upwellings in a model box of 661 as a function of Ra with different viscosity distributions in the presence of internal heating ($H = 10$). At high Ra the average density of upwellings is indicated with its standard deviation. It is emphasized by dashed line that hot plumes do not form at $\gamma = 1$.

Synthetic seismic signature of thermal mantle plumes

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The first seismic images of mantle plumes have been a source of significant debate. To interpret these images, it is useful to have an idea of a plume's expected seismic signature. We perform a set of numerical experiments to obtain dynamic thermal whole mantle plumes, with temperature contrasts below the lithosphere that are consistent with those inferred from surface observations. The plume thermal structure is converted to seismic structure by accounting for the effects of temperature, pressure, an average mantle composition including phase transitions, and anelasticity. With depth- dependent expansivity and temperature- and depth-dependent viscosity, these relatively weak plumes have lower-mantle widths of 300-600 km at one half of the maximum temperature anomaly. To attain the narrow upper mantle plumes inferred from surface observations and tomography, viscosity reduction by a factor 30-100 is necessary, either as a jump or a strong gradient. All model plumes had buoyancy fluxes of at least 4 Mg/s and it seems difficult to generate whole mantle thermal plumes with fluxes much lower. Due to changing seismic sensitivity to temperature with depth and mineralogy, variations in the plumesśeismic amplitude and width do not coincide with those in their thermal structure. Velocity anomalies of 2–4 % are predicted in the uppermost mantle. Reduced sensitivity in the transition zone as well as complex velocity anomalies due to phase boundary topography may hamper the imaging of continuous whole mantle plumes. In the lower mantle, our plumes have seismic amplitudes of only 0.5–1 %. Unlike seismic velocities, anelasticity reflects thermal structure closely, and yields plume anomalies of 50–100 % in dln(1/Qs).

Dynamics of slab-transform plate boundaries: preliminary finite element models of the south-central Mediterranean uppermost mantle and lithosphere.

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Slab edges are currently a relatively common geometrical feature in plate tectonics. We use finite element models to investigate the consequences of vertical slab edges on the dynamics of the lithosphere and uppermost mantle. In this study, we focus on the south-central Mediterranean region. The three-dimensional dynamic models are constrained by tomography, and by geological, geophysical and geodetic observations. The preliminary models we present are based on a linear visco-elastic rheology. We investigate the response to variations in the shear strength of major faults.

A time-domain method of implementing the sea-level equation in GIA for a rotating earth

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The implementation of the sea-level equation (SLE) describing the redistribution of melt water in the oceans is complicated in conjunction with the Laplace-transform method conventionally used to model glacial-isostatic adjustment (GIA). The recently developed spectral-finite element method (Martinec, 2000) solves the field equations governing GIA in the time domain and, thus, eliminates the need of applying the Laplace-transform method. Moreover, the spectral finite-element approach allows us to solve the SLE when modeling GIA for a 3-D self-gravitating, incompressible, viscoelastic earth model.

The solution of the field equations in the time domain also makes it possible to use the MacCullagh formula in the time domain and to compute the incremental inertia tensor. This allows us to solve the linearized Liouville equation governing the variation of earth rotation. From the variation of earth rotation the incremental centrifugal potential can be calculated, which enters into he SLE.

The present test is restricted to radially symmetric earth models consisting of a fluid core, a Maxwell-viscoelastic lower and upper mantle and an elastic lithosphere. The last Pleistocene glaciation is simulated using two different scenarios, with different glaciation histories followed by the deglaciation history of the global ice model ICE-3G (Tushingham & Peltier, 1991). We investigate the influence of variable earth rotation on sea level and the influence of different viscosity models and glaciation histories on earth rotation.

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— INVITED —
The fluid dynamics of plumes

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In geodynamics plumes play an important role for phenomena on different scales, ranging from local hot-spots to large scale features like superswells. Plumes evolve from thermal boundary layers if a critical paramter (similar to a local Rayleigh numbea) exceeds a critical value. In that sense plumes can be viewed as threshold phenomena. By means of numerical experiments various aspects of plume structure - and evolution will be demonstrated in this presentation.

The shape and the evolution of plumes is strongly influenced by the viscosity of the material. Especially a strong temperature dependence pf the viscosity leads to episodic bursts of hot material from the thermal boundary layer following a previously established path of low viscosity. Episodicity is a common feature of plumes in fluids with temperature dependent viscosity, even if the forcing is not varying with time. If plumes are evolving self-consistently from a thermal boundary layer they hardly entrain material during ascent, i.e. material reaching the top is very similar to the material of the source region. Besides the temperature dependence also the pressure dependence of the viscosity significantly influences the behavior of plumes. The symmetry, between the upwelling and downgoing currents is destroyed by pressure dependence of the viscosity. Strong upwellings exists while the downwellings are weakened. The effect of the viscosity increasing with pressure on the flow dynamics is further enhanced by the decrease of the thermal expansion coefficient with pressure. Both, act to increase the strength of upwelling plumes, thus leading to flows of large horizontal scales. In two dimensions, flows with aspect ratios greater than 30 have been observed.

Under appropriate conditions (combinations of pressure and depth dependence) small plumes from the thermal boundary layer gather to form massive upwellings. This is a possible scenario relevant for the formation of superplumes. Under the same condition the net viscosity profile exhibits a local maximum in the lower mantle, as indicated by recent studies.

Viscous Heating in the Mantle Induced by Glacial Forcing

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We have studied the possibility of energy transfer from glacial forcing to the Earth's interior via viscous dissipation of the transient flow. We applied our initial-value approach to the modelling of viscoelastic relaxation of spherical compressible self-gravitating Earth models with a linear viscoelastic Maxwellian rheology. We have focussed on the magnitude of deformations, stress tensor components and corresponding dissipative heating for glaciers of Laurentide extent and cyclic loading with a fast unloading phase of various lengths.

We have surprisingly found that this kind of heating can represent a non-negligible internal energy source with exogenic origin. The volumetric heating by fast deformation can be locally higher than the chondritic radiogenic heating during peak events. In the presence of an abrupt change in the ice-loading, its time average of the integral over the depth corresponds to equivalent mantle heat flow of milliwatts per m^2 below the periphery of ancient glaciers or below their central areas. However, peak heat-flow values in time are by about two orders of magnitude higher. Note that nonlinear rheological models can potentially increase the magnitude of localized viscous heating.

Fig. 1a

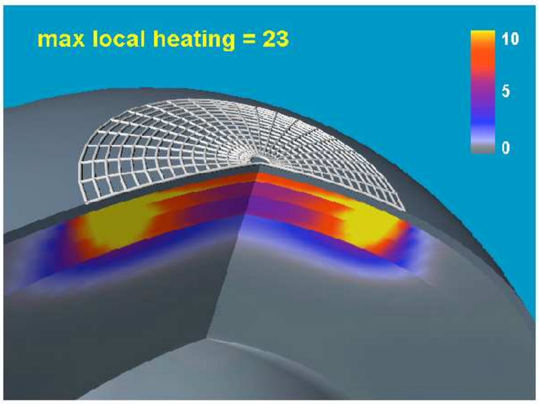
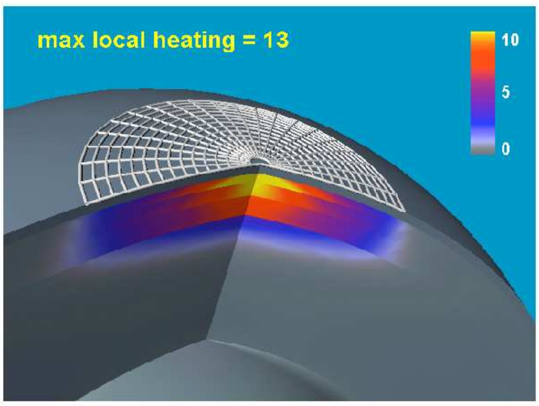


Fig. 1b



To illustrate the spatial distribution of the viscous heating for various Earth and glacier models, we have invoked the 3-D visualization system Amira (http://www.amiravis.com). Our file format allows to animate effectively time evolution of data fields on a moving curvilinear mesh, which spreads over outer and inner mantle boundaries and vertical mantle cross-sections. Two attached snapshots of the Amira movies show examples of normalized dissipative heating of the PREM model with a lower-mantle viscosity hill at the end of the instantaneous unloading of glaciers with rectangular (Fig. 1a) and parabolic (Fig. 1b) cross-sections.

Small-Scale Asthenospheric Convection and Cenozoic Extensional Tectonics of the Basin and Range Province, Western U.S.A.

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Cenozoic extension in the Western U.S. is broadly associated with widespread volcanism, high heat flow, extensive thinning or removal of mantle lithosphere, and uplift. While there is no universally straightforward temporal relation between the onset times of extension and volcanism in the basin and range province, these phenomena appear to be related to, or at least partly controlled by, dynamic processes occurring in the upper mantle. Because the mantle lithosphere is denser than the underlying asthenosphere, it is gravitationally unstable and may give rise to small-scale convective motions that result in lithospheric thinning, voluminous melt production, and high heat flow. Numerical simulations of this process, including the effects of melting, indicate that the occurrence of partial melting dramatically increases the propensity for small-scale convection. Two distinct styles of small-scale convection are observed in these models: 1) large amplitude (up to ∼300 K) sluggish convection that results in substantial convective removal of mantle lithosphere (the "drippy" mode), and 2) small amplitude (∼100 K) rapid convection which tends to leave the lithosphere largely intact (the "compact" mode). The occurrence of these two styles is regulated by the viscosity contrast between asthenosphere and lithosphere. The drippy mode occurs when the viscosity contrast is low (i.e. a soft mantle lithosphere), while the compact mode occurs when the viscosity contrast between lithosphere and asthenosphere is large (i.e. a stiff mantle lithosphere). Thus a drippy style of small-scale convection, producing silicic volcanism at the surface and resulting in substantial thinning of mantle lithosphere, is expected to accompany a "wet" mantle. A hot and "dry" mantle, on the other hand, would give rise to a compact mode of small-scale convection that will most likely produce effusive basaltic volcanism at the surface. A temporal transition from drippy mode small-scale convection associated with the mid-Tertiary ignimbrite flare-up and removal of the wet Farallon flat slab to a compact mode beginning at roughly mid-Miocene times appears to be a viable mechanism for unifying Cenozoic mantle and crustal dynamics in the Western U.S..

Small scale convection under the island arc?

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Recently Billen and colleagues (e.g. Billen et al. (2003)) extensively studied the subduction zones based on the dynamic modeling of subduction zones and proposed the existence of the low viscosity wedge (LVW), which may be produced by the water dehydrated from subducting slabs. Meanwhile, in northeast Japan, Tamura et al. (2002) found along-arc variations of distribution of volcanoes, low velocity anomalies and Bouger anomalies. They can be grouped 10 lineaments with a wavelength of ∼80 km, which are perpendicular to the trend of trench. They called these "Hot Fingers", since those features are suggestive of high temperature in the upper mantle. The morphology akin to this has previously been expected for small-scale convection beneath moving oceanic plates. We might expect such a small-scale convection under the back-arc, if the wedge mantle viscosity is low enough. This small-scale convection may be a possible origin of Hot Fingers. We explore this possibility using both 2-D and 3-D modeling with/without pressure and temperature dependent viscosity of wedge mantle. 2-D models without pressure and temperature dependence of viscosity show that, with a reasonable geometry of the LVW and subduction speed, the small-scale convection is likely to occur, when the viscosity of the LVW is less than 1019 Pa sec. Corresponding 3-D model studies reveal that the wavelength of rolls depend on the depth of the LVW. An inclusion of temperature dependent viscosity requires an existence of further low viscosity in the LVW, since temperature dependence suppresses the instability of cold thermal boundary layer. A pressure (i.e. depth) dependence combined with a temperature dependence of the viscosity produces a low-viscosity zone, and, thus, it promotes short wavelength instabilities. The model, which shows a relatively moderate viscosity decrease in the LVW (most of the LVW viscosity is 1018 - 1019 Pa sec) and the wavelength of roll ∼80 km, has a rather small activation energy and volume (∼130 kJ/mol and ∼4 cm^3/mol) of the viscosity. This small activation energy and volume may be possible, if we regard them as an effective viscosity of non-linear rheology.

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Mantle melting during continental breakup

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Despite the fact that volcanic rifted margins have been studied intensively for more than a decade, controversies over some of the most fundamental issues remain. Although details between different provinces vary, volcanic rifted margins generally show a short lived pulse of exteme magmatism that quickly abates to steady-state, plate-driven, mid-ocean ridge accretion. The generation of thick igneous crust requires either melting of hotter than normal mantle, or small scale convection so that larger amounts of mantle material are processed in the melting region than is the case for plate-driven passive flow. To assess under what conditions buoyantly driven upwelling (or small-scale convection) at rifted plate boundaries is important, we use a numerical model of convection based on the CITCOM code that incorporates feedback from melting on the physical properties of the mantle. The viscosity function is both temperature and pressure dependent, includes increases due to dehydration during initial melting, and decreases due to grain boundary sliding, which is enhanced by the presence of melt. Ignoring dehydration strengthening, we show that to induce significant small-scale convection and anomalous melt production, we must assume a viscosity structure that is inconsistent with steady-state oceanic accretion. Including the viscosity increase from dehydration does not fundamentally change this conclusion. It serves only to exacerbate the problem by suppressing buoyant upwelling above the depth to the dry solidus and restricting shallow flow to plate driven upwelling. This is critical since most melt is generated above this depth. Models that assume an abrupt change in prerift lithospheric thickness suffer the same deficits. The small scale convection induced is primarily below the depth of melting and does not lead to anomalous melt productivity. To produce a single volcanic pulse followed by plate-driven oceanic accretion, we require an exhaustable sublithospheric layer at the time of breakup. Although this layer could be a chemical anomaly of highly fertile mantle, a temperature anomaly seems more likely. Observations along SE Greenland can be matched if a 50 km thick layer with a ΔT 100–200 °C.

Asymmetric lithosphere extension: factors controlling rift mode selection

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To a large part extension of the crust and mantle lithosphere is accommodated by brittle faults and viscous shear zones. In previous work we have focused on the roles of frictional-plastic and viscous strain softening and surface processes in generating asymmetry at the lithosphere scale during extension. Here the focus is the behaviour of simple two-layer models with a frictional plastic strain-softening layer overlying a uniform viscous layer. We use estimates of the rate of energy dissipation and forward numerical mechanical modelling to investigate factors that lead to different styles of extension. Our focus is the behaviour of simple two-layer systems with a frictional- plastic strain-softening layer overlying a uniform viscous layer.

We derive criteria that control mode selection by comparing the respective rate of dissipation for each rifting mode. The mode with the least dissipation is favoured. The primary controls are the relative rates of dissipation in the frictional-plastic and viscous layers. The dissipation in the plastic layer is determined by the yield strength and its strain dependence, both of which are independent of velocity. The dissipation in the viscous layer is partly determined by the viscosity and the strain rate, and is, therefore, dependent on the rifting velocity. The remaining control is the traction coupling between the layers.

The dissipation analysis predicts that at low viscous stresses, arising from low viscosities and/or low extension velocities, the fundamental asymmetry promoted by the strain softening frictional-plastic layer is fully expressed and rifting of the lithosphere may be asymmetric. At higher viscous stresses this tendency is suppressed and symmetric or pure shear lithosphere extension is predicted. The results from the forward mechanical models are well in agreement with the dissipation analysis.

Factors controlling slab roll-back and back-arc extension

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Although subduction is a first order plate tectonic process, the factors controlling the dynamics of slab roll-back and back-arc formation are still not very well understood. The major driving forces for subduction and slab roll-back are well established as the slab pull (Fsp) and ridge push (Frp) forces, their relative importance and the relative importance of forces modifying and interacting with these driving forces is, however, not very clear. A number of forces may resist subduction and roll-back of the slab. 1) Normal and tangential forces resisting downwelling of the slab (Fn, Fs), 2) Bending resistance in the slab at the trench and at the 660 km discontinuity (Fb), 3) Resistance to lateral flow of the upper mantle below and above the subducting slab. To investigate the relative contribution of these resisting forces we use 2D plane strain thermo-mechanical finite element models. The model evolution is calculated using an Arbitrary-Lagrangian-Eulerian (ALE) method for the finite element solution of incompressible viscous-plastic creeping flows (Fullsack, 1995).

In a first set of models we test the relative roles of bending resistance (Fb) and upper mantle viscosity (i.e. Fn, Fs) with a subducting plate where an overlying plate is not included. The models extend from the surface to 660 km depth. The upper surface of the model is free to move. Upper mantle rheology is linear viscous, whereas the rheology of the subducting slab is either linear viscous or combined linear viscous and von Mises plastic. Reflective and periodic boundary conditions are used. The slab is allowed to sink in the underlying mantle under its own weight. The results are very similar to recent analogue studies of Faccenna (2001) and Funiciello et al. (2003). The models indicate that the resisting forces (Fn, Fs) form the primary control on the rate of subduction and roll-back where the velocity of trench retreat depends linear on the viscosity of the upper mantle. Variation of roll-back with viscosity of the subducting slab is minor. Interaction of the slab with the 660 km discontinuity results in a small, $< 5\,\%$, decrease in roll-back velocity. This suggests a subordinate role of bending forces. The results are compared with a scaling analysis of relative importance of contribution forces.

In a second set of models we investigate interaction of the subducting slab with the overlying plate and specifically focus on factors that may control the opening of a back-arc basin. The down going plate is driven by a kinematic boundary condition, far from the zone of subduction. After an initial stage of far-field driven contraction, the negative buoyant down welling of the mantle lithosphere may drive continued formation of the subduction zone leading to mature subduction. The models suggest that two major factors control whether the subducting system develops an extensional back-arc system: 1) The relative contribution of the imposed far-field velocity and roll-back velocity, 2) The strength of the overlying plate. We investigate the roles of small scale convection, enhanced by corner flow above the subducting plate, and far field plate velocity on the opening of the back arc basin.

Penetration of mantle plumes through the lithosphere

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The interaction between thermal mantle plumes and lithosphere is still poorly known and controversial. Different models are necessary to explain the complexity of their effects on Earth. Two different types of lithosphere exist : oceanic and continental lithospheres. They differ by their viscosity, density and thickness. Continental lithosphere is thicker, chemically different and therefore more viscous and less dense. In order to quantify the effect of these differences, we have developed an experimental approach to the problem: two layers of fluid with different density and viscosity are superimposed in a tank. The thermal plume is then suddenly generated by a point source of heat at the base of the tank. We study the effects of the power input of the heater, the density difference, the viscosity ratio, and the thickness of the layers.

We follow the thermal structure of the flow with thermocouples and we film the evolution in time of the interface between the two fluids. We also measure the height and width of the plume intrusion into the upper layer. Experiments show that the flow reaches a quasi permanent state where the height of the intrusion and the temperature at the axis of the plume are constant. At constant viscosity ratio, there are two end-member cases: (1) horizontal spreading of the plume at the base of the lithosphere or (2) upward penetration through the lithosphere. It is therefore important to characterize the degree of penetration of the plume which is controlled by two parameters: the buoyancy number and the viscosity ratio.

We also perform numerical simulations with the program STAG3D developed by Paul Tackley. We solve the equations governing the convective motion in a noncompressible viscous fluid and use active tracers to model the upper layer which is chemically less dense and more viscous. Simulations allow to vary all the parameters in a wide range and show a good agreement with experiments.

— INVITED —
Building the bridge between seismic anisotropy and upper mantle convection

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The interpretation of seismic anisotropy in the mantle requires a knowledge of the relationship between the lattice preferred orientation (LPO) of crystals and the convective flow field. In order to understand this link, one needs a model for the evolution of LPO in olivine aggregates that deform by both intracrystalline slip and dynamic recrystallization. In this presentation, we will first give a review of the pioneer works on the subject and will then focus on the most recent advances dealing with dynamic recrystallization.

Deformation mechanisms are the corner stone of any theory on LPO development. Dislocation creep is responsible of the development of LPO by slip on slip systems and induced rotation of the crystallographic axes. To calculate the plastic deformation of the crystals, three families of model are available: stess equilibrium based, strain equilibrium based, and kinematic ones. All the models predict that the LPO due to plastic deformation follows the finite strain ellipsoid (FSE).

For large deformation, an extra deformation mechanism is triggered: dynamic recrystallization. This process depends on the dislocation density of the grains, which is a function of the applied local stress and of the rate of nucleation in the grains. Depending on their density of dislocations, grains will grow or shrink so to minimize the strain energy of the aggregate. A new LPO then appears, related to the orientation of the grains with the lower density of dislocations.

Models of LPO development are constrained by observed LPO patterns in experimentally deformed olivine aggregates and by the temporal evolution of the strength of the LPO. The plastic flow/recrystallization models can then used to study systematically the relationship between olivine lattice preferred orientation (LPO) and the mantle flow field that produces it.

Numerical solutions for the mean orientation of an initially isotropic aggregate deformed uniformly show that the LPO evolves in three stages: (1) for small deformations, recrystallization is not yet active and LPO follows the FSE; (2) for intermediate deformations, the LPO rotates towards the orientation corresponding to the maximum slip on the softest slip system; (3) for large deformation, LPO is controlled by plastic deformation and rotates towards the orientation of the long axis of the finite strain ellipsoid corresponding to an infinite deformation (the "infinite strain axis" or ISA). In more realistic nonuniform flows, LPO evolution depends on a dimensionless "grain orientation lag" (GOL) parameter, defined locally as the ratio of the intrinsic LPO adjustment time scale to the time scale for changes of the ISA along pathlines in the flow. Explicit numerical calculation of the LPO evolution in simple fluid dynamical models for ridges and for plume-ridge interaction shows that the LPO aligns with the flow direction only in those parts of the flow field where GOL parameter is much smaller than 1. Calculation of this parameter provides a simple way to evaluate the likely distribution of LPO in a candidate flow field. Dense seismic data are required in area with high values of the GOL parameter, in which the comparison to the prediction is both more complex and more informative.

Eulerian spectral/finite difference method for large deformation modelling of visco-elasto-plastic geomaterials

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[2] *Geomodeling Solutions GmbH, Zürich, Switzerland*

Many problems that occur in geodynamics can be reduced to the solving of visco-elasto-plastic rheological equations. Here a spectral/finite-difference method is described that can deal with these rheologies in an eulerian framework. The method approximates derivatives in vertical direction by finite-differences and in horizontal direction(s) by a pseudospectral approach. Material boundaries are tracked by marker chains that are moved through a fixed eulerian grid and allow large deformations. It is demonstrated that the Gibbs effect is avoidable, the method is reliable up to large viscosity contrasts of 5x105 and is able to resolve strongly localised solutions like shear bands. Examples that are given range from folding instabilities, to mohr coulomb plasticity and viscoelastic convection.

The accomodation of volume changes in Phase transition zones; implications for mantle dynamics

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The change of volume associated with phase transitions needs to be accompanied by creep. Otherwise, a pressure anomaly impeding the phase change is induced. Phase transformations in mantle flows are therefore delayed by this process. The delay depends upon the thickness and the local viscosity of the zone of phase transition and is associated with deflections of the transition zone which tend to hamper the flow. This phenomenon is studied, first with the help of a simple analytical model, then for harmonic load functions in a self-gravitating mantle. This process is shown to be potentially important (deflections of the 670km discontinuity by several km) but only if transformational plasticity does not take place within the phase transformation zone.

This effect can also occur on a microscopic scale as it hampers grain growth. We show that it can induce a deflection of the phase transition zones by several kilometers even in the case of non-newtonian rheologies.

The role of crustal properties in the slab detachement

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Numerical models of subducting processes usually glance over the detachement of the subducted oceanic plate from the continental one. In fully dynamic models the detachement of the plates is achieved by prescribing a fault [e.g. van Hunen et al. 2000, Billen and Gurnis 2001, Cizkova et al. 2002]. These models demonstrate well that sinking plate is driven by the buyoancy force. On the other hand, kinematic models deal with prescribed velocity of the slab to obtain the temperature distribution of the subducted slab [e.g. Ponko and Peacock 1995] and to study phase changes in the deeper part of the subduction. Recently, the third group of models takes place: the velocity and the dip angle of the subduction remains prescribed, but in the overlying mantle wedge the fully dynamic problem is solved [van Keken et al. 2002, Gerya and Stockhert 2002].

We present a different model, where both the temperature and the velocity field as well as the shape and the position of the boundary-line between the plates are the outputs from the modeling. The model is based on the stream function formulation that easily enables the stratification of the inflowing oceanic lithosphere. Due to a viscosity dependent on the stream function, the problem is strongly nonlinear and an iterative process is used to obtain the solution. The temperature field is calculated using the heat transfer equation with the dissipation term in the whole box, which can lead to some problems with convergency. Such problems can be overcome by introducing adaptive iteration scheme:

$$X_i = K_x(i)X_{i-1} + (1 - K_x(i))X_i$$

where X_i denotes quantity (temperature, stream function, stress) in the i-th iteration and $K_x(i)$ is the function of the iteration number specific for each quantity.

We present the steady-state solution in the box 300 x 100 km with different creep properties of the lithosphre and the oceanic crust. Composite rheology including both dislocation and diffusion creep is used; the non-viscous behavior of the crust and the lithosphere is modeled by introducing the yield stress [Tackley 1998]. The ouput from the modeling gives some constraints on the magnitudes of the yield stresses - the dip of the lithosphere is proportional to the ratio between the yield stress in the crust and in the lithosphere. The subduction plate with dip about 45 degrees requires the crustal yield stress to be 10-100 times smaller than the yield stress of the lithosphere. Such a decrease can be caused by high water content [Escartin et al. 2001].

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Mass balance of the subducted slab under the Central Andes, dynamic topography and its isostatic implications

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A comparison of this observed mantle residual gravity anomaly with that predicted by simple thermal models of the subducted Nazca plate under the Central Andes shows that the modelled gravity anomaly from the subduction process appears to be substantially greater than that observed by approximately 125 mgal. Key uncertainties in the prediction of the gravity anomaly from a thermal model of the subducted slab arise from uncertainties in the thermal expansion coefficient, and subduction geometry and dip. Sensitivity tests to model parameters show that the discrepancy between observed and modelled gravity anomaly may be as great as 300 mgal or as little as 40 mgal. This discrepancy between observed and modelled mantle gravity anomaly beneath the Central Andes may be resolved by the inclusion of other subduction related mass anomalies, in addition to that of the cold descending Nazca plate, as suggested by geophysical observations and thermo-dynamic considerations. Dynamic fluid flow modelling of the preferred mantle density model predicts a dynamic subsidence at the base of the Central Andean crust that deviates the crust from local isostasy by as much as 6–10 km and 4–6 km in the Eastern and Western Cordilleras respectively. The inclusion of this dynamic subsidence in the determination of the observed residual gravity anomaly greatly improves the fit between observed and predicted mantle residual gravity anomalies from the mantle over the Central Andes. This suggests that dynamic topography and the depression of the Moho beneath the Central Andes may be important in compensating part of the mass excess arising from the cold subducting slab. Apart from the slab itself, the most important body affecting the wavelength and amplitude of the dynamic topography is the asthenospheric wedge.

Viscosity and S-wave Conversion Factor for the Earth's Mantle based on CHAMP Gravity Data and New Tomography Models

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The viscosity structure and the internal buoyancy forces of the Earth's mantle are essential for understanding the convective flow pattern. These buoyancy forces are directly related to density inhomogeneities. With the use of seismic tomography it is possible to determine the seismic velocity distribution in the Earth - but the conversion factor between the seismic velocity and density is still not properly known. This is mainly due to uncertainties in the chemical composition of the mantle. If the origin of lateral heterogeneities in seismic wave velocity is purely thermal, the conversion factor should be around 0.2 to 0.4 as deduced from mineral physics. However, recent studies to relate mantle dynamics and gravity data reported even negative values for the conversion factor in the uppermost and lowermost mantle. For the uppermost mantle this finding has been explained by depletion in iron during partial melting.

In the presented study we solved the equation of motion for an incompressible, self gravitating 6-layer shell and determined the response function for geoid, dynamic topography, and surface velocity (which can be compared to the poloidal part of plate velocities). The internal load was determined from 4 different tomography models (sb4l18, Masters et al., 1999; s362d1, Gu et al., 2001; s20rts, Ritsema & van Heijst, 2000; saw24b16, Megnin & Romanowicz, 2000). In a large Monte Carlo search we determined models with a correlation $> .87$ between the synthetic geoid and the CHAMP hydrostatic geoid for $L < 16$. Successful models show small, but not negative conversion factors in the upper 300 km and a roughly constant value of $\sim$0.28 below. The viscosity is slightly reduced (compared to the scaling value of 10^{21} Pa·s) in the asthenosphere and even stronger reduced in the mantle transition zone between 410 and 670 km where major changes in mineral geometry occur and the release of water was recently proposed in the upper part of the transition zone. Resolution for both, viscosity and conversion factor, is poor below the transition zone down to about 1500 km, but well confined in deeper parts of the mantle. Here we find a viscosity between 30 to 40 $\times 10^{21}$ Pa·s and a conversion factor of 0.28 to 0.32.

Variable thermal conductivity in subducting slabs: olivine metastability and the mechanisms of deep earthquakes

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The mineralogical make-up of subducting lithosphere is highly dependent upon its thermal state. This, in turn, is a function of the thermodynamic, kinetic, and heat transport properties of the minerals making up the lithosphere. Our understanding of slab mineralogy is therefore dependent upon accurate experimental measurements of these data, particularly for the polymorphs of $(Mg,Fe)_2SiO_4$. The first have been available for quite some time; the second have progressed from analogue systems of Ni_2SiO_4 and Mg_2GeO_4 (e.g., Rubie and Ross, 1994) to recent refinements of the kinetics of $(Mg,Fe)_2SiO_4$ phase transitions themselves (Mosenfelder et al., 2001). As the last have been, until recently, lacking, subduction zone models used constant values of thermal conductivity, isobaric heat capacity, and density in solving the heat flow equation (e.g., Minear and Toksz, 1970; Kirby et al., 1996). Hofmeister (1999) developed a model of thermal conductivity for mantle minerals as a function of pressure and temperature based on phonon lifetimes. In turn, Hauck et al. (1999) incorporated this model into thermal models of subducting slabs. Their results predicted that slowly subducting (< 8 cm/yr) slabs would be slightly cooler and faster/steeply-dipping slabs would be warmer than slabs with constant conductivities. There are now, however, high P and T measurements of the thermal diffusivities of San Carlos olivine, wadsleyite, and ringwoodite (Xu et al., 2003) that allow more realistic thermal conductivities to be used in thermo-kinetic models of subducting slabs.

Mineralogy is computed in subducting slabs using the thermodynamic data of Fei et al. (1991) for the MgO-FeO-SiO_2 system and the model of olivine transformation kinetics of Mosenfelder et al. (2001) in which growth is assumed to be rate limiting. Latent heats of transformation are fed back into our model, significantly affecting the extent of olivine metastability (Daessler and Yuen, 1993; Devaux et al., 1997; Marton, 2001). A simplified single-component system is used with a fixed composition of Fo_{90} that results in univariant phase boundaries, i.e. without two-phase loops, and the occurrence of the $\alpha \rightarrow \beta$ transition at shallower depths than the $\alpha \rightarrow \gamma$ transition at low temperature. Temperatures are computed via a finite difference algorithm (Minear and Toksiöz, 1970) that solves the heat flow equation using the conductivities from the experimental work of Xu et al. (2003). A plate model with the GDH1 parameters (Stein and Stein, 1992) was used for the initial lithospheric temperature distribution. Mantle temperatures at depths below the lithosphere were determined by using a geothermal gradient of 0.27 °C/km.

Simulations were done on 25 slabs in three groups with thermal parameters (ϕ = vertical subduction rate × age of lithosphere at the trench) (Molnar et al., 1979) ranging between 3500–17000 km. When only lattice conductivities were used, cross-sectional areas of the metastable olivine wedges do not change much when compared with models run with fixed conductivities of 3.138 W/mK (Stein and Stein, 1992). Slabs that have significant wedges with fixed conductivity have reductions of no more than 5 %. In terms of the maximum depths of the wedges, there is practically no change at all in slabs which are moving slow enough for heat to be conducted in, thus enhancing the phase transitions and preventing wedges from extending past 475 km. The wedges of slabs which are subducting more rapidly extend to depths 5-15 km shallower than in fixed-conductivity models. When radiative transfer is included, the results are significantly different. The cross-sectional areas of the wedges shrink by 20–30 % for all slabs. This translates into metastable olivine wedges that extend to depths 30–50 km shallower than those for fixed conductivity slabs, with the differences increasing with ϕ. These results agree with the results of Hauck et al.'s (1999) thermal model.

The presence of deep earthquakes, between 300 and 700 km, contained within sinking slabs, suggest that the slab material should be colder, denser, and stronger than the surrounding mantle material, a supposition supported by observations of the maximum depth of earthquakes increasing with increasing thermal parameter and hence decreasing temperature inside the slab (Molnar et al., 1979). The correspondence of deep earthquakes with the cold interiors of the subducting slabs suggests an association with the kinetically inhibited olivine phase transformations. One suggested mechanism for the earthquakes is faulting occurring along superplastic aggregations of β or γ in the slabs (transformational faulting) (Kirby, 1987; Green and Burnley, 1989). If this is the mechanism responsible for deep earthquakes then the metastable olivine must extend at least to the maximum depths of deep seismicity. However, thermal erosion of metastable wedges in our models indicate that the olivine should be completely transformed well before the depths of deepest seismicity. This indicates that for deep earthquakes, other mechanisms should be considered.

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The influence of the large-scale mantle flow field on the interaction of the mid-Atlantic ridge and the Iceland plume

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The interaction of the Iceland plume with a global mantle flow field is investigated by 3D numerical models. The approach consists of two steps. First the large-scale mantle flow field was calculated in a global modal, which includes the whole volume of the mantle. This global and robust flow field served as a background flow in the regional model, in which the interaction of the mid-Atlantic ridge and the Iceland plume was calculated.

A time-dependent model of the large scale mantle flow field was obtained by using paleogeometries of the Atlantic and Eurasian plates reconstructed from magnetic anomalies [1] and by advecting density anomalies backward in time. The motion of the plume source on the bottom of the model box is calculated according to the distortion of an initally vertical plume conduit in the large-scale mantle flow field [2]. In the regional model the changing large-scale flow field and the moving plume source are introduced as time dependent boundary conditions. In this way, the interaction of the Iceland plume and the mid-Atlantic ridge is investigated in a 3D model containing detailed ridge geomtery.

Results with time independent boundary conditions show that the large-scale mantle flow field is an important factor which controls the development of the plume. In the regional model the plume is tilted in the upper mantle, which is also shown by seismology. However, the northward channeling of the plume material in the model does not explain the geochemical anomalies, which show an increased plume influence south of Iceland.

Simulations with time dependent boundary conditions (time dependent ridge geometry and plume source position) may modify this channelling of plume material and give a more precise view of plume-ridge interaction

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Clustering of plumes and small-scale convection in the upper mantle: consequences of lower-mantle plume dynamics

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The clustering of plumes in the South Pacific and evidence for small-scale upper-mantle convection are longstanding issues in geodynamics, which have been around for a long time. These features may be explained by considering the interaction of the upper-mantle flow structures to the lower-mantle plume dynamics. The key to this problem is the presence of a low-viscosity channel in the vicinity of the 660 km phase transition. We have employed high-resolution 3-D spherical shell convection model in which PREM like density has been used along with other depth-dependent thermodynamic and transport properties, such as the Grueneisen parameter, thermal expansivity and viscosity. We have imposed an endothermic phase change at 660 km depth with a Clapeyron slope of 3 MPa/K. We have examined a suite of viscosity profiles, ranging from constant viscosity to complicated depth-dependent viscosity profile with a viscosity peak in the mid lower-mantle (Mitrovica an Forte, 2002) and a low viscosity zone in the vicinity of the 660 km transition zone, first noted by Kido and Cadek (1997). We have employed 256 points in the radial direction and 256 spherical harmonics, which can resolve all of the small-scale features, generated in the flow in which the total power emanated from the mantle is around 35 TW and is internally heated with a strength about two times the chondritic abundance. The two features of clustering of plumes and small-scale (Richter-like) rolls are manifested only in the models in which a low viscosity zone around 660 km depth is present. They are absent in all other viscosity models. In the figure below we show the lateral thermal anomalies associated with the lower mantle which is bared to visual inspection (left panel). This panel can be contrasted to the right panel in which the lower mantle is now covered by an opaque veil at 660 km depth. These results show clearly the dynamical consequences in the upper-mantle features from interacting with the lower-mantle dynamics. Both clustering of plumes and small-scale convection in the upper mantle can be observed simultaneously in the bottom panel. These results underscore the dynamical importance of the presence of a low viscosity zone under 660 km, which can be caused by grain-size reduction due to phase transition or lubrication by impinging hot lower-mantle plumes which fail to penetrate through the 660 km phase change

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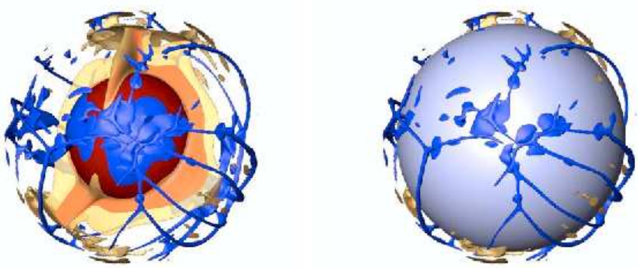

— INVITED — Finite-frequency tomography reveals a variety of plumes in the mantle

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Morgan (1972) proposed that hotspots are due to plume-like upwelling from the lower mantle. Despite the abundance of evidence in support of Morgan's idea, there is another current of thinking that believes hotspots originate from the upper mantle as a by-product of plate tectonics (Anderson, 1998, 2000; Foulger & Natland, 2003). Seismic tomography has been so far unable to detect such narrow deep rooted features. If plumes would appear in seismic tomographic images, we would finally have a direct visual verification of the plume theory, and we will have a mean for determining their origin in the mantle.

Our first global finite-frequency tomography of compressional waves shows unambigous evidence that at least 5 hotspots originate in the deep lower mantle: Hawaii, Easter Island, MacDonald, Samoa and Tahiti, and suggest that few others, such as Kerguelen and Cape Verde might be connected to the core-mantle boundary (Montelli et al., 2003). Major hotspots which do not seems connected to a deep lower mantle plume include Afar, Ascension, Galapagos, Kilimanjaro, Madeira, Reunion and Tristan. These seem to originate in the mid mantle. Iceland originates at a shallow depth, confirming the results of Ritsema et al. (1999); Foulger & Pearson (2001); Foulger et al. (2001) and Foulger (2003) and clearly contradicting the finding of Bijwaard & Spakman (1999), who proposed a plume extending all the way to the core-mantle boundary. Thus, what was the problem with the previous tomographic studies?

Almost all global P-wave tomographic models have been so far obtained by applying the approximation of ray theory. The traveltime is only in by the Earth's properties along an infinitesimally narrow path that follows Snell's law. This simplifies the mathematics, but it is quite far from physical reality, in which rays have a given thickness depending on the frequency content of the propagated wavefield. The traveltime of a finite-frequency wave is sensitive to velocity structure off the geometrical ray within a volume known as the Fresnel zone. Classical ray theory predicts that even a small heterogeneity on the raypath would in the traveltime. But physics teaches us that small scale objects do not really in the propagation of waves. They only do when their scale length is comparable to the width of the Fresnel zone. Dahlen et al. (2000) and Hung et al. (2000) show that a broadband P traveltime is sensitive to anomalies in a hollow banana-shaped region surrounding the unperturbed path, with the sensitivity being zero on the ray. The banana-doughnut kernel is thinner near the source and receiver but the cross-path width extends up to about 1000-1300 km near the turning point, where the region of insensitivity around the geometrical ray can reach hundreds of kilometers. Because of the minimax nature, surface reflected PP waves show a much more complicated shape of the sensitivity region, with the "banana-doughnut" shape replaced by a "saddle-shaped" region region upon passage of a caustic. Not surprisingly, the introduction of such complicated sensitivity has consequences for the final tomographic images. Mantle plumes are narrow and therefore the most affected by an inappropriate modeling of finite-frequency effects. Because of their size, plume tails could partially be hidden in the region of insensitivity around the unperturbed ray. Wavefront healing is neglected by classical ray theory, but is properly accounted for in our finite-frequency modeling; this enhances the capability to detect such Earth's structures.

We present the final results of our inversion of finite frequency P, PP and pP waves with a dominant period of 20 s, whose travel time sensitivity kernels are modeled by using the formalism derived by Dahlen et al. (2000); combined with short period P and pP extracted from the ISC data set (Engdahl et al., 1998) modeled by using standard ray theory. The velocity structure is sampled using an irregular distribution of points to form a Delaunay mesh (Watson, 1981, 1992; Sambridge et al., 1995). Node spacing is adapted to the expected resolving length of our data and ranges from about 200 km in the upper mantle to about 600 km in the lower mantle. This gives an additional improvement in the tomographic images.

An anisotropic viscous representation of Mohr-Coulomb failure

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In mantle convection models it has become common to make use of a modified (depth sensitive, Boussinesq) von Mises yield criterion to limit the maximum stress the lithosphere can support. This approach allows the viscous, cool thermal boundary layer to deform in a relatively plate-like mode even in a fully Eulerian representation. In large-scale models with embedded continental crust where the mobile boundary layer represents the oceanic lithosphere, the von Mises yield criterion for the oceans ensures that the continents experience a realistic broad-scale stress regime.

In detailed models of crustal deformation it is, however, more appropriate to choose a Mohr-Coulomb yield criterion based upon the idea that frictional slip occurs on whichever one of many randomly oriented planes happens to be favorably oriented with respect to the stress field. As coupled crust/mantle models become more sophisticated it is important to be able to use whichever failure model is appropriate to a given part of the system.

We have therefore developed a way to represent Mohr-Coulomb failure within a code which is suited to mantle convection problems coupled to large-scale crustal deformation. Our approach uses an orthotropic viscous rheology (a different viscosity for pure shear to that for simple shear) to define a prefered plane for slip to occur given the local stress field. The simple-shear viscosity and the deformation can then be iterated to ensure that the yield criterion is always satisfied. An additional criterion is required to ensure that deformation occurs along the plane aligned with maximum shear strain-rate rather than the perpendicular plane which is formally equivalent in any symmetric formulation.

It is also important to allow strain-weakening of the material. The material should remember both the accumulated failure history and the direction of failure. We have included this capacity in a Lagrangian-Integration-point finite element code and will show a number of examples of extension and compression of a crustal block with a Mohr-Coulomb failure criterion. The formulation is general and applies to 2D and 3D problems, although it is somewhat more complicated to identify the slip plane in 3D.

On the curvature of oceanic arcs

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The key feature of plate tectonics is the subduction of cold oceanic plates into a hot convective mantle. These subducting plates, as seen from the surface, mostly portray a distinct concave arc shape at the trench with respect to the leading edge of subduction. The origin of arc curvature is not yet understood. A common belief is that it is probably an effect of the Earth's sphericity. However, the spherical effect of the Earth creates convex, long-wavelength arc shapes. We thus investigate whether concave arc curvature can be explained by: (1) Exogenic feedback between the migrating lithosphere and the secondary induced mantle flow, (2) Endogenic heterogeneities within the lithosphere itself, e.g. owing to differences in cooling ages of the plate at the trench. Although both mechanisms create concave arcs, for isolate subduction systems, only the endogenic effects are sufficient to explain the magnitude of observed arc curvature. We compare our results to the Aleutian and Sandwich arcs.

Our method is based on a novel 3-D numerical tool. We model the subduction process as a solid (lithosphere) - fluid (mantle) interaction. Two different numerical methods are used to solve for the constituents: Implicit Finite Element (FEM) for the lithosphere and Implicit Boundary Elements (BEM) for the mantle. This joint approach extends the 2-D setup of Funiciello et al., (JGR, 2003) into 3-D by adding the BEM solution as a semi-analytical solution for the mantle drag. The BEM solution builds on the Stokeslet theory, which shows that the drag force mainly depends on the integration of the singularities at the extremities of the slab. A short summary of the Stokeslets theory and its possible application in geodynamics is given.

The effect of the stress field on the melt channel instability

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We investigate melt transportation in partially molten rocks under different stress fields above the head of a mantle plume or beneath a spreading mid-oceanic ridge. We model such aggregates in a 2D-FD code by means of a porous deformable matrix with melt under the influence of a given stress field to clarify the following key questions:

- Could channeling occur in a matrix containing a random melt distribution under a given stress field?
- Which orientation does it take?
- Is it possible to achieve a focusing of melt towards a MOR (dykes)?
- Does applying simple or pure shear to the matrix result in a difference in the formation and orientation of channels?
- How does the channel instability evolve during finite simple shear?

Numerical solution of the problem

The 2D-FD code FDCON [1] solves the relevant fluid-dynamic equations (conservation of mass and momentum, according to McKenzie [2]) for melt and matrix respectively.

These equations are solved assuming the Compaction Boussinesq Approximation (CBA), using a stream function formulation for the momentum equation and an ADI scheme with upwind for the energy equation. For the time being, the calculations are isothermal, so the energy equation is not solved. Lately, the conservation of water has been included and is presently being tested.

The boundary conditions in the code are: Pure shear with free slip and simple shear with no slip.

The initial porosity field consists of a random distribution of $3.5 \pm 0.6\,\%$ porosity.

Melt Channel Instability

In a deforming partially molten aggregate, weakening of the solid matrix due to the presence of melt creates an instability in which melt is localized by the following mechanism: regions of initially high melt fraction are areas of low viscosity and pressure, so that melt is drawn into these regions from higher pressure surroundings. This further enhances the melt weakening, producing a self-excited localization mechanism [3].

Results and Conclusions

The channeling developing (under the conditions of simple shear) in a random melt distribution shows that melt is accumulated preferably in inclined channels. For both, simple as well as pure shear, the growth rate is highest for an orientation parallel to the direction of the maximum compressive stress and proportional to applied stress and the reverse of the Melt Retention Number.

This also confirms the theoretical growth rate found by Stevenson [3].

Comparing different viscosity rheologies [1,2,4], we are able to clarify the influence of the CBA. The CBA influences only the growth rate at high wave numbers in the way of shifting them constantly to higher values.

In the isothermal models we found that the influence of water reduces the growth rate. However Hall's models [5] with water and constant melting rate show higher growth rates, which suggests it may play a major role.

Under simple shear melt channels evolve from an irregular melt distribution at angles of 45 degrees to the direction of shear. Upon further straining they rotate out of the orientation of maximum growth rate and partly disrupt.

We further seek to clarify which physical quantities may affect the orientation of channels and their wavelengths. Possible factors are the compaction length and the nature of the stress field. The latter assumption will be tested combining pure and simple shear and defining different stress gradients.

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Effects of magnetic field and radioactive heating in the core on thermal evolution of the convecting mantle and core

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A couple of our previous studies have investgated the availability for parameterized convection models in the heterogeneous mantle and possible scenarios of thermal evolution of the core by using the heat flux through the CMB which is estimated from complicated mantle convection model [Nakagawa and Tackley 2002, AGU Fall Meeting; Nakagawa and Tackley, 2003, IUGG General Assembly]. In recent progress of thermal evolution of the Earthś core, the importance of radioactive heat source in the core and heating by magnetic field (ohmic dissipation) is focused on by various researchers [Labrosse, 2003; Buffett, 2002; Buffett, 2003; Gubbins et al., 2003]. In this study, several preliminary results obtained from thermally coupled model between convecting mantle and core including ohmic dissipation in the core are showed for proposing other possible scenarios of thermal evolution of the Earthś interior.

Numerical model of mantle convection is based on Tackley and Xie[2002], which includes material differentiation, multiple phase change, plate-like behavior and partial melting. Thermal evolution of the core as a bottom thermal boundary condition of mantle convection is based on Buffett [2002], which includes compositional convection, inner core growth and ohmic dissipation.

Three criteria for possible thermal evolution are checked in this study: (1) Radius of the inner core, (2) Surface heat flux and (3) Heat flux through the CMB. In addition to these criteria, the ohmic dissipation as a function of time is also checked for understanding the magnetic evolution of the Earth's core.

Geodynamic interpretation of temporal geoid variations

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Introduction

Density distributions derived from highly resolved seismic tomography and viscosity models of Earth's mantle are investigated in analytical and numerical flow models. The aim of this project is to fit the models' predicted observables to the GRACE satellite-mission's gravity and geoid measurements and the field's variation with time, with special focus on lateral variations of the viscosity in the region of the lithosphere and asthenosphere.

Advection of a given density field yields temporal variations in the geoid and dynamic topography. In order to investigate whether identifiers of such mantledynamic processes may be discerned from other signals contained in GRACE-data, these quantities will be analyzed in the spatial and spectral domain. This permits predictions for regional mantledynamic contributions and renders variations of the harmonic coefficients with time, thus providing corrective fields to apply to GRACE-data.

Modelling

Advection of mantle density distributions derived from seismic tomography drives a flow.

The variables of the governing flow equations are expressed in terms of products of radial functions and scalar spherical harmonics, yielding a set of coupled first order differential equations. Spheroidal and toroidal terms decouple, the initial solutions for a set of boundary conditions are propagated through a series of shells of constant values for the sought variables by the propagator matrix [Panasyuk and Hager, 1996]. This in turn yields solutions in the form of boundary vectors that give the fluid velocities, stresses, gravitational potential and its radial derivative at any radial level in the earth.

We plan to implement lateral viscosity variations into our analytical code [Zhang and Christensen, 1993]. While they report no significant improvement of the geoid fit, allowing for lateral viscosity variations within the lithosphere and asthenosphere yielded best fits according to most recent publishings [Cadek and Fleitout, 2003].

Temporal geoid variations

Advection of tomography-based mantle densities yields first estimates of the magnitute of temporal geoid variations. Additionally, we determine the signal's change caused by subducting slabs or mantle plumes employing geoid kernels. Geoid kernels represent the geoid produced by a unit mass anomaly of a given wavelength at a given depth, including the effects of dynamic topography. The geoid anomaly δN_{lm} caused by any assumed density distribution in the mantle is obtained by a convolution of these kernels with the density field [Turcotte et al., 2001]. Advection of a density distribution (substituting $\delta\rho$ with the equation of state for incompressible fluids) with a vertical velocity of v_z yields the temporal geoid variation

$$\frac{\partial \delta N_{lm}}{\partial t} = \frac{4\pi G r_e}{(2l+1)\,g} \int_{r_c}^{r_e} \frac{\partial G_l(r)}{\partial r} \alpha \rho_0 \delta T_{lm} \delta r v_z. \qquad (1)$$

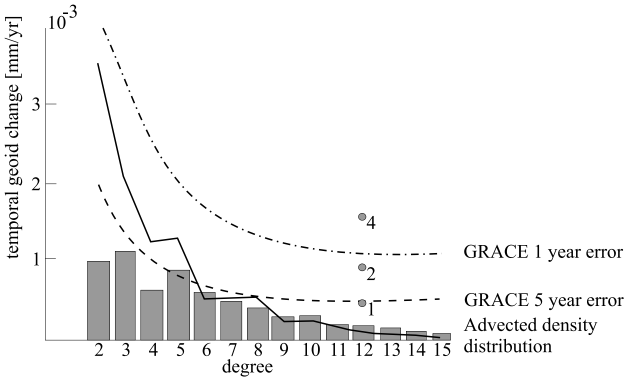

Fig. 1: Expected resolution of temporal geoid changes for a 1 - and 5 - year GRACE mission duration and an estimate of geoid variations for mantledynamic processes. The latter were calculated with a slab sinking model (Marquart, pers. comm.) (*bars*), estimated using eq. (1)

(*dots*) and obtained by advecting density distributions derived from seismic tomography (*solid line*).

Conclusions

Mantle-dynamic processes produce time-dependent geoid signals which, according to preliminary results, reach or exceede the resolution limits of the 5 - year GRACE mission. While the results shown are preliminary, an iterative search of the parameter space should yield models of good fit to the observed geoid and its variation. Estimates of the models' dynamic topography provide an additional constraint.

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Constraining Venus structure by gravity and topography: global methods

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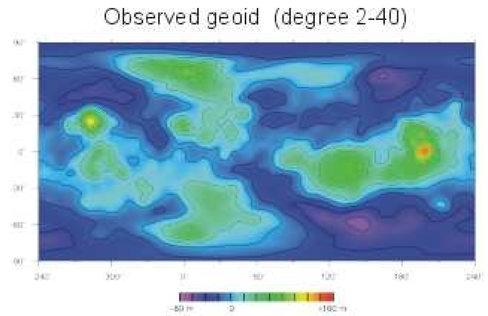
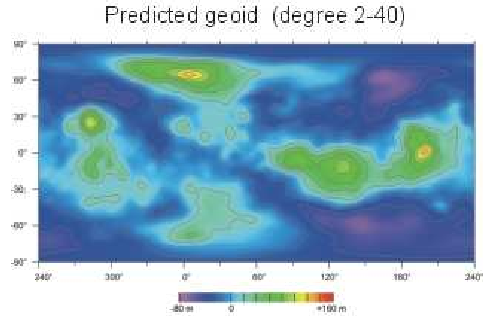
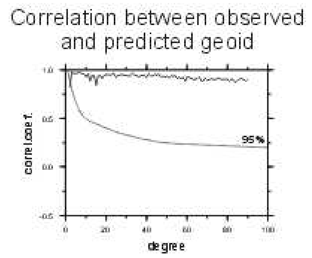
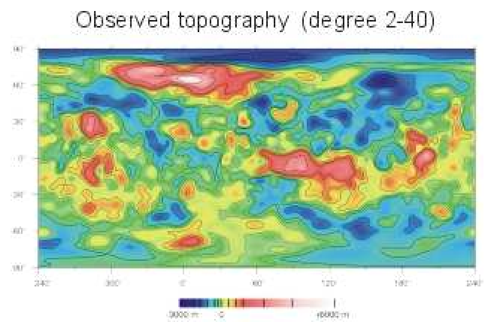
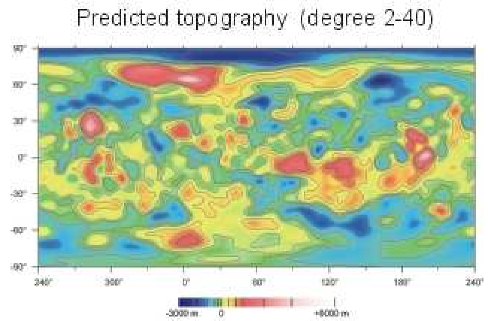
We examine on the global scale two different principles of a topographic support. Our goal is to find such an interior structure of planet which best predicts the geoid data. Both venusian geoid and topography are represented by the most recent spherical harmonic models (MGNP180U and GTDR.3 respectively). The predicted data are compared with observed ones on the basis of common spectral methods. First, we apply the principle of isostasy and we look for an average apparent depth of compensation (ADC). For the whole spectrum, dominated by the low degrees, a 165 km depth is found which might correspond to a bottom of the lithosphere. However, the predicted geoid does not fit well to the observed data in the whole spectral interval. Studying the degree-dependent ADC and the admittance function we obtain a uniform depth of compensation around 35 km for degrees higher than 40. For the geoid at degrees lower than 40 we propose a dynamic origin. This hypothesis is investigated in the framework of the internal loading theory. Assuming that the buoyancy force does not vary with depth (which roughly corresponds to a plume-like style of mantle convection) we can well explain about 90 % of both geoid and topography (see below). The best fit to the data and the observed admittance function is found for the viscosity profile with a ~100 km thick lithosphere and a viscosity increase by factor 10–100 through the mantle.

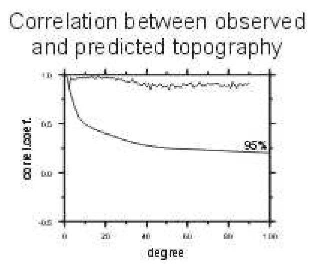












Gravity field and topography of Venus: localization methods

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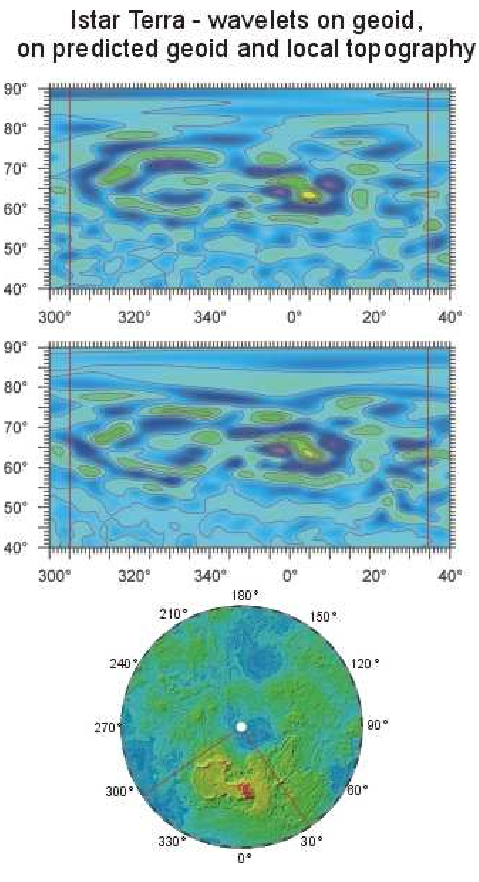
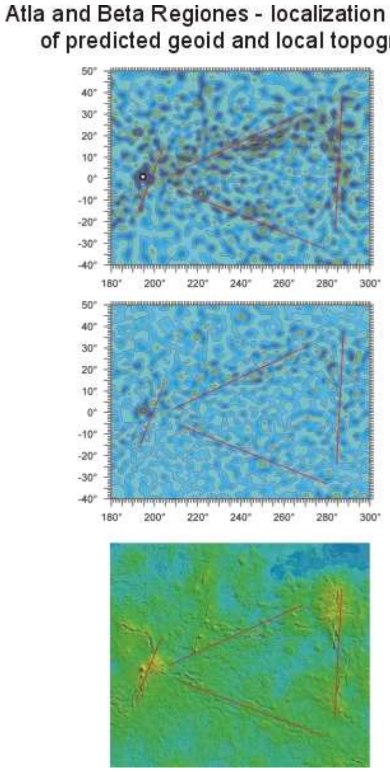
Localization of the geophysical fields is a useful tool for filtering the full-spectra signal. In comparison with the spherical harmonics the wavelet base (or some other suitable function) is well localized (i.e. has non-zero amplitudes only in a vicinity of the point of interest). So using this method we obtain true field anomalies without artificial oscillations. In our study of geoid and topography of Venus we also look at localized "qualitative" fields: correlation and admittance. There are two major approaches - spectral one presented by Simons et al. (1997) and spatial one presented by Kido et al. (2003). We use the later one motivated by a possible improvement of resolution in the selected regions. For an intermediate and short wavelengths the spherical harmonic expansions of the geoid contain too much of global signature which makes the local features unreadable. In contrast, the use of a localization function gives us a clear picture with individual features (see below). This could be a base for intuitive comparison of structures on the given scale. Localization of the qualitative functions as of correlation or admittance could give us information about observed geophysical models as well as about degree of agreement with our results.





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A model of kinetics effects in the transition zones: application to the postglacial rebound

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The type of mantle convection strongly depends on different kinetics effects such as heat transfers across the transition zones, chemical diffusion during phase transformation or stress relaxation occuring in response to volume changes. At a macroscopic scale, we model these effects through a single parameter which is a frequency-dependent compressiblity in the transition zones, in order to see its influence on postglacial rebound observables. A realistic axisymmetric and compressible Earth model based on PREM parameters and on a viscoelastic rheology is submitted to the last Laurentide ice-sheet glacial load (110 ky cycle). Because of the lack of data, a wide range of time characteristics of phase transformations is tested (10ky-10My). It shows that the viscosities of the upper and lower-mantle are not much affected by kinetics effects but that the pressure-field is strongly delayed in the transition zones during loading. This indicates a specific rheological behaviour of the tansition zones depending on both their thickness and their time characteristics.

Modelling continental roots in a convecting mantle

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Continental roots represent extensive regions of seismically fast, cold, and buoyant material compared to the surrounding mantle. The fact that they are cold undoubtedly produces large lateral variations in temperature, and hence viscosity in the mantle below. The effects of continental roots on the mode of mantle convection are studied using a 2-D Cartesian viscous flow model in which both the mantle and lithosphere are described as compressible, Newtonian fluids. Rayleigh numbers between 10^5 and 10^7 are considered. Viscous dissipation, adiabatic heating, and internal heating are incorporated into the energy equation. The radiogenic heat produced by the decay of radiactive elements in the mantle and the lithosphere respectively are incorporated into the model. The heat production in these two regions is distinct, as determined by studies of mantle xenoliths and heat flow. The freely-moving continental root is modelled as a highly viscous, undeformable region with a viscosity 10^2–10^3 times higher than that of the surrounding mantle. The presence of the continental root is shown to impose time-dependent behaviour in the mantle circulation below. The continental heat flow, displacement, and strain rates vary significantly depending on the combination of parameters listed above. Investigation of the time-dependence of the results requires the consideration of both conductive and convective timescales.

— INVITED —
The physics of subduction: statics, kinematics and dynamics

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The subduction problem has been tackled by many different methods. The simplest method is analytical/numerical modelling of static stress equilibrium assuming elastic or elasto-plastic subducting slabs in steady state emphasizing on flexural topography; the next is analytical and fluid dynamic kinematic solutions for corner flow style models emphasizing on temperature solutions derived from kinematically prescribed mantle flow; another is the laboratory analogue modelling of idealized scenarios which display part of the elasto-plastic or visco-elastic dynamics; the last approach is numerical fluid dynamic modelling of stratified viscous fluids aiming to solve dynamical modes of subduction which arise in (1) subduction initiation, (2) interaction with discontinuities (660 km), (3) slab breakoff, (4) solid slab-fluid mantle interaction, (5) deep earthquakes, (6) dynamic topography and lastly (7) interaction of subduction with overriding plate with implications for orogeny. While each method has its individual advantage, we show that fluid dynamical modelling of subduction is chiefly useful for kinematics. However, dynamical fluid dynamic Rayleigh-Taylor modes do not correctly describe the physics of Earths subduction. Elasticity must be incorporated as a key ingredient of subduction. It is non-dissipative and the energetically favoured mode of deformation. Therefore it is imperative to investigate dynamic modes 1) to 7) with consideration of elasticity. We will give a few examples highlighting the role of elasticity in dynamics of subduction and show the limitations of purely viscous modelling.

Modeling shear instabilities with block sliders: brittle and ductile

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Block slider-type models have been succesfully used for almost 35 years to describe the spatio-temporal development of shear instabilities in the brittle crust (Burridge & Knopoff, 1967; Olami et al., 1992). More recently, increasing attention is paid on the extension of the classical Burridge-Knopoff model (based on a pure Mohr-Coulomb rheology) with a viscous component, either to include depth-dependent properties into the model or aiming at a more accurate description of fore- and aftershock sequences of a main earthquake event (e.g. Hainzl et al., 1999). In addition, the development of shear-localization in the ductile mantle lithosphere has become an increasingly attractive mechanism for the generation of intermediate-depth and deep-focus earthquakes. Heat generated during viscous deformation provides a positive feedback to creep and eventually faulting under high pressure (Karato et al., 2001, Bercovici and Karato, 2003).

The present paper discusses the specific properties of block slider-type models that are extended with a viscous component and compare their behaviour with the pure brittle ("classical") case. It is shown, that block slider-type models for ductile instabilities in the mantle lithosphere are numerically much less demanding than solutions based on the corresponding, thermal-mechanically coupled continuum equations. Furthermore, they allow to include easily possible non-equilibrium effects associated with mineral phase transformations in a subducting slab (kinetic overshoot, grainsize reduction) into the rheological model.

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The effect of hydrous melting on plume dynamics

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Convection models including the effect of melting normally assume that the mantle is anhydrous, because water contents seem to be very low in the upper mantle. On the other hand, it is known that hydrous damp melting occurs e.g. beneath the principal melting zone of mid-oceanic ridges and results in the extraction of even the small water content in mantle rock after a few percent melting and a concomitant stiffening of the residue. We use a recent parameterization of hydrous and anhydrous melting, available data for partitioning of water and the water content of normal mantle and plumes in the frame of a combined convection–melting numerical model to calculate the effect of hydrous melting and dehydration stiffening on the convection and melting dynamics of a plume in the upper mantle. The models confirm that dehydration leads to a strong viscosity increase over a depth range of a few tens of kilometers during initial melting, at a depth which would be treated as rheologically weak in a model with only pressure and temperature-dependent viscosity. As this region lies deeper in the mantle in a plume, there is a depth interval, where the plume actually has a greater viscosity than normal mantle despite its higher temperature. If the plume contains more water than average MORB-source mantle, the depth of this high-viscosity region could lie as deep as 200–250 km. The viscosity increase results in a strongly reduced active upwelling, so that the crust produced above the center of a hydrous plume is less thick than that above an otherwise similar dry plume; on the other hand, the crustal anomaly is more pronounced over a larger along-ridge interval in the hydrous case. The differences in viscosity structure also result in different stress fields for anhydrous and hydrous models. Several authors have proposed that the stress field controls the orientation of dikes and/or melt channels in the melting region of the mantle. Using the mantle velocity field from the convection models, an attempt is made to predict the orientation of tabular tensile dikes in anhydrous and hydrous plume-ridge settings and the resulting direction of melt migration. Comparison of both cases reveals notable differences especially in the shallower parts of the melting region, where dike orientation in the hydrous plume resembles more the pattern also determined for normal MOR. Furthermore, dike orientation seems to support defocussing of melt away from the plume center in several parts of the plume head, especially at greater depths.

Dynamic implications of mantle serpentinization for intra-slab seismicity

Lars Rüpke[1], **Jason Phipps Morgan**[1], **Gabriele Morra**[2], **Klaus Regenauer-Lieb**[2], **James Connolly**[2] and **Matthias Hort**[3]

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Subduction zones commonly show inclined seismic zones than can extend down to $\sim$ 670km depth. The origin of subduction related intermediate and deep earthquakes remains, however, not fully understood. Many studies emphasize the importance of dehydration reactions (dehydration embrittlement). Released fluids may increase the pore pressure which decreases the effective confining pressure and thereby facilitates seismic rupture. An additional – less well understood – factor promoting intra-slab seismicity may be sudden volume/density changes during metamorphic reactions.

This process may be most important during the dewatering of serpentinized mantle where volume/density changes are high (up to 40 %). The incoming plate's lithospheric mantle may become significantly serpentinized between the outer rise and the trench axis. Here the bending plate develops normal faults that potentially provide the conduits for sea water to reach the slab's mantle to make serpentine. Deeper within the subduction zones, both slab deserpentinization and the gabbro-to-eclogite transition are associated with a strong volume reductions. The potential dynamic implications of volume/density changes during subduction have, however not yet been thoroughly studied using numerical models with most current models treating slabs as an incompressible viscous fluid.

Here we further explore the potential dynamic implications of slab metamorphism (i.e. serpentinization, deserpentinization, eclogitization) using a coupled analytical-solid-mechanical FEM model. We treat the subducting slab as a visco-elasto-plastic plate using a realistic, experimentally based, rheology. The model solves the implicit coupled temperature-deformation problem; metamorphic reactions are modelled using look-up tables calculated with the PERPLEX program. We account for volumetric changes by adding a volumetric strain component to the 'visco-elasto-plastic' strain rate decomposition.

We find that slab deserpentinization significantly changes the stress state of a subducting slab. The volume reduction during deserpentinization leads to very high strain rates. These high strain rates may lead to seismic failure by either (1) reactivating pre-existing hydrated 'bend-faults' or (2) producing new rupture planes. These findings suggest that dehydration reactions and the associated volume changes may be important for triggering intermediate and deep intra-slab earthquakes.

Modelling crustal accretion above the Iceland plume

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The Icelandic crust, though oceanic in origin, is distinctively different from normal oceanic crust. Excess temperatures of the mantle plume generate anomalously high amounts of melts resulting in crustal thickness on an average of 24 km, with a maximum value of 50 km. Seismic velocities of the crust are high, and have to be explained by thermal or chemical effects.

We model crustal accretion in Iceland by a two fold approach. In a 2D spreading model with anomalous mantle temperature beneath the ridge we solved the Navier-Stokes-, the heat tansport, the mass conservation and the melting equations to determine the enhanced melt production beneath the ridge. This melt was extracted and emplaced on top of the model to form the crust. Two cases are distinguished: a) Extruded crustal material is taken out of the model and is only advected according to the spreading of the plate, b) extruded material is fed back into the model from the top to mimic isostatic subsidence of extruded crust. We find that the feed back of case b) is only moderate. For example, if extruded crustal material as thick as 40 km is fed back into the model, the melting region is depressed only by as much as 10km, and the total amount of generated melt is reduced by about 20 %. On the other hand, upper 30 km of the model is cooled considerably by several 100 degrees.

A second set of models focuses on the details of crustal accretion without explicitly solving for the melting and extraction. Knowing the spreading rate, the rate of crustal production can be estimated, but the site of emplacement is not obvious. For Iceland we define four source regions of crustal accretion: surface extrusion, intrusion in fissure swarms at shallow depth connected to volcanic centres, magma chambers at shallow to mid-crustal level, and a deep accretion zone, where crust is produced by widespread dyke and sill emplacement and underplating. We solved the Navier-Stokes-, the heat tansport and the mass conservation equations and prescribed different functions in space and time for crustal production in the four defined regions. The temperature of the imposed material depends on the source region and the process of accretion is monitored by identifying material from different source regions by a marker approach. After some time of spreading and accretion, a characteristic temperature distribution and crustal layering evolves, which is compared to observation data.

Model sensitivity of GIA induced high resolution gravity anomalies and geoid heights

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Glacial Isostatic Adjustments (GIA) models compute the response of a model Earth to an ice loading history, for example using normal mode or finite element models. Common results are sea-level curves, free air gravity anomalies and geoid heights. We have investigated the influence of a number of model assumptions on the high resolution free-air gravity and geoid signal, using a semi-analytical normal mode technique and a pseudo-spectral sea level code. We have focussed on coast line migration and the influx of melt water, the layering of the Earth, including crustal low velocity zones, and the use of different ice loading histories. The results can be compared with sensitivities of future satellite gravity missions as GOCE, which is expected to map the static gravity field with an accuracy of 1 mgal for gravity anomalies and 1 cm for geoid heights, at a resolution of 100 km or less. This research is a first step in the direction of using a high resolution finite element model to study the influene of lateral heterogeneities on GIA.

— INVITED —
From sealevel to space geodesy: the past and the future of postglacial rebound

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Since the pioneering work of Haskell (1935), the approach to the postglacial rebound problem has varied considerably. The flat, homogeneous, newtonian fluid half space has been non substituted by modern 2D and 3D models of the Earth, which can deal with both linear and non linear mantle rheologies and with lateral variations in the mechanical properties of the lithosphere and of the mantle. The overtaking of MD models has been generally motivated by the increased amount and quality of the data available, which now include geodetic GPS and VLBI observations along with the classical relative sealevel data. A great effort has been made to improve modeling, with considerable success, but our knowledge on the Earth interior as inferred by postglacial rebound observations is still imperfect. We review some of the milestones of the development of postglacial rebound studies, the physical and geological observations available, and we give a few examples of interesting case studies.

— INVITED —
Planetary interior dynamics

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The dynamics of the interiors of earthlike planets and satellites is most likely governed by interior convective flow. But in allmost all cases this flow does not extend to the surface as on Earth (plate tectonics) but is confined to the mantle below the lithosphere. The coronae on Venus, large circular domes, have been speculated to be either caused by plume heads extending to the surface or by the roots of downwelling cold plumes. There is also debate about early phases of plate tectonics or plate-like tectonics possibly on Mars and on the Jovian Moon Ganymede and about lithosphere delamination. But for the present day plate tectonics on these planets can be excluded. Heat transfer to the surface is then by conduction through the lithosphere and through volcanic vents piercing through the lithosphere. In the early evolution mantle melting and extensive volcanism led to the differentitaion of the mantle and the formation of the crust. This differentiation probably occurred simultaneously but extended beyond the more rapid formation of the core. Mars is the planet of which the early evolution is best understood thanks to the isotope data from SNC meteorites and the remnant magnetization of the very early crust. The isotopic evidence suggests that this differentiation occurred very early on Mars, in the first few 100 million years, and left reservoirs that have experienced very little if any mixing thereafter leading some researchers to speculate that may be the Martian mantle has not been convecting since. Isotopic evidence also suggests that core formation on Mars was very rapid and occured in the first few 10 million years. The formation of the gigantic volcanic Tharsis dome occurred together with crust formation but the volcanic activity remained focussed there and extended albeit at an ever decreasing rate until the geologically recent past.

The magnetic properties of the planets is best understood by applying the theory of hydromagnetic dynamos driven by thermal and compositional convection in the cores. Thermally driven dynamos appear to be confined to the early cooling phases of the planets when vigorous mantle convection cooled the cores. Mars, Moon and Venus are likely to have had these early dynamos. In these planets, dynamo activity stopped when core cooling by the mantle failed to keep the core convecting and, moreover, failed to freeze inner cores. On Earth and Mercury inner core growth is thought to have kept the dynamos alive to the present day. On Earth this is almost certainly due to plate tectonics effectively cooling the deep interior. On Mercury core freezing is attributed to the core being comparatively large and the mantle being comparatively thin. The puzzle in this model is Ganymede which should be similar to the Moon and Mars but which appears to have a self-sustained magnetic field.

The Jovian system provides a laboratory for studying additional features of planetary dynamics and evolution such as tidal heating and coupled thermal- orbital evolutions (Io and Europa), heat transfer in partially molten interiors (Io), internal oceans (Europa, Ganymede and Callisto), and differentiation that failed to run to completion (Callisto).

Melt extraction in two-phase flows

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Melt extraction in two-phase flows is often modelized using equations developped by McKenzie (1984). Recently Bercovici et al. (2001) proposed a somewhat different set of equations where, for example, the isotropic compaction depends on the porosity and where the two phases (matrix and melt) are submitted to different pressures. We extended these equations to take into account the phase change in the case of a univariant phase diagram. We show how the pressure difference between the two phases is related to the melting rate and the rate of porosity change. We suggest that as the two phases undergo different pressure conditions, the melting does not occur under the usual thermodynamic static conditions (a single pressure field). Although preliminary, this study will show various simulations of 1D melting.

A self-consistent mantle convection model: generation of a low-viscosity zone and plate-like features

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A numerical mantle convection model with a temperature-, pressure- and stress-dependent rheology can generate different tectonic styles as they are observed for various terrestrial planets. The temperature dependence of the viscosity, the basis of the rheological model, prescribes a viscosity change between the cold material at the surface and the hot material at the bottom of the three-dimensional Cartesian box regarded. Thus, the assumption of a strong temperature dependence leads to a highly viscous surface. The degree of deformation in this rigid surface ('stagnant lid') is controlled by the applied yield stress. The variation of the yield stress for a constant pressure dependence results in four different regimes. For a high value stagnant lid convection like on Mars and Mercury maintains, i.e. convection is confined beneath a rigid and immobile surface. For intermediate values an episodic behaviour as assumed for Venus appears. In this case deformation is limited to narrow zones. Parts of the surface behave like a rigid plate, but as subduction is faster than conductive cooling from above, intermittent behaviour is a consequence. For relatively low yield values plate-like behaviour is found. Extended plates move continuously in time, because the influence of stress compared to that of pressure is diminished allowing for slower subduction. Finally, for even lower values of the yield stress the surface shows strong internal deformation in such a way that the surface can be regarded as fluid-like.

Besides plate-like features as for example cylindrical upwellings, sheet-like downwellings and trench migration, a low-viscosity zone (LVZ) arises self-consistently. The LVZ, however, only appears under a certain parameter combination. In the four regimes described above, only the plate-like regime displays a viscosity drop at shallow depths. Thus the existence of continuously moving plates and the presence of a low-viscosity zone are two coupled phenomena. The reason for the formation of the LVZ is definitely the applied pressure dependence. Without a pressure-dependent viscosity neither plate-like behaviour nor a low-viscosity zone is observed at all. However, pressure-dependent viscosity convection does not necessarily form a low-viscosity zone. Only on a narrow range of parameters the self-consistent generation of a low-viscosity zone and plate-like behaviour is achieved.

Using TABOO for postglacial rebound predictions

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TABOO is a simple postglacial rebound calculator written in Fortran 90, which allows for the computation of displacement, velocity fields, and variations of the Stokes coefficients forced by surface loads. TABOO, which has been mainly developed for pedagogical purposes and is freely available, can be employed to compute the response of layered (1D), incompressible, self-gravitating, Maxwell viscoelastic Earth models to surface loads of various geometries and time-histories. In this poster we illustrate its basic features and we give examples of interesting geophysical applications.

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

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Thermal convection has been modeled in a 3-D model box, in order to study the structure (diameter and temperature anomaly) of mantle plumes and their surface manifestation (topography, geoid anomaly, heat flow).

The variable parameters in the different models are the Rayleigh number (it varies between $5{\cdot}10^6$and 10^8), the depth-dependent viscosity and the rate of internal heating. In the simplest models the viscosity is assumed simply exponential increasing with depth by a factor of 10 and 100. Trying to model the real mantle viscosity distribution in some cases a narrow high and a low viscosity layer was added to model the lithosphere and the asthenosphere. In some models the possible bottom boundary layer of mantle convection, the D" layer is also included. In some models internal heating was added with a non-dimensional value of H=10 corresponding to the concentration of radioactive elements in chondrite meteorites.The upper and the lower boundaries are supposed to be isothermal and stress-free. The sides of the box are reflecting boundaries. The size of the box was chosen to allow the evolution of only one plume in the corner of the box. Applying these conditions, the box represents one quarter of the whole convective cell. To calculate the anomalies, both upper and whole mantle scaling were used.

Summarizing and comparing the result with the observations, the following remarks can be drawn:

- The interior of the convective cell had a lower temperature in the case of high 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 the asthenosphere decreases the geoid and topographic anomalies. The lithosphere makes higher the temperature of the interior of the convective cell and reduces the surface heat flow anomaly leading towards better agreement with the observed values.The high viscosity layer at the CMB (D" layer) has no effect on the surface manifestations, but changes the structure of the convection. The interior of the convective cell will be warmer.

- Basal heating dominates in every model, but the effect of internal heating on the studied features suggests that it cannot be neglected. It decreases the topographic, geoid and temperature anomalies.

- Seismic tomographic studies (Bijwaard and Spakman, 1999, Wolfe et al., 1997) suggest lower temperature anomalies of the upwellings than the calculated ones (Fig. 2). The most complex whole mantle model has the most similar value to the observations. The diameter of the plume (Fig1.) also indicates rather a whole mantle convection, because the values at upper mantle convection are very low (< 80 km).The calculated values of heat flow anomaly (50–600 mW/m^2) are much higher than the observed values (10–20 mW/m^2, Courtney and White, 1986). In general, the amplitudes of the calculated anomalies (geoid, topography, Fig. 4 and Fig. 5) fit better to the observations, when upper mantle convection is supposed. Usually all modeled topographic heights are larger than the observations, except the lowest values. Geoid heights lie in the range of the real anomalies for almost every upper mantle model. The problematical part of these models is the horizontal extent of the anomalies, which is significantly smaller than the observations. The horizontal extent (Fig. 3) suggests whole mantle convection, but the amplitude of the topography in these models is significantly larger than the observed values. The geoid anomalies in these models are higher than the observed ones, except the models with asthenosphere and lithosphere.

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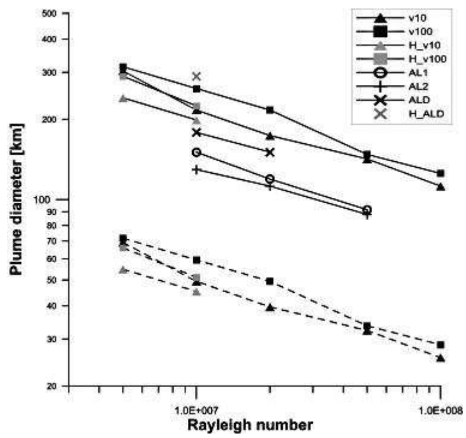

Fig. 1. The half-widths of the fitted Gaussian curves to the temperature distribution of the plume as the function of the Rayleigh number in the case of whole mantle convection (continuous line) and upper mantle convection (dashed line). Notation: **v10** - simple exponentially increasing viscosity from the top to the bottom by a factor of 10; **v100** - simple exponentially increasing viscosity from the top to the bottom by a factor of 100; **H_v10** - the same as **v10**, but internal heating is added; **H_v100** - the same as **v100**, but internal heating is added; **AL1** - lithosphere and asthenosphere was added to **v100**; **AL2** - same like **AL1**, but the lithosphere is narrower; **ALD** - the same as **AL2**, but also D" layer is included; **H_ALD** - viscosity distribution is the same as **ALD**, but internal heating is added.

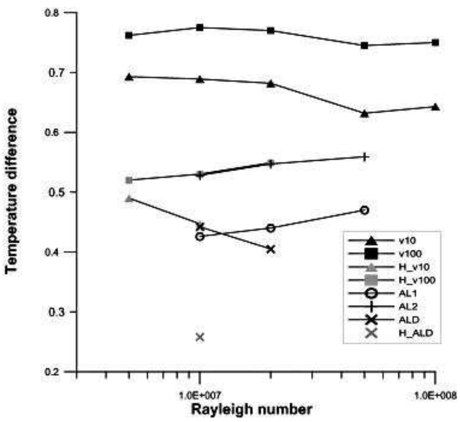

Fig. 2. The dimensionless temperature difference between the center of the plume and the interior of the convective cell plotted against the Rayleigh number. (Notation can be seen at Fig 1.)

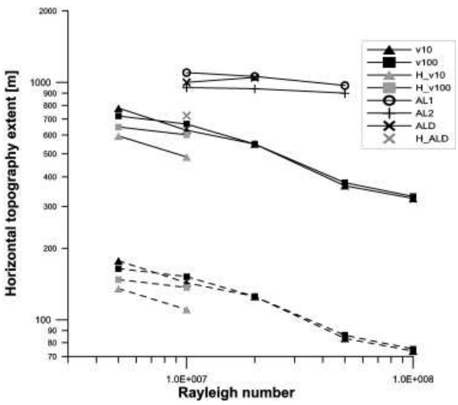

Fig. 3. The horizontal extent of topographic anomalies above plumes as a function of the Rayleigh number in the case of whole mantle convection (continuous line) and upper mantle convection (dashed line). The lateral size of anomalies is characterized by the half-width of the fitted Gaussian curve. The extent of real hotspot swells varies between 500 and 1000 km (Monnereau and Cazenave, 1990). (Notation can be seen at Fig 1.)

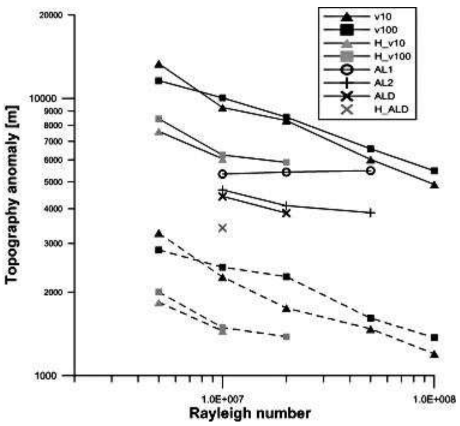

Fig. 4. Topographic anomalies above the plumes as the function of the Rayleigh number in the case of whole mantle convection (continuous line) and upper mantle convection (dashed line). The height of hotspot swells ranges from 350 to 2200 m (Monnereau and Cazenave, 1990). (Notation can be seen at Fig 1.)

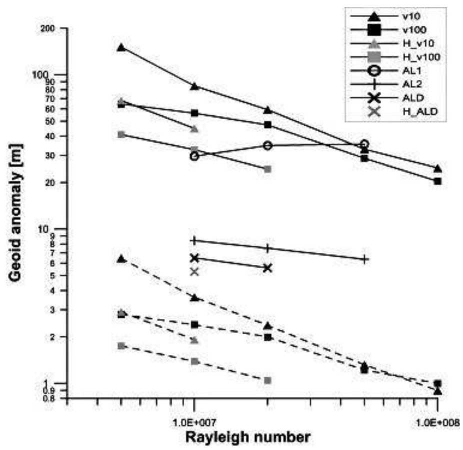

Fig. 5. Geoid anomalies above the plumes as the function of the Rayleigh number in the case of whole mantle convection (continuous line) and upper mantle convection (dashed line). The geoid height of hotspot swells ranges from 1 to 150 m (Monnereau and Cazenave, 1990). (Notation can be seen at Fig 1.)

— INVITED —
Modeling the coupled chemical and thermal evolution of terrestrial planets using mantle convection models with geochemical tracking

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To investigate dynamical mechanisms that have been proposed to explain geochemical observations, a model of mantle convection is presented that combines a treatment of major and trace-element geochemical evolution with a dynamically-consistent mantle convection-plate tectonics model. Melting is simulated using an experimental solidus and assumed to erupt instantly, forming a crust, thereby generating chemical heterogeneity including the partitioning of trace elements between oceanic crust and residue. Trace elements studied are the U-Th-Pb and Sm-Nd isotope systems, helium and argon. Both olivine and pyroxene-garnet system phase transformations are included, with the relative density profiles of basalt, pyrolite, and harzburgite following those of Ringwood (1990) and Ono et al (2001) up to 800km depth, but varied in the deeper mantle to reflect present uncertainties. A suite of numerical experiments has been run to systematically investigate the sensitivity of the results to uncertain physical properties such as the density of subducted crust in the deepest mantle and elemental partition coefficients.

If eclogite is denser than pyrolite or residue in the deep mantle, the system becomes chemically stratified, with a basal layer of subducted crustal material enriched in heat-producing elements and an upper mantle dominated by depleted residuum. Local stratification occurs across the 660-700 km region due to the compositionally-dependent phase transitions. Results indicate that the system can self-consistently evolve regions that have a HIMU-like signature (by segregation of subducted crust at the CMB) and regions with high 3He/4He. Here we focus particularly on 3He/4He ratio distributions, and on the isotopic 'age' that is associated with U-Th-Pb and Sm-Nd system.

The system self-consistently evolves regions with the observed range of 3He/4He, but the exact distribution depends strongly on physical parameters. Furthermore, the distribution depends on sampling method, with the distribution in erupted material often being different from mantle-averaged distributions. Some parameter combinations simultaneously lead to MORB-like distributions of 3He/4He ratios in erupted material, and ~50 % outgassing of radiogenic 40Ar consistent with geochemical constraints. MORB-like 3He/4He histograms are produced in erupted material either when the shallow mantle has a high proportion of residue that evolves MORB-like 3He/4He due to the high incompatibility of He, or when sufficient recycled crust mixes back into the shallow mantle to suitably reduce its 3He/4He.

Isotopic measurements on Mid Ocean Ridge Basalts and Ocean Island Basalts indicate effective 'ages' (from e.g., Pb-Pb or Sm-Nd systems) in the range 1-2 billion years- much less than the age of the Earth, even though melting should have been much more vigorous early on, skewing the mean time since melting to older values. This relatively young 'age' has generally been explained in terms of stretching of heterogeneities by mantle convection, which might reduce them to dimensions too small to be individually distinguishable in short timescales of less than 1 Gyr. On the other hand, published numerical models that use tracers to track differentiated material (Christensen and Hofmann, 1994, Davies, 2002) suggest that Earth-like 'ages' can be obtained without taking stretching-induced erasure of tracer signatures into account, although this might effectively happen if the lengthscale for sampling the isotope systems was large enough. In those models, the only explicit mechanism for resetting isotope systems was re-melting, but for this to explain the isotopic ages observed for basalts, the global rate of melting in the recent past would have had to be very much higher than present-day values. We investigate stretching vs. re-melting in these numerical experiments. The time of last melting and the total strain is tracked on each tracer (in addition to isotopic information). The results confirm that a model matching today's crustal production rate and with a reasonable secular cooling history generates 'ages' that are substantially larger than those observed, with the extent of crustal settling above the CMB making some difference but not enough. The effect of sampling lengthscale on observed 'age' is also tested and found to be insufficient to explain the data. Thus, these results reaffirm the importance of stretching as a key mechanism for effectively deleting older heterogeneities. From analysis of strain vs. age and matching of the observed ages, it is estimated that erasure of heterogeneities occurs at strains of 10^3–10^4, somewhat larger than has often been assumed.

The role of slabs on plume development

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We show that with a wide range of reasonable plate kinematics and material properties, slabs can reach the core-mantle boundary in models; even for cases with a high-viscosity lower mantle, a phase transition at 660 km depth, depth-dependent thermal expansivity, and depth-dependent thermal diffusivity, we find that ancient slabs could be associated with lateral temperature anomalies ~ 500 °C cooler than ambient mantle. Plausible increases of thermal conductivity with depth will not cause slabs to diffuse away in the lower mantle. There are important consequences of deeply penetrating slabs. Plumes preferentially develop on the edge of slabs. In slab-free areas, plume formation and eruption is frequent, and the basal thermal boundary layer is thin; while in areas beneath slabs, the basal thermal boundary layer is thicker and plume formation infrequent. Beneath slabs, a substantial amount of hot mantle can be trapped over long periods of time, leading to 'mega-plume' formation. We predict there may be large volumes of mantle with low seismic velocity directly beneath large-scale high seismic velocity structures at the core-mantle boundary, structures interpreted as ancient slabs. The predicted structure has been found in the Caribbean region.

Three-dimensional small scale convection below the oceanic lithosphere

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Sublithospheric small scale convection (SSC) has been proposed to explain the deviation in oceanic topography and heatflow from the cooling half-space model for oceanic plates spreading away from the mid-ocean ridge. The dynamics of this SSC process have been previously studied in several numerical and laboratory experiments. Most numerical studies use a two-dimensional setup, either parallel or perpendicular to the plate motion.

Here, we present results of a 3-D study, which combines the characteristics of each of the 2-D models. We use a realistic, strongly temperature-dependent rheology. First, we present detailed comparison between earlier 2-D results for Newtonian rheology and the new 3-D results, and show that SSC dynamics are fundamentally different: in 2-D roll/convection cell orientation is predicted by the model setup, while in 3-D longitudinal 'Richter' rolls are dominant. Background shearing due to plate motion enhances longitudinal rolls, but prohibits SSC in 2-D. The behaviour of a non-Newtonian fluid is differs significantly from a Newtonian one: for comparable mantle viscosities, onset is earlier for increasing powerlaw exponent n, and downwellings are more vigorous.

Thermal structure of lithosphere above SSC can be compared to the cooling halfspace model, which leads to a 'thermal age' that deviates from the real plate age due to SSC. Comparison of numerical results with a surface wave tomography model show a large degree of agreement, which provides strong support for the existence of SSC.

We modeled the effect of a sudden change in the plate motion, such as suggested by the bend in the Hawaii-Emperor volcanic chain, on the development of SSC under various thermal and rheological conditions. Results show that rapid alignment of rolls with the new plate motion does not easily occur, which suggests that SSC will not present itself as Richter rolls.

Ultra-high Ra convection and applications of wavelet

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Thermal convection is a nonlinear phenomenon, the qualitative changes of its behavior can occur while increasing controling parameters. To understand the fundamental physics, we conducted a convection model in the Bousinesq approximation for infinite Prandtl number and a 2-D axisymmetrical spherical shell geometry. When scaled to the Earth's mantle, the computational domain of this model has an aspect-ratio of around six. For comparing with 3-D situation, we have also used a three-dimensional Boussinesq model taken from Dubuffet et al. (2000) with an aspect-ratio of $5 \times 5 \times 1$.

We have found different convection regimes for increasing Rayleigh number Ra. Two convection cells with raising secondary instabilities ($Ra = 10^6$) will change to three and more celled convection regimes ($Ra = 10^7$ and more). Thermal plumes are starting to be ubiquitous at high Rayleigh number convection. Secondary instabilities (called also Whitehead instabilities, see Skilbeck and Whitehead, 1978, and Whitehead, 1982) will occur. We have also found that secondary Whitehead instabilities can develop naturally in 3-D large aspect-ratio convection.

At a higher Rayleigh number between 10^9 and 10^10 the system goes to a layered convective state, as the plumes become more feeble and cannot reach the top bounday layer. Such a transition may be important in the high Rayleigh number regime of a young planet and in magma chambers. For non-Newtonian rheology this transition from single cell to layered convection would take place at lower effective Rayleigh numbers. Malevsky and Yuen (1992) had shown that non-Newtonian rheology could lower the threshold Rayleigh number for secondary instabilities to develop by at least an order of magnitude or a factor of 2 in the surface Nusselt number.

Wavelet transform is a powerful tool for data analysis. The 1-D wavelet transform is useful for time-frequency representation of signals in low Rayleigh number convection (Vecsey and Matyska, 2001). As the high Rayleigh number convection is more complex, we prefer the 2-D wavelet transform, with a nice ability to detect structures of different scales (Vecsey et al., 2003).

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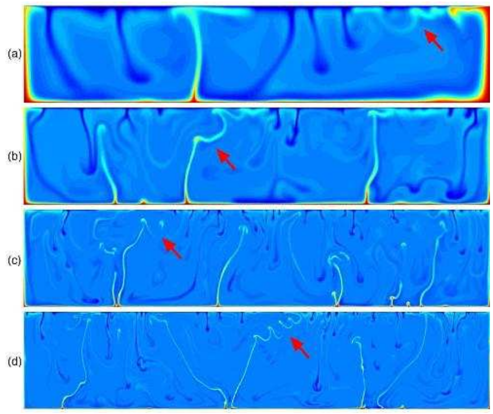

Fig.: Examples of Whitehead instabilities developed in temperature fields. The used Rayleigh numbers: (a) $3 \cdot 10^6$, (b) $3 \cdot 10^7$, (c) $3 \cdot 10^8$, and (d) 10^9. The red arrows point to (a) Whitehead-like instability and (b)-(d) Whitehead instabilities (Murphy et al., 2000).

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