Hot and cold instabilities in a fluid with a strongly temperature-dependent viscosity

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We have studied the characteristics of thermal instabilities developing when a layer of sugar syrup, a fluid with a strongly temperature-dependent viscosity, is heated from below and cooled from above Prandtl numbers ranged between $7.3 \ 10^3$ and $1.3 \ 10^6$, Rayleigh numbers between $1.7 \ 10^6$ and $3.3 \ 10^7$, and viscosity ratios between $7 \ and \ 4100$.

A new visualization technique allowed us to determine both the temperature and velocity fields in situ inside the experimental tank, so that we have access to the local properties of the instabilities.

As the viscosity ratio increases, three regimes are encountered: classical nearly constant-viscosity convection, sluggish lid and stagnant lid. In the latter two regimes, the cold thermal boundary layer (TBL) is thicker than the hot TBL. At high viscosity ratios, convection occurs in a sublayer beneath the coldest and most viscous part of the TBL which remains stagnant. At intermediate viscosity ratios and large Rayleigh numbers, two scales of convection co-exist, a large-scale circulation involving the lid, superimposed on the classical cold and hot instabilities. Scaling laws are determined for their onset, size, velocity, and heat flux. We then applied our results to infer the dynamics of the mantle "box" beneath the Pacific.

Numerical modelling of the influence of subduction parameters on partial melting

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Nowadays, a lot of models study subduction zones without any geometrical constraint. We use here a different approach, and model subduction zones with known geometry, for which both geophysical and geochemical constraints are available. The latter data provide information about partial melting conditions and rock chemical compositions.

A new 2D numerical model is developed to study the influence of subduction parameters on partial melting. We use a thermo-mechanical model which solves classical fluid mechanics equations using the finite element solver FreeFEM++ (http://www.freefem.org/ff++/). Conservation of energy is solved using a Galerkin procedure, whereas Stokes equations use the penalty method. A non-linear rheology is computed with both nonnewtonian viscosity for the mantle and a brittle regime for the crust. We also introduce, in viscosity computations, a water-dependent term corresponding to the decreasing of rocks strength (Arcay et al., 2005) with water content. Water is introduced in the model according to phase diagrams relevant to the mantle and the crust, respectively. Melting curves are controlled by water contents (Katz et al., 2003).

In order to investigate the relations between subduction zone parameters and partial melting, we resume subduction zones parameters to the convergence rate, to the dip angle and to the age of the subducting lithosphere (Heuret and Lallemand, 2005). We add an other parameter, the crustal thickness of the overriding plate, which could have some influence on the partial melting and thermal regime in the mantle wedge (Plank and Langmuir, 1988). Several actual subduction zones are investigated in order to inquire the largest range of values for each parameter.

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Intraplate volcanism due to small-scale convection

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Although most of the intraplate volcanism in ocean basins is expressed in linear chains, not all of these can be attributed to a stationary hotspot. Many ridges do not show linear age-progressions predicted by this model (e. g., Pukapuka ridges, Magellan and Line Islands). The well-studied Pukapuka ridges reside among other short-lived seamount-chains in the eastern part of the South Pacific Superswell. They are aligned by plate motion and by topography and gravity lineations with a wavelength of ~ 200 km.

In order to account for the gravity lineations and the volcanism, three types of models have been put forward yet. Firstly, cracks in the lithosphere due to diffuse extension of the Pacific Plate or due to thermal cracking might sample pre-existing melt. Secondly, melt generated at the South Pacific Superswell might undergo fingering and channelling by flowing towards the East Pacific Rise. Thirdly, small-scale convection (SSC) might dynamically produce melting and the associated gravity lineations. Gravity and tomography studies have rejected the lithospheric cracking model [Harmon et al., 2007], which furthermore presumes a reservoir of pre-existing partial melt in the asthenosphere. Channelized return flow might be a good explanation for the volcanism and the associated density anomalies. But it remains unexplained, why most of the ridges do not extend as far west as Pukapuka and why many of the gravity lineations are not associated with volcanism at all. The SSC-hypothesis is instead able to explain the lineaments and the volcanism altogether.

In the Earth's uppermost mantle SSC is likely to develop due to instabilities of the thickened thermal boundary layer below mature oceanic lithosphere (usually ~ 70 Ma). It is characterized by convective rolls aligning plate motion. Their onset is earlier (i.e. beneath younger and thinner lithosphere) for lower mantle viscosities (e.g. for hot or wet mantle) or adjacent to lateral thermal or compositional heterogeneity. In these cases, partial melt potentially emerges in the upwelling limbs of SSC. Partial melting changes the compositional buoyancy owing to melt retention and additional depletion of the residue. Therefore, it promotes upwelling and allows for further melting. This self-energizing mechanism is able to sustain melt production in a once partially molten layer for a couple of million years.

In this study, we take the step towards fully thermo-chemical 3D-numerical models of SSC (using the FEM-Code CITCOM) with a realistic, temperature- and depth-dependent rheology in order to quantitatively test the SSC-hypothesis on intraplate volcanism. We explore the 3D-patterns of melting associated with SSC, the age of seafloor over which it occurs, and the rates of melt generation by varying the key parameters mantle viscosity and temperature, T_m . We also investigate the effect of lateral heterogeneity that locally reduces the onset age of SSC.

Melting due to SSC is predicted to emerge in elongated features (\sim 700 km) parallel to plate motion and not just at a fixed spot, which does not imply linear age progressions of the associated volcanism contrary to the hotspot model. The seafloor age at which volcanism occurs is sensitive to T_m . For moderate T_m (1350 °C), volcanism develops beneath relatively young lithosphere (\sim 30 Myr) for viscosities nat higher than $1.5 \cdot 10^{19}$ Pa·s. Increasing T_m retards the onset of SSC because of the presence of a thicker buoyant residue from previous mid-ocean ridge melting. Mantle viscosity controls the rate of melt production with decreasing viscosities leading to more vigorous convection and volcanism. The geochronology and volumes of volcanism of the Pukapuka ridges, Line and Marshall Islands are consistent with our predictions.

Long-wavelengths subductions in the lower mantle

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According to seismic tomography (see e.g. Bijwaard et al. 1998, Karason and van der Hilst 2001), the subducting litospheric slabs have plate-like character in the upper mantle. However, the wavelength of the fast seismic anomalies increases in the lower mantle and slabs have blob-like rather than plate-like shape (Ribe et al. 2007). The wavelength of the lower mantle seismic velocity anomalies is closely related to the viscosity structure of the lower mantle and has important implications on the global geodynamics, geoid, etc.

Here we try to find the rheological model, which would produce slabs with plate-like character in the upper mantle and forming blobs in the lower mantle. We present the results of the numerical modelling of subduction process in a 2-D Cartesian box. We use extended Boussinesq approximation and our numerical code is based on the method of Gerya and Yuen (2003). We employ the composite rheology including diffusion creep, dislocation creep and power-law stress limitor. The effects of phase transitions at the depths 410 km and 660 km are taken into account. We concentrate on the shape of the slab in the lower mantle depending on the viscosity increase between the upper and lower mantle, on the value of the yield stress and on boundary conditions. We are trying to find the conditions under which the blobs appear in the lower mantle. We found that for relatively low yield stress value (10^8 Pa) and for the viscosity jump 10-30 at 660km the blob-like features can indeed be observed (see illustration figure).

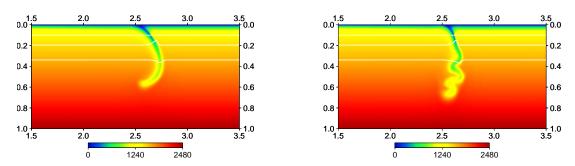


Figure 1: Illustration figure, temperature [°C] for models with viscosity increase 10 at 660km, yield stress limit 10⁹Pa (left plate) and 10⁸Pa (right plate), at time 30My.

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Modeling of craton stability using a viscoelastic rheology

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Archean cratons belong to the most remarkable features of our planet since they represent continental lithosphere that has avoided continental recycling for several billion years. Dating of inclusions in diamonds and thermobarometric measurements on xenoliths from kimberlites indicate that Archean cratons and their more than 200km thick lithospheric keels have remained cold and stable ever since their formation. Numerical modeling of craton stability has yet failed to reproduce this observed stability for billions of years. Using a two-dimensional FEM model, we show that high viscosity contrasts between the convecting upper mantle and the cratonic lithosphere are fully sufficient to account for the long-term stability of cratonic keels. We know from laboratory experiments that for mantle rocks at temperatures as in the cratonic keel, these viscosity contrasts are very high indeed; thus, one should use high viscosity contrasts in modeling of convecting mantle-lithosphere interaction. Furthermore, we suggest that the application of a viscoelastic rheology for the mantle helps to avoid the need to use intractably high viscosity contrasts, a problem modelers are commonly confronted with when using a viscous rheology. With a viscoelastic rheology, there is a transition from viscous to elastic behaviour above a certain threshold of viscosity contrast, resulting in stability of the cratonic keels. This approach is consistent with the viscoelastic nature of rocks.

Revisiting models of the core of Mercury

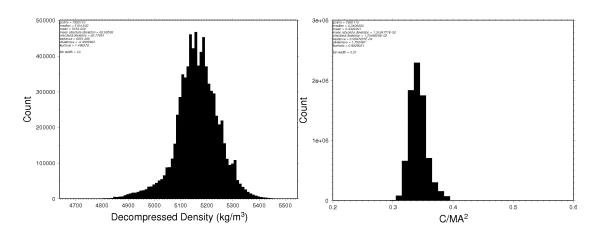
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Mercury is unique among the terrestrial planets for its relatively low mass and high average density, implying an unusual iron-rich bulk composition and so providing constraints on planetary formation and evolution. Previous density models of Mercury's interior have considered cores composed of a single solid layer or a few constant-density solid layers. In light of the recent detection of a partially molten Mercurian core [Margot et al., 2007], we model plausible interior density structures of Mercury using the thermoelastic properties of both solid and molten core materials.

Using planetary mass and radius as primary constraints, we apply Adam-Williamson-type self-compression along planetary adiabats (or other imposed hermeotherms), using Birch-Murnaghan finite strain equations of state, to generate a large suite of plausible models of Mercurian interior structure and composition. We analyze the distribution of various planetary properties (*e.g.*, decompressed density, moment of interia, inner/outer core radii) across the sample space of such models. We find, for example, that the expected value of decompressed density is smaller than values commonly quoted in the literature. We illustrate the importance of incorporating molten and/or layered cores (and of obtaining better measurements of thermoelastic properties of molten alloys) in accurately modeling Mercury's interior structure and composition, observations that will be important for interpreting anticipated geophysical observations by spacecraft.



[Fig.: Some statistics for a sample suite (#230607) of Mercurian models.]

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3-D structure of the Earth's mantle and core, from a large database of P, PKP, PcP travel-times.

Observations of the travel time of seismic waves reflected from, or refracted through the Earth's core are essential to our understanding of the deep Earth. These seismic phases are sensitive to features difficult to image like the topography of the core-mantle boundary (CMB), the short-scalelength structure of the D" region, and the structure of the Earth's core. I invert tomographically a large database of P, PKP, PcP travel-times from the ISC (International Seismological Centre) bulletins, to map P-velocity heterogeneities in the Earth's mantle and outer core, and undulations in the topography of the CMB. The pattern of heterogeneity I find in the outer core is correlated with that of CMB undulations; outer-core heterogeneity can therefore be explained as an effect of gravity anomalies within the core, produced, in turn, by the heterogeneous structure of the mantle and CMB themselves.

With respect to earlier studies by myself and co-authors (Soldati, Piersanti, Dziewonski), I take advantage of an increased computational power, to conduct a large number of linear inversions, changing the values of the numerous available regularization parameters. This way, it is possible to monitor accurately the trade-off (smearing) between structure mapped in differently sampled regions of the deep Earth. This should lead to identify a relatively error-free solution model, or assign to any selected solution an appropriate "error-bar", before subjecting it to geodynamic interpretations.

A new comparison of numerical and analogue model experiments of crustal-scale processes

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Numerical and analogue modelling methods are widely used, but rarely compared directly to one another. Direct comparisons for well-defined setups can help in testing and understanding model behaviour and increase confidence in modelling results by establishing the robust features of models. A challenge in such comparisons is to have boundary conditions and material behaviour as similar as possible.

Recent comparisons of crustal-scale experiments have shown that to a first order, analogue and numerical results have a similar evolution with localisation of deformation onto shear zones and that different numerical solution methods successfully reproduce structures seen in the sandbox experiments. However, the results also highlighted differences in, for example, location, spacing, dip and evolution of shear zones. The aim of the new experiments is to better constrain and understand the variability among analogue and numerical models and to improve our understanding of the causes of differences among the models results.

'Benchmark' experiments should, among others, have a simple set-up, with prescribed model dimensions, resolution and time step size, and use material properties, including those of sidewalls and the base, that are well quantified. We present two experimental setups for the new numerical and analogue model comparisons and invite discussion on all aspects of the proposed benchmarks.

More information on: http://www.geodynamics.no/benchmarks

Numerical and analogue models of lithosphere dynamics

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Modelling dynamic processes on the scale of the crust and lithosphere poses challenges related to the simulation of elastic, non-linear viscous and brittle material behaviour, the ability to achieve large deformations for high resolution, accurate quantification and visualisation, the simulation of sedimentation and erosion, and the representation of the interaction with the underlying mantle. Many of these challenges apply to both numerical and analogue (laboratory) models of lithospheric processes. Numerical and analogue methods are often used separately, but an increasing number of studies utilise the partly complimentary nature of both modelling techniques. The strengths of numerical models lie in the easy quantification and visualisation of results, the large freedom in choice of material properties, boundary conditions and geometries, and the possibility to perform a wide range of sensitivity studies. Some approaches lose accuracy in large deformation (because of remeshing for example) or for high viscosity contrasts. In analogue models, the physics of the process under consideration does not need to be captured in equations. The technique is very suitable for studying the 3D evolution of structures, but limited in temperature-dependent rheologies, phase changes and variations in geometries. It is a challenge to achieve a reasonable level of reproducibility of the experiments. A combination of numerical and analogue models can help to establish robust features of modelling results and thus aid the application of models to natural examples.

In this overview talk, i will discuss analogue and numerical model techniques, show examples of model 'benchmarks' and discuss the strengths and challenges of numerical and analogue models using examples of extension, such as basin formation and shear zone propagation, and convergent processes, such as subduction and fold-and-thrust belt formation.

A Multi-Discipline Approach to Investigate Shear-wave Anomalies in the Lower Mantle

A. L. Bull, A. K. McNamara, J. Ritsema, C. Lithgow-Bertelloni and L. Stixrude

Broad, low velocity anomalies in the lower mantle beneath Africa and the Pacific are conspicuous features in global shear-wave tomographic images. Currently it remains uncertain whether these structures are dense thermochemical piles or superplumes or clusters of relatively narrow isochemical plumes which appear blurred due to the nonideal distribution of sources and receivers used in the tomographic process. In collaboration with Jeroen Ritsema, Carolina Lithgow-Bertelloni and Lars Stixrude, we develop a multi-discipline approach (geodynamics-tomography-mineral physics) to analyze conceptual geodynamical models that have been filtered by the resolution matrix of the tomographic model S20RTS. Using this method, which allows us to quantify the effects of heterogeneous resolution in seismic images, we aim to distinguish between thermochemical structures and thin isochemical upwelling as the cause of the seismic anomalies. Using wavespeeds derived from first-principle mineral physics, we consider both spherical thermochemical and isochemical geodynamic convection models with imposed plate history for recent geologic history. We show that although both isochemical and thermochemical structures in the geodynamic models undergo some degree of blurring during filtering, the thermochemical model is better able to recreate the anomalous structures observed in tomography. We also choose to investigate the influence which the imposed core-mantle boundary temperature has on the geometry of the anomalous structures in our filtered geodynamical models, demonstrating that the temperature at the base of the mantle is an important parameter to constrain when considering models of lower mantle structure.

^{40}Ar , eclogite and the evolution of Venus internal dynamics

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Although it is often termed Earth's 'sister planet' due to similar mass and size, Venus today probably lacks many of the characteristics typical of the Earth. This is true for example, in terms of global dynamics of the solid interior and their surface manifestation - the most interesting question here being rather 'why does Earth get plate tectonics?' than 'why Venus does not?'; a key feature that models of Venusian evolution addressed, for example, deals with the apparently random distribution of impact craters implying a mean surface age of about 0.3-1 Ga. Theories about this 'resurfacing' history generally involve one of the two following scenarios:

- an episodic evolution (e.g. with plate tectonics events or periodic Rayleigh-Taylor like instabilities) with the last of such events corresponding to the global resurfacing,
- a transition from one dynamical regime to the other (layered to whole mantle, time-dependent to steady convection, plate tectonics to stagnant lid).

In this study, I consider various scenarios mimicking the several evolutions mentioned above and confront these with other constraints than the age of the resurfacing event such as the outgassing history and today's lithosphere characteristics (thickness, heat flux). Simple one-dimensional evolutions based on scaling laws (tested against fully spherical convection models in a few cases) are used for their rapidity - the most discussable aspect in these models is likely to be the treatment of magmatic transport from depth to surface.

Although the parameterized models clearly need to be extended and although the uncertainty on the constraints used here (heat flow, lithosphere thickness, argon budget in the atmosphere) is large, strong conclusions are obtained for relatively wide ranges of parameter values: among the proposed models, internal histories with no recycling of the lithosphere during at least the second part of Venus evolution are favored thus indicating that the last 'resurfacing event' should be of magmatic (rather than tectonic) origin. The relatively low argon content of Venus lithosphere as well as various estimates of the lithospheric state are well described by successful models.

The effect of post-perovskite rheology on the deformation of slabs in the lowermost mantle

Hana Čížková¹, Ondřej Čadek¹ and David A. Yuen²

Recent evidence on perovskite to post-perovskite phase change in the lowermost mantle suggests, that post-perovskite piles or lens should be present in the relatively cold downwelling areas, while hot upwelling plumes consist of perovskite. It has been suggested by Carrez et al. (2007), that rheology of post perovskite is dominated by dislocation creep and there are some indications that the activation parameters of dislocation creep in post-perovskite induce lower viscosity than is the viscosity of perovskite at the same pressure and temperature conditions. That can result in a viscosity inversion in the lowermost mantle - viscosity in cold downwellings transformed to post-perovskite might be lower than viscosity of warm perovskite plumes. Such a viscosity structure was indeed recently reported by Čadek and Fleitout (2006). Here we further investigate the dynamics of the cold slabs transformed to post-perovskite in the lowermost mantle. We perform simulations of convection in a 2D cartesian model with composit rheology including diffusion creep, dislocation creep and power-law stress limiter. Different creep parameters are used for upper mantle material, lower mantle material and for post-perovskite respectively. We concentrate on the effect of post-perovskite rheological weakening, on slab-plume interaction and possible consequences for seismic anisotropy in the D''.

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Xenon constraints on the thermal history of the Earth

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There is still a controversy over the thermal evolution of the Earth and particularly about its early history. The evidence of a hotter mantle in the Archean comes mostly from the relative abundance of the magnesian lavas (komatiites) within the old cratons. But the thermodynamic conditions needed to generate them are disputed such that the proposed cooling since the Archean lies between 100 to 500K [1]. Furthermore first principle models of thermal history have difficulties avoiding unrealistically high cooling rates and thermal catastrophe [2,3], leading several authors to reconsider the sensitivity of heat flow parameterizations to mantle temperature [4]. As a consequence, further approaches are needed to better understand early Earth geodynamics and the onset of plate tectonics. In this study, we show how the isotopic Xenon signature of mantle rocks can constrain the thermal and degassing histories of the mantle. To account for the present day Xenon data, the mantle must have cooled very efficiently within the first 700m.y. before cooling at a slow modern rate through plate tectonics. We predict that the mantle has been partially melted about 8 times since its formation, 6 times during the Hadean alone when magmatic heat loss was dominant.

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When hot thermochemical instabilities trigger subduction and continental growth

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Cratons generation often starts with massive mafic-ultramafic volcanism, to climax about 30 m.y. later with intrusion of voluminous granitoids. In terms of mantle dynamics, the first episode could be created by a mantle plume, while the second corresponds to subduction. To understand this sequence of events, we have studied the circulations induced by the onset of thermochemical hot instabilities at the bottom of the mantle, using laboratory experiments. A strongly temperature-dependent viscosity fluid, glucose syrup, was used. Initially a thin layer of syrup, made denser by the addition of salt, was at the bottom of the tank. Then the tank was heated from below and cooled from above. The temperature and velocity fields were measured in situ using thermochromic liquid crystals and PIV. The experiments were run for low buoyancy numbers, in the regime where episodic hot thermochemical doming occurs. The presence of denser material at the bottom of the tank delays the onset of hot instabilities, and convection usually starts by cold downwellings. Then hot domes develop from the hot chemically denser layer, with a morphology of cavity plumes since they are less viscous. When they hit and spread under the top surface, they peel off the cold thermal boundary layer there. This triggers a ring of enhanced cold instabilities around each thermochemical dome. The velocity of the cold downwellings is significantly increased compared to its value in absence of domes. Scalings laws derived from the experimental data suggest that this sequence of events is similar to what was observed on Earth in the archean. Moreover, such a mechanism could explain geophysical observations around the Ontong-Java and Caribbean plateaus.

A comparison of finite difference formulations for the Stokes equations in presence of strongly variable viscosity

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Numerical modeling of geodynamic problems typically requires the solution of the Stokes equations for creeping, highly viscous flows. Since material properties such as effective viscosity of rocks can vary many orders of magnitudes over small spatial scales, the Stokes solver needs to be robust even in the case of highly variable viscosity. Currently, a number of different techniques (e.g. finite element, finite difference and spectral methods) are in use by different authors. Benchmark studies indicate that the accuracy of the velocity solution is satisfying for most methods. The accuracy of deviatoric stresses and pressure, however, is typically less than that of velocity. In the case of highly variable viscosity, some methods even result in oscillating pressures. This problem becomes particularly important in coupled problems, where the pressure feeds back to the solution. An example of such coupled problems is melt migration through deforming viscous media.

The purpose of this study is therefore to evaluate the accuracy of the pressure solution for a number of numerical techniques. Thereby, we make use of a recently developed 2D analytical solution for the stress distribution inside and around a viscous inclusion in matrix of different viscosity subjected to pure-shear or simple-shear boundary conditions (Schmid and Podladchikov, 2003). Results will be presented for a staggered grid velocity-pressure finite difference method, a stream function finite difference approach and a rotated staggered grid velocity-pressure finite difference method.

The setup of the viscosity within the numerical grid is extensively discussed since it strongly affects the accuracy of the results. The problem is investigated by studying a simple physical 1-D model with a contact of two media representing the contact between an inclusion embedded in a matrix (2-D case). Mathematically and numerically, it is demonstrated that interpolation of the viscosity using a harmonic average leads to the best results.

The developed finite difference codes have furthermore been compared with analytical solutions for a constant viscosity mid-oceanic ridge and for density driven flow (the Rayleigh-Taylor instability).

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Plate strength drives trench motion:

Insights from numerical models

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Subduction operates by bending of the lithosphere plate at trench. During the bending, the lithosphere weakens loosing some of its strength. The variation of the slab strength at trench has consequences on the kinematics and dynamics of subduction. Thus, the motion of the plate at convergent margin is partitioned on the Earth's surface between advancing and retreating modes and is susceptible to abrupt changes in velocity and direction.

Here we explore the idea that trenches motion represents the surface manifestation of the dynamics of subduction. We performed three-dimensional numerical models of self-consistent subduction zones in an attempt to understand the complex trench dynamics. Numerical models allow a quantitative investigation of a wide range of parameters and the assessment of derived quantities such as the amount of energy dissipated during the whole subduction process. The adopted model setup is as simple as possible.

Simulating a multilayered lithosphere-upper mantle system, we found that slabs with different geometries and rheological properties interact differently with the 660-km discontinuity, which is modeled in this case as an impermeable barrier. The main driving force is the slab pull deriving from the negative buoyancy of the downgoing lithosphere; the viscous resistive forces arise from the coupling of the mantle flow and the plate motion. Strong (thicker/high viscous/less dense) plates move in advancing style, while weak (thinner/less viscous/denser) plates move in retreating style. The energy dissipated in the system varies during the several phases of process and also, it is partitioned differently between slab and upper mantle depending on the subduction mode. In both advancing and retreating (rollback) modes, most of the total initial energy is dissipated by the mantle, around 60% and 70%, respectively. The extra 10% in the retreating mode is caused by a more vigorous backward toroidal flow compared with forward toroidal flow in the advancing style. Furthermore, the rollback motion is the favorable configuration

from an energy point of view. In the intermediate situation, plates fold and pile up on the discontinuity. In this mode, the plate dissipates around 60-65% of the total energy, with an evident minor contribution of the surrounding mantle.

We conclude that the potential energy provided by the negative buoyancy of the subducting plate is mainly dissipated by the mantle viscous flow, and the remaining part to bend and deform the lithosphere.

Probing the uppermost mantle rheology using surface deformation associated with the Lake Mead load fluctuations

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Water level fluctuations in the Lake Mead (Basin and Range, USA) act as a time varying load on the lithosphere. The monitoring of the surface deformation induced by the water load is performed by InSAR using ERS-1, ERS-2 and Envisat radar acquisitions between 1992 and 2007. The comparison between load and deformation could bring constraints on the uppermost mantle viscosity structure, provided a sufficient accuracy of InSAR measurements.

Interferograms from ERS-1 and ERS-2 SAR acquisitions were previously calculated and inverted to retrieve the temporal and spatial subsidence around lake Mead between 1992 and 2001. A peak to peak subsidence of 1.5 cm is recorded between 1995 and 1999 and corresponds to 10m of lake level increase. It was shown in a previous study that the ground motion evolution can be closely associated with the load/unload of lake Mead water level fluctuations (Cavalié et al., J. Geophys. Res, 2007). The ground motion amplitude, evolution, and pattern could be best explained by a visco-elastic rebound of the lithosphere-asthenosphere, with a 30 km thick elastic plate overlying a 10^{18} Pa.s asthenosphere.

In order to provide further constraints on the lithosphere and asthenosphere rheology it was found necessary to extend the monitoring of surface deformation up to 2007. We need, in particular, to record the uplift that is associated with the drastic lake level fall (30 m) from 2000 to 2004. This should theoretically allow to measure not-in-phase ground motions with respect to loading, that were not yet clearly visible in the 1992-2001 time series. To achieve that goal, we use Envisat data from 2003 to 2007, and a few additional ERS-2 data from 2004 to 2007, acquired with a "reasonable" Doppler centroid frequency. The link between the ERS 1992-2001 and the Envisat 2003-2006 time series is obtained through a few cross-platform ERS/Envisat interferograms and a few ERS-2 interferograms covering the data gap in 2002-2003. We shortly describe (1) the mitigation of atmospheric artefacts, (2) the formation of cross-platform ERS/Envisat interferograms. More than 350 -ERS/ERS, ERS/Envisat and Envisat/Envisat- interferograms, performed with the JPL ROI-PAC software, are then included in an inversion to obtain maps of the ground subsidence from 1992 to 2007. We give the elastic thickness and asthenosphere viscosity that allow the best adjustment between the model and the spatial and temporal behavior of the inverted displacement. Although extended to 2007, the ERS-Envisat displacement time series accuracy is still marginally acceptable to place strong constraints on a complete asthenosphere/lithosphere layered mechanical behavior.

Exploring the model space of thermo-chemical convection using spherical geometry Deschamps F.(1), P.J. Tackley(1), Duchoiselle L.(1)

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Inferring the thermo-chemical structure of the Earth's mantle is a key problem in geophysics. Both thermal and chemical sources contribute to lateral variations in density, and the mode of convection strongly depends on the relative strength of these two sources. The thermo-chemical structure of the Earth's mantle is a central framework, because it can be linked to many fields of geophysics: mineral physics gives insight on the thermochemical properties of the mantle mineral assemblage; seismic tomography maps heterogeneities in the mantle from observed seismic data; geodynamics, and in particular numerical models of convection, predict mantle flow and structure for a given set of input parameters and properties. Among the important parameters that control the mode of convection are the buoyancy ratio, the thermal expansion, the geometry, and the presence of a phase transition. Because each mode of convection predicts a distribution of temperature and composition, it can be tested against geophysical observations that are sensitive to these distributions, mainly seismic data. In particular, probabilistic tomography maps chemical heterogeneities throughout the lower mantle and a successful thermo-chemical model of convection will have to be able to maintain such heterogeneities over long period of time: Exploring the model space of 3D cartesiens thermo-chemical convection, we found that a phase transition at 660km can play that role. The viscosity ratio between the dense and regular material is also likely to play an role we now focus our search on the role of the post-perovskite phase transition using thermochemical models of convection with spherical geometry.

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Small-scale convection under mid-oceanic ridges: influence of transform faults

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Small-scale convection develops at the base of oceanic lithospheres during their cooling history. This small-scale convection has often been mentioned to be responsible for seafloor topographic flattening (Stein and Stein, 1992; Dumoulin et al., 2001), although other phenomena have been invoked (Zhong et al, 2007). In any case, the development of small-scale convection might have an impact on the thermal structure of oceanic lithospheres, seismic anistropy, partial melting, gravity anomalies...

In this study, we focus on the influence of a transform fault (TF) on the initiation, development and geometry of small-scale convection. 3-D numerical models, using a multigrid code (Choblet and Parmentier, 2001) are performed over a wide range of parameters (Rayleigh number, viscosity temperature-dependence, spreading rate...). We observed that advection schemes seem to have a strong influence on the onset and on the geometry of thermal instabilities. Different schemes are therefore tested and discussed.

Former 2D studies tend to show that topography of lithospheric isotherms (ie, lateral thermal heterogenities) induce smaller onset times (Huang and Zhong, 2003; Dumoulin et al., 2005). Here, the third direction allows material to flow inside the lower part of the lithosphere, in a direction depending on the topographic step (created by the coexistence of two lithospheres of different ages) and on the spreading. This flow moves the topographic step ("TF trail" on figure) farther and farther from the initial position of the TF, in the older part of the lithosphere, during ageing. Furthermore, the onset time of small-scale convection, on both sides of the TF, does not seem smaller than for a case without TF.

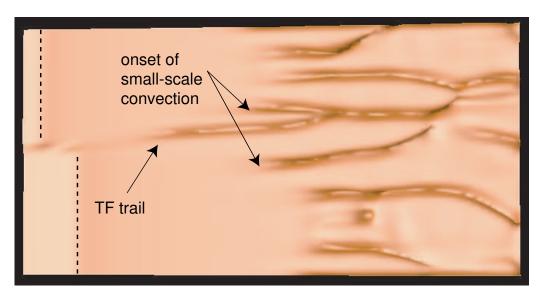


Figure 1: Isotherm of the base of the lithosphere.

10th International Workshop on Modeling of Mantle Convection and Lithospheric Dynamics

September 2-7, 2007, Carry-le-Rouet, France

Abstract

Rheology of ice in glaciers and polar ice sheets: experimental results and modelling

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The slow motion of polar ice sheets is governed by the viscous deformation of anisotropic ices. Strain rates and temperature are respectively between 10^{-9} and 10^{-13} s⁻¹ and between -57°C and the ice melting point. The viscoplastic deformation induces the development of lattice preferred orientation (textures) giving a nonrandom orientation of the c-axes in the largest part of ice sheets. Initially isotropic ice formed after the transformation of snow into ice becomes anisotropic as textures develop. But, recrystallization textures associated with dynamic recrystallization are also found near the bottom where temperature is the highest. Up to now, numerical models describing the flow of ice sheets have not accounted for the evolution with depth of the anisotropy of such ices.

Several approaches are used to simulate the behavior of anisotropic ice. Micromacro models consider a representative volume of ice as an aggregate of grains, a polycrystal and, assuming that the behavior of the grain is known (the micro-scale), these models give the macroscopic behavior of the aggregate by a homogenization procedure. The computation of the mechanical behavior of anisotropic polycrystalline ice using a *self-consistent* approach is nowadays a standard approach. These models consist in regarding each crystal of the polycrystal as an inclusion embedded in an infinite homogeneous equivalent medium whose the

behavior represents that of the polycrystal. A good prediction of the mechanical behavior of anisotropic ices is obtained on condition that stress and strain rates fluctuations within grains are introduced in such models.

Single crystals undergo plastic deformation as soon as there is a component of shear stress on the basal plane. Basal slip is observed for shear stresses in the basal plane lower than 0.02 MPa and takes place from the motion of basal dislocations with the $a/3 < 11\overline{2}0 >$ Burgers vector. Non-basal slip associated with the cross slip of basal screw dislocations is invoked for the multiplication of dislocations. But, its contribution to the deformation of the ice crystal is very small. Due to the low lattice friction, dislocations glide cooperatively and long-range internal stresses develop with deformation. The plastic deformation takes place through isolated bursts or dislocation avalanches as soon as diffusion processes are not significant.

At the both scales of the ice crystal and the polycrystal, the deformation is highly heterogeneous. This behavior is associated with the anisotropy of the ice crystal and the mismatch of slip at grain boundaries for the polycrystal.

After an introduction on the deformation conditions in glaciers and polar ice sheets, I will describe the creep behavior of the ice crystal and the polycrystal with emphasis put on physical processes which produce and control the deformation. The development of textures and recrystallization processes will be specially discussed. Micro-macro self-consistent models used to simulate the deformation of anisotropic polycrystals will be shortly described. Finally, an overview of the flow of polar ice sheets will be given. Variation of the ice viscosity in glaciers and ice sheets will be given. These data could be useful when looking for the behavior of ice in Europa.

Retrating continental plate: numerical modeling and observations

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Subduction zones are sites where a dense plate sinks into the mantle. Mostly, oceanic plates are good candidates for such a behavior, but in few cases a subducting (and retreating) continental plate is observed at trenches. We performed some numerical models of oceanic/continental subduction with thermo-mechanical I2VIS code (Gerya and Yuen, 2003) that account for dehydratation reactions and other phase transformations, and we compare results with the Northern Apenninic belt, where a huge amount of geological/geophysical data are avalaible. Results show that water released from the initially subducting oceanic plate creates with time a hydrated interface between the two plates that lessens plates coupling. When the subducting slab reach a reasonable depth such that the pulling force overcome plates coupling and the horizontal velocity field stresses, the subducting slab starts to retreat pulling down togheter the continental plate. Weak crustal material is scraped off by the uprising asthenospheric wedge and thrusted landward. An extensional (on the back) and compressional (on the front) waves, togheter with the coast line and the mountain belt, migrate toward the foreland. The extensional domain is characterized by thin continental crust, high heat flux and magmatism, while the compressional zone has thick crust, low heat flux and deep seismicity due to the thicker brittle layer. Results are consistent with what observed in the Northern Apenninic belt, supporting the idea that the Apennines are the result of a retreating continental plate.

Plate formation in a mantle convection model: The effect on the dynamic topography

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With increasing computer power the numerical simulation of mantle convection becomes easier, allowing more complex models of mantle convection. In such a way characteristics of rheological aspects like variable viscosity can be investigated. A result of temperature- and stress-dependent viscosity is the occurence of serveral flow regimes like the stagnant-lid, the episodic and the mobile-lid regime (Stein et al. (2004), Phys. Earth Planet. Int 142, 225). In this study we examine the surface signal different flow regimes induce, in particular we consider the dynamic topography Δh . It can be computed by assuming the boundary condition that normal stress on the surface is zero. This leads to

$$\Delta h = \frac{1}{\rho g} \left(P_D - \sigma_{zz} \right),\,$$

where ρ is the density of the mantle material, g the gravitational acceleration, σ_{zz} the normal part of the stress tensor and P_D the dynamic pressure. Our model uses primitive variables, so that the dynamic pressure is directly available to calculate the topography.

We present a selection of two- and three-dimensional simulations in several flow regimes and their relating flow structure. We show different styles of plate formation on the surface and their effect on the topography.

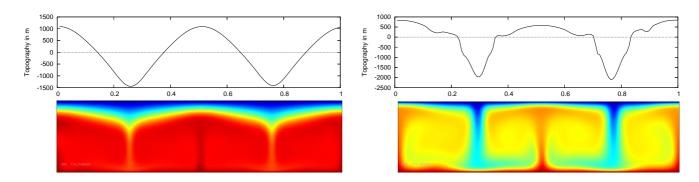


Figure 1: Two examples of mantle convection in different flow regimes. A snapshot of the temperature field and the relating topography at the surface are shown. On the left hand side the flow forms a stagnant lid and on the right hand side a mobile lid is established. This two examples show differences in the roughness of the topography.

Dynamics and internal structure of a mantle plume conduit

Recent studies on Hawaiian lavas, including those made possible by the 3000m drill core into Mauna Kea Volcano (Hawaiian Scientific Drilling Project, HSDP) have provided a rich detail of the plume compositional heterogeneity, which is seen on several length and time scales, ranging from differences in melt inclusion compositions of single olivine crystals to broad differences between the two parallel volcanic chains (the so called Kea and Loa trends).

However, the interpretation of such observations in terms of plume internal structure is far from straightforward and several models have been proposed. The pioneering work by Hauri et al., (1996) suggested a concentrically zoned plume structure induced by entrainment of surrounding mantle, while more recent models interpret the shorter-term compositional fluctuation of the HSDP lavas as reflecting predominantly vertical fluctuations of the rapidly rising plume (Blichert-Toft et al., 2003) or predominantly horizontal variations associated to vertical filaments in the plume conduit (Abouchami et al., 2005).

Clearly, a better understanding of how the geochemical observations reflect the actual compositional structure of the plume requires an understanding of plume dynamics. Deep mantle plumes are often thought of as thermal structures, the key parameter being their excess temperature with respect to the surrounding mantle, while the associated velocity field is frequently neglected. However, in order to understand the internal structure of a plume conduit it is necessary to change perspective and focus on velocities and strain rates. Like the hands of an invisible sculptor, velocity gradients constantly modify the shape of heterogeneities rising in the plume conduit.

Our high resolution numerical simulations show how initial heterogeneities in the basal thermal boundary layer evolve as they are drawn into into the plume conduit and transported upward in the Earth's mantle, and subsequently how they are deformed when the plume approaches a fast (9 cm/yr) moving oceanic lithosphere. Our two main objectives are: First, to investigate the relation between initial length-scales of heterogeneities across D" and the length- and time-scale of geochemical variations induced in the plume conduit. Second, to investigate the relation between heterogeneous structures in the mantle plume and the spatio-temporal geochemical variability registered by the volcanos drifting over an heterogeneous plume.

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WHAT BRAKES FOR PLATE TECTONICS?

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What is the relative importance of interplate friction, of dissipation in the bending zone, of deeper viscous resistive stresses and of processes linked to phase transitions for supporting the subducting slabs? Short- and intermediate-wavelengths gravity and geoid anomalies are used to provide constraints on the mechanical structure of subduction zones and on the forces involved.

This study is based on 2D cartesian dynamically self-consistent models with Newtonian and power-law rheologies. For Newtonian models, we show that both strong decoupling (t $\sim 10^7 Pa$) of the two convergent plates and weakened bending lithosphere are necessary to reproduce the observed geoid and gravity data. The former impedes stress transmission from the slab upward to the upper plate, preventing the development of a large gravity down-warping over the arc. The latter is required to avoid unreasonably large trenches and forebulges. For high values of the stress exponent, models with a power-law rheology display a relatively thin "fault-like" weak zone, which naturally emerges without the need for any predefined faulting region. Good fit to gravity data is found for a relatively low failure stress (~ 3-5.10⁷Pa). The models which do not fit the gravity data because of a too stiff rheology in the decoupling or bending region are also characterized by plates which tend to fall vertically. For all models providing a reasonable fit to the gravity data, only a small fraction of the weight of the down-going slab (~ 3- 6.10¹²N/m, less than the equivalent of a slab section 100km long) is transmitted to the surface plates. About 10% of the energy is dissipated in the contact zone between the two plates, 10% to 20% in the bending region, and more than 70% in the sublithospheric mantle. The shear stress on a plane at 80km depth (bottom of the lithosphere) has a large amplitude both in the plate-slab contact zone and below the arc, with a sign reversal between these two regions. These basal tractions tend to pull the two plates towards each other (forces of the order of $\sim 1-4.10^{12}$ N/m). However, the net shear-stress may be non-zero. This results in a net motion of the plates with the subducting plate moving faster than predicted by the no-net motion principle. As the models which fit the short-wavelength gravity anomalies are characterized by a slab mainly supported from below, in the case of pure whole mantle convection, a marked positive geoid anomaly is predicted above subduction zones at medium wavelengths(l=2000-4000km). Such large geoid highs are not observed. Introducing 'partial layering' linked to the phase transformations is necessary to reconcile model predictions and observations for these medium wavelengths.

The Stability and Instability of Continents

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Although ancient continents are commonly described as stable, many of them underwent major perturbations, not only on their margins, but also within their interiors. As they occurred far from oceans basins and they are not related to other tectonic events, such perturbations have been explained as consequences of mantle plumes, or, relying on plate tectonics analogies, as processes due to forces applied at continental boundaries. The difficulty in interpreting these events relies on a lack of competing explanations and limited knowledge on the dynamics of the continent-mantle system.

In order to better constrain conditions for continental stability, we conduct numerical simulations in which we consider a two layered system and use active tracers to track lithospheric evolution. Lithosphere density, intrinsically lower than mantle density, is allowed to vary as well as its thickness, temperature gradient and viscosity which depends on tracers concentration and temperature. Therefore we investigate a wide range of values for the governing parameters.

Our results are in good agreement with laboratory experiments which show that convective stability of lithosphere depends strongly on both the critical Rayleigh number, Ra_c , and the buoyancy number, B. We are particularly interested in (B, Ra) values close to the instability threshold to reveal the underlying dynamic processes.

In parallel, laboratory experiments are carried out to characterize the processes affecting continental lithosphere of finite horizontal extent. Experiments and numerical simulations allow us to study the geometry of lithospheric instabilities and compare the observed behaviour (e.g. uplift/subsidence, magmatism, heat flow variations) to geological and geophysical observations.

Laboratory Models of Subduction: State of the Art

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The use of experimental tectonics to study tectonic processes is not a novelty in Earth Science. Following *Sir James Hall*'s pioneer work (1815), many modellers squeezed, stretched and pushed inexpensive materials like sand, clay, oil, painters's putties, gelatins, wax, paraffin, syrups and chocolate to simulate geological structures present in nature with the aim to determine parameters that control their origin, development and final geometry. However only recently the experimental analogue modeling had been advanced considerably. Thanks to the proper scaling relationships and the improvement in the knowledge of the rheology of both natural and model materials, experimental tectonics is proving to be a useful and relatively cheap technique to study tectonic processes. Experimental tectonics has examples both in large-scale geodynamic applications (subduction, evolution of thrust belts, formation of basins, pluton emplacement, mantle and crustal convection) and in smaller scale structural geology (faults, folds, diapirism, boudinage).

To illustrate what is a laboratory model, the information can be extracted from and how they can be applied to natural system I will try to review the experimental works performed in the last decades in laboratory to reproduce one of the most intriguing aspect of the Plate Tectonics: the subduction process. In particular, it will be illustrated how has been experimentally studied the "life" of a slab, from its birth to the interaction with the 660 km discontinuity at depth. highlighting differences between kinematically prescribed and dynamically self-consistent models, 2D-like and 3D models and, weak- and stiff slab models.

Large scale mantle dynamics modeling

Thomas Geenen, Arie van den Berg and Wim Spakman. Faculty of Geosciences, Mantle dynamics group, University Utrecht

To model the geodynamic evolution of plate convergence, subduction and collision and to allow for a connection to various types of observational data, geophysical, geodetical and geological, we developed a 4D (space-time) numerical mantle convection code. The model is based on a spherical 4D Eulerian fem model, with quadratic elements, on top of which we constructed a 4D Lagrangian particle in cell(PIC) method. We use the PIC method to transport material properties and to incorporate a viscoelastic rheology. Since capturing small scale processes associated with localization phenomena require a high resolution, we spend a considerable effort on implementing solvers suitable to solve for models with over 100 million degrees of freedom. We implemented Additive Schwartz type ILU based methods in combination with a Krylov solver, GM-RES. However we found that for problems with over 500 thousend degrees of freedom the convergence of the solver degraded severely. This observation is known from the literature [Saad, 2003] and results from the local character of the ILU preconditioner resulting in a poor approximation of the inverse of A for large A. The size of A for which ILU is no longer usable depends on the condition of A and on the amount of fill in allowed for the ILU preconditioner. We found that for our problems with over 5×10^5 degrees of freedom convergence became to slow to solve the system within an acceptable amount of walltime, one minute, even when allowing for considerable amount of fill in.

We also implemented MUMPS and found good scaling results for problems up to 10^7 degrees of freedom for up to 32 CPU's. For problems with over 100 million degrees of freedom we implemented Algebraic Multigrid type methods (AMG) from the ML library [Sala, 2006]. Since multigrid methods are most effective for single parameter problems, we rebuild our model to use the SIMPLE method in the Stokes solver [Patankar, 1980]. We present scaling results from these solvers for 4D spherical models. When dealing with problems of this size efficient data storage becomes essential. We describe a general purpose interface that allows for the distributed, compressed storage of large datasets in VTK XML format, using compression routines from the PNG library.

We rely on the meshing application developed by van Thienen to provide high resolution 3D spherical meshes (see poster "Finite element meshing of threedimensional faulted domains")

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Shell tectonics - the pre-cursor of mantle convection

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The early stages of terrestrial planetary accretion and differentiation are largely enigmatic and require extensive realistic numerical modelling efforts especially in 2D and 3D geometries. One of the hypothesised processes is destabilization of the cold undifferentiated core that builds up during "cold" accretion, by a surrounding liquid iron layer that builds up through iron segregation in a magma ocean, or by the accumulation of 'blobs' sinking from local magma ponds. This destabilization breaks the spherical symmetry of the planet and, therefore, can not be addressed properly in existing 1D models of accretion. We have developed a 2D thermomechanical numerical model of primordial core destabilization including self-gravity, visco-elasto-plastic rheology of materials, a free planetary surface and feedback from shear heating. By varying the size of the planet and metal/silicate ratio we tested various cases corresponding to early stages of terrestrial planet growth. Primordial core destabilisation causes rapid planetary scale reshaping that we call "shell tectonics" as the units involved in rearrangements are planetary shells. The gravitational redistribution process lasts for less then 1 Myr (depending on the effective rheology), being fully dominated by shear heating and thermal advection. Internal gravitational redistribution processes result in planetary shapechanging revealing significant transient aspherical deviations from the original perfectly spherical geometry. During this stage the primordial core can become exposed at the planetary surface making possible its reworking during ongoing accretion processes. Most of the enormous amount of heat is produced during this very short time span associated with the core-formation and is then chaotically distributed throughout both the core and the mantle. Gravitational energy dissipation along the localized deformation zones dramatically increases rates of rearrangement and can potentially result in thermal runaway processes and sudden primordial core fragmentation. The magnitude of thermal perturbations can reach several thousand degrees, which cataclysmically raises the effective Rayleigh number for the planetary mantle to a very large number favouring onset of powerful mantle convection and possibly results in the formation of a magma ocean with the molten mantle rocks rising from the deep planetary interior. In future work, such instabilities will be considered in the context of ongoing planetary accretion in 2D or 3D rather than starting from the end state of a 1D accretion model.

Towards geodynamic interpretation of seismic mantle structure

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Seismology has probably yielded the most tantalizing images of the Earth's interior, yet their geodynamic interpretation is not straightforward, due to limits on seismic resolution and uncertainties in how seismic velocities depend on temperature, pressure and composition. Furthermore, available data do not fully constrain the mantle's seismic structure. So, although published seismic models represent optimum data fits (in some sense), other models may also be acceptable, leaving room for alternative interpretations. The first direct interpretations of 1-D seismic models provided some very strong geodynamic constraints on the approximate composition of the mantle, the existence and nature of the transition zone, and on the relative homogeneity of the lower mantle. Since then tomographic images on scales ranging from global (1000's km) to local (few kms) have provided various insights in the dynamic deviations from this spherical background structure. Most prominent in these is the expression of subducted material in upper and lower mantle, continental roots, and two large slow regions in the deepest lower mantle. The detailed interpretation and composition of each of these remains a topic of debate, although in recent years it has become increasingly clear that not only thermal structure, but also compositional variations play a significant role in mantle dynamics. Other topics of controversy are the existence, structure, and role of mantle upwellings, whether the base of the transition zone corresponds to a boundary layer in any sense (i.e., possibly temporally and spatially discontinuous), and what the exact contributions of chemical differentiation and thermal structure are to the boundary layers on the mantle's top, the lithosphere, and its base, encompassing the seismic D". Because of the non-uniqueness of seismic models, the most promising way to improve our understanding seems to step away from direct interpretation and instead turn towards the testing of geodynamically plausible hypotheses against the data, increasing them in complexity if justified by I will discuss some examples for the mantle's spherical significant data misfits. background structure (what is its physical meaning?), for the structure of the lithosphere and asthenosphere (can we distinguish the signature of composition and melt from temperature?), for subducting plates (how much material is located where and when was it subducted?), and for possible active mantle upwellings (what should they look like and is this imagable?). I will cover aspects of seismic sensitivity, methods and uncertainties for converting thermo-chemical structure into seismic velocities, and show results from dynamic hypothesis tests of our and other groups.

Earth's core formation aided by flow channelling induced by Rayleigh-Taylor instabilities

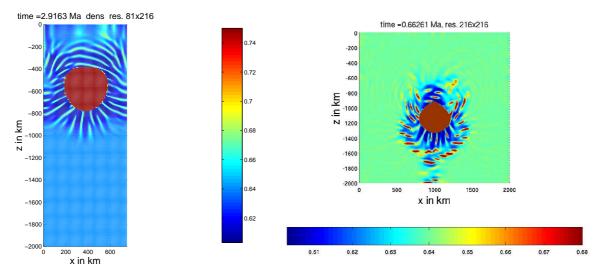
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The core formation process remains poorly known. Isotopic constraints by Hf/W systematics indicate a fast process which was largely completed within 33 Ma for the Earth. An unstable gravitational configuration of a dense molten metallic layer overlying a cold chondritic protocore is predicted by most studies, which leads to the formation of a Rayleigh-Taylor instability. We propose the application of Stevenson's (1989) stress-induced melt channelling mechanism in the region surrounding an incipient iron diapir. We therefore perform numerical experiments solving the two-phase, two compositions flow equations within a 2D rectangular box with symmetrical boundary conditions. We apply the Compaction Boussinesq Approximation (CBA) and include a depth-dependent gravity. For simplicity we use a constant viscosity for the solid phase and melt-fraction dependent rheology for the partially molten region around the diapir.

A systematic investigation of the physical conditions under which the melt channels can form in comparison with the isotopic time scale of core formation and whether they are applicable to the early Earth is in progress. As a result, for sufficiently small retention numbers iron-rich melt channels develop within a region of approximately twice the diapir's size as shown on Fig. 1a. This could lead to effective draining of the surrounding region and might initiate cascading daughter diapirs (Fig. 1b). The region of the protocore drained by this cascading mechanism is expected to significantly increase with depth, and thus proposes an effective mechanism to extract iron melt also from deeper parts of the initially chondritic protocore. This mechanism could effectively enhance melt accumulation in the protocore, accelerate the process of core formation and affect the metal-silicate equilibration.



- a) Density plot showing the development of melt channels
- b) Density plot showing the formation of small daughter diapirs

Figure 1. Induction of flow channelling and cascading mechanism

Onset of plate tectonics and the effect of continental-like heterogeneities

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One of the first order and still debated questions in Earth sciences is why the Earth exhibits plate tectonics. Understanding the onset and development of plate tectonics in terrestrial planets is a key to the comprehension of the internal dynamics of planets and of their thermal history.

What controls the appearance and the position of weak zones at the surface of a planet? What dictates the shape of the plates, their velocity and motion direction? These questions are still open and can be addressed by numerical modelling of mantle convection with an approach that allows the self-consistent development of rigid plates and of weak zones, marking the boundaries of these plates.

We use the approach described by Moresi and Solomatov (1998) and Tackley (2000): the mantle is modelled by a fluid with a strongly temperature-dependent viscosity, which stiffens its cold upper part into a rigid lid, and this fluid exhibits plastic yielding above a given yield stress σ_y , which generates weak zones and allows to break the upper rigid lid into plates.

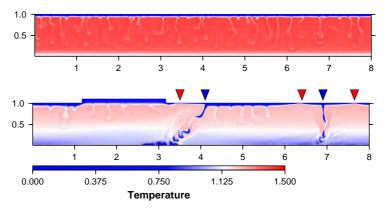


Figure 1: Fluid heated from below and from within (Rayleigh number Ra= 10^7 and internal heating rate $H=25~(\sim 15~\rm nW.m^{-3})$) with a strongly temperature-dependent viscosity (contrast $\Delta\eta=10^5$) and pseudo-plastic yielding, with a yield stress $\sigma_y=3.10^5~(\sim 250~\rm MPa)$. (Top) Without a continental lid, a stagnant-lid regime is observed. (Bottom) With a continental lid that is internally heated (H=25), a plate-like regime occurs: the red and blue triangles denote respectively the divergent and convergent plate boundaries.

One shortcoming of this method is that a fairly low yield stress σ_y (generally around five times lower than what is given by laboratory experiments on the strength of rocks) has to be used in those models in order to break the highly viscous stagnant lid. The conditions that allow the development of plate tectonics even with a high imposed yield stress σ_y will be presented.

A factor that helps the onset and the stability of plate tectonics is the presence of lateral heterogeneities at the surface of the modelled mantle. Homogeneous boundary conditions at the surface of the mantle lead to a stagnant lid regime under conditions that yield a plate-like regime when thermally insulating continental-like heterogeneities are added at the surface of the model (see figure 1). The characteristics and possible origins of such heterogeneities will be discussed. The position of weak zones and the organization of tectonic plates in regard to the position of these heterogeneities will also be addressed.

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Influence of skin formation on thermal convection

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We have investigated the characteristics of thermal convection in micelle-based viscous fluids. The rigid bottom of the experimental tank was heated from below while its upper free surface was cooled from above in a climatic chamber. The latter also allows to maintain a constant humidity. Micelle-based fluid crystallizes at low temperature (ductile solid), and is Newtonian at high temperature. Top and bottom temperatures were chosen so that during an experiment, crystallization of the upper surface occurs, forming therefore a thin skin. The thermal and velocity structures were visualized using liquid crystals and Particle Image Velocimetry. Preliminary results at low Rayleigh numbers ($Ra \sim 10^4$) show a moving upper surface and asymmetric convection patterns.

What controls passive and active mantle upwelling beneath Mid-Ocean Ridges?

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The basic mechanisms underneath a mid-ocean ridge and the magma generation are reasonably well known: The mantle is passively pulled upwards by the plate divergence and crosses its solidus temperature at 50-100km depth. However, the details of subsequent processes (e.g. melt migration mechanisms or the reason(s?) for melt focusing) remain much less well understood.

Using a newly developed Finite Element Code we reproduce some numerical calculations done in the early Nineties by Turcotte and Phipps Morgan [1992] and conduct several new numerical model runs to explore the structure of ridge upwelling when there is a stratified mantle rheological structure beneath the axis. Calculations including a weak and buoyant asthenosphere layer show a return flow towards the ridge within the lower asthenosphere, which also affects mantle flow and melting processes at the shallow (<100km) level.

By using a modified tracer particle advection scheme, we simulate a number of different mantle components (e.g. peridotite, pyroxenite, etc), which differ in their melting behavior and chemical trace element contents. By tracking geochemical evolution during melting, we calculate synthetic melt compositions that give us additional constraints on our calculations. We also test the influence of mantle heterogeneities of different sizes to gain more insights into the upper mantle composition that melts near a ridge axis. We find that buoyancy forces like melt and Fe-depletion become important if viscosity is lowered to about 10¹⁸Pas. Mantle flow then shows a transition from passive to active upwelling.

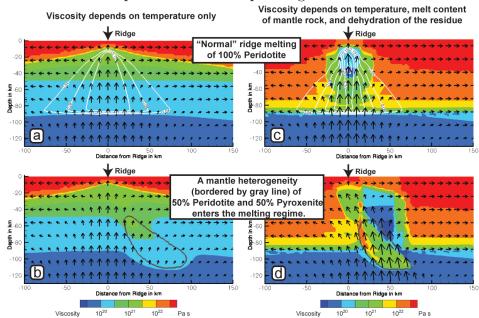


Figure 1: Flow, melting rates (white lines), and viscosity field (colors). Left pictures: Viscosity depends only on temperature. The flow field of a single-component mantle (a) is only slightly affected by the fertile mantle heterogeneity entering the melting zone (b). Right pictures: Viscosity depends also on mantle dehydration and the melt. The melting zone is narrower and bordered by highly viscous mantle (c), faster upwelling leads to higher melting rates. Enhanced off-axis melt production by a fertile mantle heterogeneity (d) weakens the mantle so that the highest upwelling rates are shifted away from the ridge. This may cause the ridge to change its morphology and/or location.

Planforms of self consistently generated plate tectonics in 3D spherical models of mantle convection

H.J. van Heck and P.J. Tackley

Abstract

In the past decade, several studies have documented the effectiveness of plastic yielding in causing a basic approximation of plate tectonic behavior in mantle convection models with strongly temperature dependent viscosity, strong enough to form a rigid lid in the absence of yielding. The vast majority of such research to date has been in either two-dimensional, or three-dimensional cartesian geometry. In the present study, mantle convection calculations where done to investigate the planform of self consistent tectonic plates in three-dimensional spherical geometry. The results are compaired to the outcome of similar calculations where a three dimensional cartesian geometry is used, as by Tackley (2000). In general, the observed structures are in line with the structures observed in cartesian geometry. Two previously unobserved planforms were found. At low lithospheric yield stresses one greatcircle downwelling formed, with fragmented oceanic plates at both hemispheres. At intermediate yield stresses two hemispherical plates formed, separated by a spreading centre and a downwelling.

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Statistical Distribution of Seismic Velocities in Earth's Deep Mantle and Dynamical Implications

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The existence of strong differences between elastic shear (S) and compression (P) wave velocity variations in Earth's mantle has long been recognized as a characteristic that might only be explained by the presence of significant chemical and/or phase heterogeneity, with important implications for the dynamics and evolution of Earth's interior. Making a one-to-one comparison between tomographic models for P and S velocity $(V_P \text{ and } V_S)$ variations for a particular geographic region is ill-posed, however, their global statistical distributions reveal several robust characteristics. We find that all of the V_P and V_S model distributions at a given depth are surprisingly Gaussian-like throughout the lower mantle. On the other hand, a distinct low velocity feature is present in V_S distributions below ≈ 2200 km depth that is not present at long periods or is relatively weak at short periods in V_P models. While the numerical damping required to stabilize tomographic inversions affects the amplitude of seismic velocity variations, the presence of anomalously low V_S material cannot be explained as an artifact, nor can the absence of a similarly strong feature in long period V_P models be ascribed to under-resolution. We propose that this kind of feature can be partly explained by laterally variable occurrences of post-perovskite in the D" layer, however, the persistence of anomalously slow V_S at heights up to ≈ 700 km or more above the core-mantle boundary is incompatible with a post-perovskite origin and might only be explained by the presence of laterally discontinuous piles of chemically distinct material and/or some other kind of phase heterogeneity. The origin of the Gaussian-like distribution of seismic velocities is puzzling since it has no straightforward explanation in terms of mantle convection. Nevertheless, there exist large discrepancies between tomographic models with respect to the width of the Gaussian-like portion and modeled peak of the distributions (indicating the most abundant velocity at a given depth) and the model baseline value. This reveals the ill-posed nature of attempting to calculate quantities such as $R = d \ln V_S / d \ln V_P$, however, adjusting the baseline values to the peak of the distributions and scaling by the ratio of standard deviations provides a clearer picture of differences between V_P and V_S , even though quantitative estimates of such differences are uncertain by more than a factor of two. Although not uniquely constrained, and subject to large errors, the results appear to be simply explained by the existence of chemical piles about 700 km in radial thickness and occupying $2\pm0.3\%$ of the mantle's volume. This is similar to the volume abundance of continental lithosphere, although the smaller surface area of the core-mantle boundary requires thicker "roots" than their shallower counter-parts.

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Time-dependent solutions for a convection problem with variable viscosity in codim-2 zones

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The formation of the rocks indicates that viscosity in the interior of the Earth and planets strongly depends on temperature, and this influence is fundamental to understanding the mantle convection and subduction motions [1, 4, 7]. This is the goal for which a convection problem with temperature-dependent viscosity in the Navier-Stokes equations is studied. The dimensionless hydrodynamics equations considered are as follow:

$$\nabla \cdot \vec{v} = 0$$

$$\partial_t \theta + \vec{v} \cdot \nabla \theta = \Delta \theta$$

$$\partial_t \vec{v} + (\vec{v} \cdot \nabla) \vec{v} = P_r \left[(R_a \theta - b) \vec{e}_z - \nabla P + \nu_0^{-1} div \left(\nu (\theta \triangle T) \left\{ \nabla \vec{v} + (\nabla \vec{v})^t \right\} \right) \right],$$

where \vec{v} is the velocity vector field, θ is the temperature field, P is the pressure, ν the variable viscosity, R_a and P_r the dimensionless Rayleigh and Prandtl numbers.

This work studies the time-dependent solutions for a convection problem with the viscosity as an exponential function of the temperature $\nu(\theta \triangle T) = \nu_0 \cdot exp(-\gamma \triangle T\theta)$ for different exponential rate γ .

The physical set-up considered is a two-dimensionless box [5, 2]. This box is subjected to an uniform heating from the bottom with a temperature higher than the upper layer. The boundary conditions for the velocity correspond to rigid and free-slip in the bottom and in the upper walls respectively.

The time-dependent solutions in codim-2 zones for different aspect-ratios, Rayleigh numbers and other parameters in which constant viscosity and strongly temperature-dependent viscosity appear are obtained.

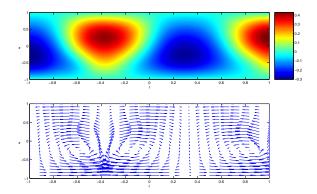


Figure 1. Time-dependent solution for $\gamma = 30000$, $R_a = 73.9497$ and l = 0.1011.

From the bifurcation study in a convection problem with temperature-dependent viscosity in a parallel infinity layer [6] and then with an appropriate change into the wave number of the stability curve the codim-2 zones are obtained.

A bifurcation study with the stability results for constant viscosity [3] and variable viscosity are also exposed [6].

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A Dynamical Model for Generating Sharp Seismic Velocity Contrasts Underneath Continents: Application to the Sorgenfrei-Tornquist Zone

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Global and regional seismic tomographic models consistently show significant variability in P- and S-wave velocity at all depths and especially in the uppermost mantle. Mineral physics experiments and thermodynamic calculations indicate that the variability in the mantle above the transition zone must be mostly due to temperature. Differences in composition (for likely mantle materials) can only account for seismic velocity perturbations of about 1%. While large temperature differences are expected in dynamically active regions such as subduction zones, mid-ocean ridges, rifts, and mantle plumes, variations in seismic wave speed of the same magnitude are commonly found also in tectonically quiet regions.

We present seismic velocity models of the Sorgenfrei-Tornquist Zone (between Denmark and Sweden) based on teleseismic traveltime tomography. Between 100 and 250 km depth, the models show a sharp lithospheric boundary with P-waves about 4% faster and S-waves 6%faster within the cratonic lithosphere to the north. The standard, static type of lithospheric temperature and heat flow modeling cannot account for such seismic velocity differences because the last major tectonic event was at least 200 Myrs ago and heat diffusion over this timescale would have largely equilibrated any initial temperature contrast. In order to explain the observations, we propose a dynamical model of convection in the upper mantle that is consistent with rheological data and that satisfies the seismic observations by maintaining an abrupt lateral temperature contrast over 100s of Myrs. A step-like increase in lithospheric thickness from 100 to 250 km is assumed to have formed in a Triassic rifting event at the Sorgenfrei-Tornquist Zone (around 220 Ma) and is subsequently exposed to active convection below. A lithosphere that is distinct from the mantle in terms of temperature and composition remains stable against convective erosion. Heat advection to different depth beneath the thin and the thick lithosphere leads to a maximum horizontal contrast of 500°C at 150 km depth over a lateral transition distance of 100 km, sufficient to generate 5% and 8% in maximum P- and S-wave velocity perturbation, respectively. A purely conductive model under the same conditions yields only $\Delta v_p \approx 1\%$ and $\Delta v_s \approx 2\%$, while a lithospheric evolution simulation without a compositional effect on the rheology leads to significant thermo-mechanical erosion of the lithosphere giving $\Delta v_p \approx 2\%$ and $\Delta v_s \approx 4\%$.

In our study, we use the Sorgenfrei-Tornquist Zone as an example because of the high-resolution seismic data available. The results are of course applicable to other regions as well where lateral differences in compositional lithospheric thickness allow mantle convection to reach different depth levels. However, while our model provides a plausible explanation for horizontal variations in seismic velocity at the lithosphere-asthenosphere interface, significant velocity variability extends much deeper. Lateral temperature differences of several hundred degrees within the convecting mantle (away from subduction zones) are difficult to reconcile with most models of mantle convection. More work is required to bring convection models and mantle tomography into agreement.

Optimal domain decomposition for 3D spherical mantle convection codes using minimal energy configurations of classical electrons

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To run a 3D spherical simulation with a reasonable resolution in an appropriate time, the code must work with more than one CPU in parallel. Typically a domain decomposition of the grid is applied, which is responsible for an optimal breakdown of the grid into p equal volumes, where p specifies the amount of domains and processors. An efficient domain decomposition minimizes the area between those sections, leading to a minimized overhead of data exchange between the processors. The resulting speedup of this method with the newly developed GAIA mantle convection code is presented in Figure 1 (right).

Halo-cells, or sometimes called ghost-cells, arise in domain decomposition as additional cells in each domain to build an overlapping zone where data is exchanged. These cells border each domain and are on the same position as their active cells on the neighboring domain. The ratio between the amount of halo-cells to grid cells is a first measure of efficiency for parallelization because it determines the amount of data transported from one domain to another.

One approach to decompose a sphere laterally is to distribute p points on the surface of a sphere so that the global potential energy becomes minimal. This is known as the Thomsom problem [Thomson, 1904]. After this step the domain affiliation for every cell is derived by its closest "Thomson" point. The resulting decomposition as shown in figure 1 leads to equal volumes which is important to balance the computational efforts for each CPU. Some p reproduce platonic solids; p=4 creates a tetrahedron, p=6 a cube and p=12 a dodecahedron. However, all p>1 show a certain symmetry [Wales and Ulker 2006].

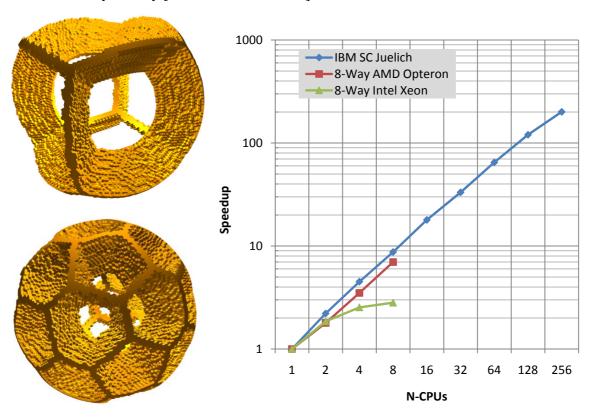


Figure 1: The resulting halo-cells after a domain decomposition of the spiral grid with a resolution of 0.55 and 24 shells. Left Top: Domain decomposition for six CPUs (equal to the cube); Left Bottom: 32 CPUs. Right: Code Speedup vs. CPUs.

Thomson, J. J. (1904), On the Structure of the Atom: an Investigation of the Stability and Periods of Oscillation of a number of Corpuscles arranged at equal intervals around the Circumference of a Circle; with Application of the Results to the Theory of Atomic Structure, *Philosophical Magazine Series 6, Volume 7, Number 39, pp. 237--265* **Wales, D. J. and S. Ulker (2006)**, Structure and Dynamics of Spherical Crystals Characterised for the Thomson Problem, Phys. Rev. B, 74, 212101

Tethyan Closure, Andean Orogeny, and Westward Drift of the Pacific Basin

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A recent global survey of subduction zone parameters highlights that the net westward rotation of the lithosphere is accompanied by a net westward drift of trenches. To explain the relationship between the drift of lithosphere and trenches, we focus on the Pacific basin, where most of the trenches and slabs are found. Because the Pacific upper mantle is almost entirely circumscribed by subducting slabs and leaks are sparse, its incompressible volume must be constant. Therefore, any trench or slab retreat must be accompanied by trench and slab advance at another location. Circum-Pacific upper plates are moving to some degree to the West, inducing compression and extension at the eastern and western Pacific trenches, respectively. We evaluate the magnitude of the forces on plates based on the kinematics of the upper plates and show that these forces are large enough to explain the asymmetrical dynamics of the Pacific domain. These forces shear the upper mantle beneath the Pacific basin at rates that are comparable to the westward drift of the Pacific plates and trenches for a typical mantle viscosity of $\sim 3\,10^{20} Pa\,s$. This Andean orogeny is the main driving force. Andean building was induced by the asymmetric spreading of the Atlantic following the closure of the Tethys and the aggregation of the gigantic Africa-Eurasia high viscosity lithospheric keel.

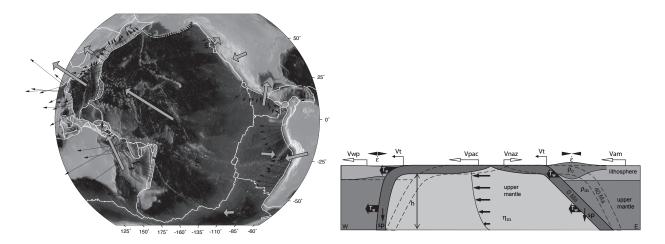


Figure 1: a) Kinematic of the Pacific domain. Black and gray arrows indicate trench and plate velocities in the hot spot reference frame, respectively; b) East-West Poiseuille flow across the Pacific domain.

Spatial Variations of Attenuation in the Mantle beneath North America from P Wave Spectral Ratio

Y. K. Hwang and J. Ritsema

Abstract

We explore spatial variations of seismic wave attenuation in the mantle beneath North America using teleseism $(30^{\circ} - 90^{\circ})$ of deep (> 200 km) earthquakes. Attenuation is quantified using the t* operator and measured from P wave spectral ratio to explore whether spectral ratio of P wave signals can be used to map the variable anelastic properties of Earth's asthenosphere. Preliminary results indicate that regional variations in t* correlate with the tectonic terrains of North America. Low values of t* are seen for stations in Canadian Shield and relatively high t* values in North American Cordillera. We will discuss a detailed comparison to surface wave Q results.

Porous Compaction in Transient Creep Regime and Implications for Melt and Petroleum Extraction

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Liquid segregation through a porous medium depends on the ability of the matrix to deform and compact. Earth's materials have a complex rheology, in which the balance between the elastic and viscous contribution to the deformation is time-dependent. We propose a Burgertype model to investigate the implications of transient rheology for viscous compaction of a porous material. The model is characterized by three dimensionless parameters: (1) the Deborah number, De, defined as the ratio of an elastic time scale over the compaction time scale, (2) the ratio of the transient and steady viscosities, λ_{μ} , and (3) the ratio of the transient and steady rigidity moduli, λ_G . For De<10⁻² the compaction occurs in the classical viscous mode and solitary waves (magmons) are generated. For larger De, compaction is mainly controlled by λ_{μ} . For small transient viscosity, compaction occurs in an elastic mode and shock waves are generated. For increasing λ_{μ} , two new regimes are observed, first "shaggy" shock waves and then "polytons". Shaggy shock waves are characterized by the presence of secondary peaks at the wave propagation front. The length-scale of the peaks is a decreasing function of λ_G and their amplitude decreases along the propagation. In the polytons regime, the peaks tend to detach and mimic the behavior of solitary waves. Polytons and shaggy shock waves are expected both in the mantle and in sedimentary basins. Polytons will require a particular attention as they imply larger extraction velocities and smaller compaction length-scales than the usual magmons.

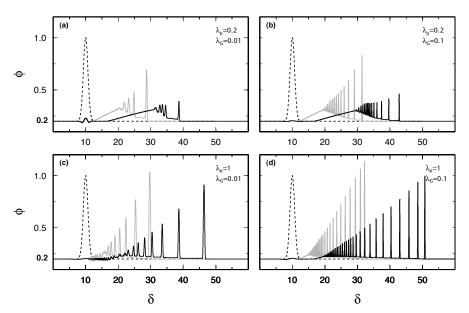


Figure 1: Evolution of porosity for a viscoelastic Burger's with a large Deborah number De=0.5, and for different values of viscosity ratio λ_{μ} and rigidity modulus ratio λ_{G} . The curves are shown for t=0 (dashed line), t=1.5 (thin grey line) and t=3 (black line). A shock wave is formed and then evolves into a train of peaks of small length scale and large amplitude, or "polytons".

2D/3D Numerical Modelling of Lithosphere-Mantle interaction.

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Whereas 3D numerical modelling of mantle convection is a standard procedure these days, numerical modelling of lithospheric-scale processes have so far mainly been performed in two spatial dimensions. Part of this is probably due to the somewhat more complicated rheologies that are thought to be important for lithospheric-scale processes. Rather than just behaving viscously, surface-near rocks may also deform in an elastic or plastic (brittle) manner, which manifests itself in faults or shear zones. Moreover, rocks on a lithospheric scale are fairly heterogeneous, undergo complex phase transitions, partial melting and have strain-dependent material properties. All of these complexities result in numerical simulations with a rather large number of adjustable ("free") parameters. In order to get an insight in the physics of geodynamic processes, various workers have therefore concentrated on smaller scale problems (e.g. crustal deformation) in which the "bigger" picture was introduced by kinematically prescribed boundary conditions. Whereas such studies undoubtedly increased our understanding of geodynamic processes, it is also important to understand the lithosphere-mantle system in a more self-consistent manner (in which mantle flow drives lithospheric deformation).

From a theoretical point-of-view it is clear how this can be done: take a mantle flow code, add a free-surface, elasticity and plasticity and work on ways to track heterogeneous phases (with phase transitions). From a practical point of view, things appear to be slightly more complicated. The self-consistent free-surface requires a very small time step for stability reasons; elasticity requires tracking of stress tensors and plasticity and material heterogeneities may result in large variations in viscosity over small length scales (which deteriorates the efficiency of multigrid solvers). Questions arise whether the low-order (inadmissible) elements typically used in mantle flow code are still sufficient or whether higher order (admissible) elements are necessary.

Here we discuss how we addressed some of these issues in a 2D thermo-mechanical finite element code (SloMo) that has been employed to study coupled lithosphere-mantle interaction processes. A semi-implicit free surface algorithm (SIFSA) was developed to overcome some of the time step restrictions related to the presence of a free surface. Tracers are used to track material properties, stress tensors and temperature and the governing equations are solved on a Lagrangian background solver (with remeshing to allow large deformations). Furthermore we discuss a recently developed 3D parallel finite element code that was written in the PETSc framework, has direct, iterative and multigrid solvers and both linear and higher order elements (as well as tracers to track material properties).

Finally we give examples of self-consistent modelling of lithosphere-mantle interaction (a case study on Taiwan), as well as address questions such as: does elasticity modify large-scale geodynamic processes? What is the effect if surface-processes on mantle and crustal deformation? Do we need a free-surface or is a free-slip upper boundary condition sufficient?

Convection in Mercury's Mantle: Linear Upwellings Not Plumes

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To investigate the planform of convection in a thin silicate shell, applicable to Mercury, I use the finite element code CitcomS to solve the equations for 3D spherical, incompressible, convection with a free-slip surface and core mantle boundary and a core-mantle boundary radius of 0.75 times the planetary radius, giving a silicate mantle thickness of 600 km. The calculations run for several billion years model time from a hot, nearly-isothermal initial condition (T=1880~K) and include a core-cooling boundary condition. The viscosity temperature-dependent with an activation energy of 300 kJ mole⁻¹. I will present calculations using Rayleigh numbers ranging from 10^4-10^6 and two endmember internal heat generation rates of no internal heating or an Earth-like value (0.0115 μ W/m³.) The results of more than fifteen 3D calculations with various Rayleigh numbers, internal generation rates, and initial conditions will be summarized. The heat flux at the core-mantle boundary from these calculations ranges from 4.8-15.8 mW/m², consistent with Mercury core dynamo and thermal history models.

While mantle convection on Venus, Earth and Mars takes the form of cylindrical upwellings, the upwellings on Mercury take the form of long, linear rolls (Figure 1a) or hemispherical sheet upwellings and cylindrical downwellings (Figure 1b). This convective planform is observed over the range of Rayleigh numbers relevant for Mercury $(10^4 - 10^6)$ and with our without the inclusion of heat producing elements. It is a direct consequence of the thin silicate shell and the corresponding low Rayleigh number applicable to convection in Mercury's mantle and, the planform is dependent on the initial condition. Calculations with linear upwellings and downwellings (i.e., rolls) in the low-latitude regions of the spherical shell and a cylindrical upwelling (or downwelling) at the pole form within 300-500 Myrs of the initial condition and remain in this stable pattern through out the remained of the calculation except in cases with low-degree spherical harmonic initial conditions (e.g., Figure 1b). With low-degree initial conditions, a nearly-hemispherical pattern of upwelling and downwelling cylinders is observed throughout the calculation. In the other terrestrial planets, instabilities near the base of the mantle begin as linear, 2D features that quickly break into distinct cylindrical plumes as the instabilities rise. Sheets coalesce into plumes at the intersection of two or more linear sheets. The Mercurian mantle is too thin for the basal boundary layer instabilities to break up into cylindrical plume structures and thus linear upwellings extend throughout the mantle.

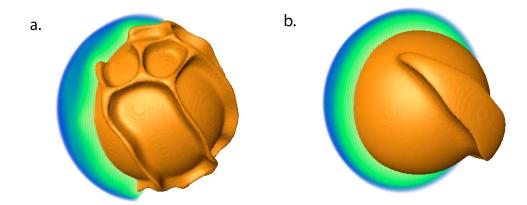


Figure 1: Temperature field after 750 million years of model evolution. a. calculation Merc LM1 b. calculation Merc L2. The orange surface represents the 0.9 (1804 °K) temperature isosurface. Note the transition between long, two-dimensional roll structures in the low latitudes to a more complicated hexagonal pattern in the high latitudes in a.

Contribution of glacial-isostatic adjustment to tectonic plate motion

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The horizontal surface motion induced by glacial isostatic adjustment (GIA) is usually considered in formerly glaciated regions only, whereas apart from those regions (far-field) this motion is neglected. The reason for this is (1) the assumption of a moderate viscosity contrast between upper and lower mantle which does not allow for an effective channeling of material flow in the upper mantle and (2) the application of a spherical symmetric earth model which does not allow for the consideration of isolated plates.

In this study, we investigate the effect of GIA on tectonic plate motion assuming the tectonic plates to be elastic and viscously connected along the plate boundaries. The elastic thickness is parameterized according to the thermal state of the lithosphere. Assuming a large contrast of $\eta_{\rm UM}/\eta_{\rm LM}=5\times10^{-2}$, we show the motion of the plates as well as the intraplate deformation to be of the order of mm/a which is observable by modern geodetic methods such as GPS. We discuss the mechanism of the GIA induced horizontal motion and the influence of plate boundaries. Figure 1 shows the present-day velocities along a cross-section between Australia and Antarctica. We can see a large change of the velocity field at the mid-ocean ridge, denoted by the triangle, and the channeling of lateral material flow in the upper mantle.

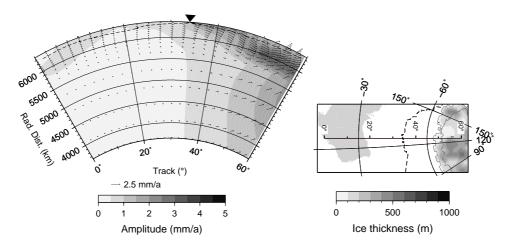


Figure 1: Left: Present-day displacement rates on a cross-section that passes the the Southeast Indian ridge between Australian and Antarctic plates. Dashed line shows the lithosphere considered. Inverted triangle denotes the position of the ridge. Right: Location of the cross-section, the ice thickness relative to present day and its extension (solid line) at the last glacial maximum and the mid-ocean ridge (dashed line).

Numerical model

The material property of the earth's mantle is described by a linear viscoelastic rheology. The driving force is the surface loading due to the last glacial cycle. We use a spectral finite-element code which solves the field equations of a viscoelastic, incompressible, self-gravitating continuum in spherical geometry allowing for lateral variations in viscosity. The filed variables are parameterized by finite elements in radial direction and by spherical harmonics in horizontal direction. The time evolution of the adjustment process is treated by an explicit finite-difference scheme.

Evolution of a dense magma ocean at the base of the mantle

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Since the discovery of the ultralow-velocity zones in the lowermost mantle, evidence for the presence of partial melt at the bottom of the mantle have continually accumulated. The maintenance of the magnetic field for at least 3.2 Gyr requires cooling of the core over that period and implies an even larger quantity of melt in the lowermost mantle in the past than at present. We investigated the implications of such an hypothesis in terms of thermal and chemical evolution of the mantle and found that it can offer a explanation for several different observations.

The mass of melt decrease, controlled by the energy balance, is exponential to first order, with a time scale set by the heat capacity of the core and the phase diagram of the mantle, typically of order 1Gyr. The melt is denser than the overlying solid that crystallizes from it, due to a larger Fe content. In addition, the huge viscosity contrast renders entrainment of melt by convection in the mantle negligible. The melt is then the ideal deep mantle reservoir and can contain about 20% of the Earth's budget in incompatible elements. Moreover, because of the difference between the partitioning coefficients of Sm and Nd, the crystallization of the this melt over time creates a positive $\varepsilon_{142}{\rm Nd}$ in the solid and the complementary negative one in the liquid when compared to chondrites. This can then explain the systematic difference of chondrites with all terrestrial samples.

The existence of melt in the lowermost mantle for most of Earth's history, implied from geophysical arguments offers a solution for some of the most important geochemical problems of the mantle.

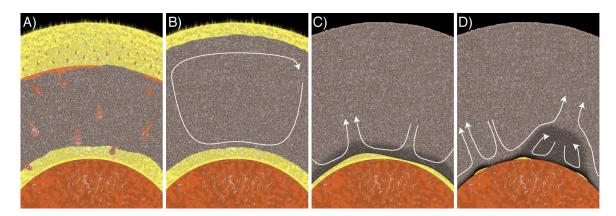


Figure 1: Four stages of the evolution of the deep Earth. (A) formation of the core. The gravitational energy released heats up the core and the lower mantle, allowing the latter to partially melt. The Fe-enriched melt is denser than the solid in equilibrium and stays at the bottom of the mantle. (B) Crystallisation of the mantle proceeds from the middle, up- and down-ward. The up-ward crystallisation is controlled by radiation to space and occurs in about 10 Myr. The downward crystallisation is limited by convection in the already solidified part of the mantle and is buffered by the heat capacity of the core, and is then protracted (C). The progressive enrichment in Fe of the melt and the solid establishes a chemical stratification at the base of the mantle (C) which becomes stable against entrainment by large scale convection and piles up under up-welling currents (D). Pockets of melt persist today at the edges of piles and are responsible for ultra low velocity zones (D).

Influence of thermochemical piles on topography at Earth's core-mantle boundary

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Abstract

Numerous seismic studies reveal the presence of two large, low velocity anomalies beneath Africa and the central Pacific. Efforts to characterize these anomalies have yielded a variety of interpretations over the years, both isochemical and thermochemical. Previous interpretations have included large, isochemical superplumes, clusters of smaller thermal plumes, and doming thermochemical superplumes. A conceptual mantle model that is presently growing favor involves long-lived thermochemical piles. In anticipation that current techniques may yield better constraints on core-mantle boundary (CMB) topography, we investigate the relationship between CMB topography and thermochemical piles. Numerical modeling of isochemical convection illustrates a clear relationship between upwellings and downwellings to CMB topography in which downwellings lead to negative CMB topography and upwellings lead to positive topography. In our thermochemical models with piles, however, this relationship is not so straightforward. Despite their intrinsic density, a pile's effective density is significantly reduced by a density reduction associated with thermal expansion. As a result, thermochemical models tend to result in a much lower overall CMB stress/topography than do their isochemical counterparts. Our results suggest that, in general, thermochemical convection with temperaturedependent rheology does not lead to negative CMB topography beneath piles. As a result, observations interpreted as positive topography beneath proposed piles cannot be used to discriminate between isochemical and thermochemical mantle models.

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Controls on Plume Heat Flux and Plume Excess temperature

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Plume heat flux and plume excess temperature in the upper mantle inferred from surface ovservations may pose important constraints on the heat flux from the core and mantle internal heating rate. This study examined the relationship between plume heat flux Q_p , core-mantle boundary (CMB) heat flux Q_{cmb} and plume excess temperature ΔT_{plume} in thermal convection using both numerical modeling and theoretical analysis. 3-D regional spherical models of mantle convection were computed with high resolution and for different Rayleigh number, internal heat generation rate, and viscosity structures. An analytic model was developed for variations in Q_p and ΔT_{plume} with depth. The results can be summarized as following. 1) Mantle plumes immediately above the CMB carry nearly 80%-90% of the CMB heat flux. 2) Q_p and ΔT_{plume} decrease by approximately a factor of two for plumes to ascend from near the CMB to the upper mantle depth. 3) Our analytic model indicates that the decrease in Q_p and ΔT_{plume} is mainly controlled by adiabatic cooling and the reduction ratios for Q_p and ΔT_{plume} due to this effect are $exp(\gamma D_i \Delta r)$ for plumes to ascend over a distance Δr , where D_i is the dissipation number and γ is the ratio of the Earth's radius to the mantle thickness. 4) The subadiabatic temperature also contributes to the reduction of Q_p and ΔT_{plume} , but its contribution is only 20% to 30%. Subadiabatic temperature from our models ranges from 70 K to 240 K for CMB temperature of 3400 °C. 5) Our results confirms that 60%-70% internal heating rate for the mantle or Q_{cmb} of ~ 12 TW is required to reproduce the plume-related observations.

Anisotropic Viscosity and Geodynamical Flow Models -Rayleigh-Taylor Instabilities as a Test Example

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Rocks often develop fabric when subject to deformation, and this fabric leads to anisotropy of properties such as viscosity and seismic wave speeds. We employ analytical solutions and numerical flow models to investigate the effect of anisotropic viscosity on the development of Rayleigh-Taylor instabilities, a process strongly connected to lithospheric instabilities.

Our results demonstrate a dramatic effect of anisotropic viscosity on the development of instabilities - their timing, shape and, most notably, their wavelength are strongly affected by the initial fabric. An interplay between regions with different initial fabric gives rise to striking irregularities in the downwellings. Our study show that for discussions of lithospheric instabilities, and likely of other mantle processes, the approximation of isotropic viscosity may not be adequate, and that anisotropic viscosity should be included.

As part of our investigation we also compare the anisotropic fabric predicted by three different methods for various flow fields. Such calibration of methods is essential as anisotropy predicted from geodynamical flow models becomes a widely used tool for constraining and discriminating between models.

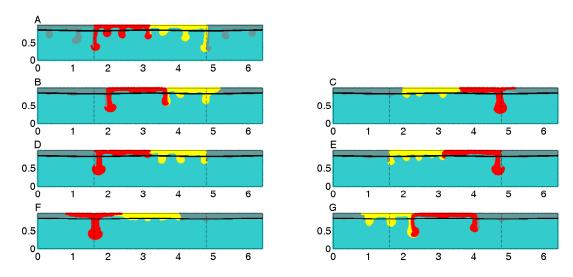


Figure 1: Results of a set of numerical experiments of Rayleigh-Taylor instabilities in the presence of anisotropic viscosity. The panels show material distribution in models with different configurations of initial anisotropic fabric. The snapshots are taken after the fastest downwelling sinks over half the box depth. Red material starts with a horizontal easy-shear direction; Yellow material starts with easy-shear direction dipping at 45°. Green materials are isotropic. Panel A shows the results for a purely isotropic model. The results show that:

- a) The wavelength of instabilities at the initially-horizontal region is much longer than for the dipping or isotropic materials
- b) The points of contact between regions of different fabric are particularly unstable
- c) Anisotropic viscosity can offset the location of the major downwelling

The crust and upper mantle structure of East China and adjacent sea

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The East China, Yellow Sea and Korean Peninsula located on the east of Eurasian Plate and west of Pacific Plate(Philippine Plate), the interesting research area includes North China Block, Korean Peninsula Block, Lower Yangtze Block, Dabie Orogenic Zone, Sulu Block and Yellow Sea. The 3-D seismic tomography image (114° -130° E,29° -38° N) have been inversed by using the Multiphase Traveltime method after relocated earthquakes by DD and GA. The crust can be divided into upper, middle and lower. The buried depth, interface velocity for upper, middle and lower crust are: 12-15km, 6.16-6.27km/s, .22-26km, 6.74-6.80 km/s, 29.1-39.8km, 7.88-8.21km/s, respectively. The average depth of Moho in Korean peninsula is 29.8km with interface velocity of 8.01km/s. The Moho in Yellow Sea is about 30km. The features of deep structure for various sub-tectonic provinces are: for Dabie Orogenic Zone: deepest Moho, shallower focus, highest interface and RMS velocity; for North China Block, most shallow Moho, more deeper focus, more higher interface and RMS velocity, for Lower Yangtze Block, deeper Moho, more deeper focus, lower layer velocity and RMS velocity. The Moho contour is agree basically with tectonic provinces. The velocity differences among different tectonic province for Korean Peninsula are obvious, especially, Kyonggi Massif, Okchon Fold Zone, Taebaesan Fold Zone, Imjingang Fold Zone. The Tancheng-Lujiang fault belt with 2400km long is biggest deep fault in eastern of China,. It appears different movement mode for various segments. In the southern segment (south of 33 ° N) the velocity in belt is higher than out. The velocity difference both of fault belt is obvious, it is appears thrust or normal fault. The compressional action from Dabie Orogenic Zone to Lower Yangtze Block may be the causation for the feature. In 33° -38° N, the velocity in belt is lower than out., it is appears strike slip with thrust, may be the tectonic action is not stronger between North China Block and Lower Yangtze Block.

Zhu Jieshou & et al consider that the lithosphere thickness for Lower Yangtze Block is 90km, for eastern North China Block is 72km, the Lower Yangtze Block may subduct into North China Block under Sulu Orogenic Zone, the high-velocity slab is also remnants ancient subducted Yangtze Block. They consider that the thickness of lithosphere in west Pacific marginal Seas, North China, South China, continental shelf of East Sea are 50-80km with 4.25-4.4km/s of bottom S velocity, but in Pacific Plate and Philippine Plate the lithosphere velocity is higher than above, appears the Pacific Plate subduct into Eurasian Plate. The thickness of lithosphere in the middle and west of east Asian continent are about 80-100km with 4.5-4.6km/s of bottom S velocity, the thickness of asthenosphere are about 40-100km. There is a big lower velocity zone in upper mantle, like as velocity structure of Pacific mid-oceanic ridge. May be it is the evolution result from Mesozoic to Cenozoic period for East Asian continent.

Viscosity structure of icy satellites: constraints from topography relaxation

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The extensive data collected during the Galileo and Cassini missions provide a better insight into the internal structure and dynamics of icy satellites of giant planets. However, more constraints on the rheological parameters of the satellites' interior are still needed. Examining the viscous relaxation of topography, in case of an icy satellite especially of the topography of impact craters, may constraint the viscosity structure of the satellite's ice mantle. In this study, we model the mantle of a satellite as a viscous spherical shell with radially dependent viscosity. An arbitrary topography is decomposed into spherical harmonics and the topography relaxation is studied separately degree by degree. We show that a single parameter, relaxation time, is sufficient to describe the relaxation at each degree even for relatively complex viscosity models. We investigate the dependence of the relaxation time on the model geometry, gravity acceleration, boundary conditions and especially the viscosity stratification of the mantle. Finally, the relaxation times are determined for several models with parameters of selected icy satellites. Applicability of this approach in determining the viscosity structures of icy satellites is discussed.

Refined prediction of GIA-induced variations in the Earth's rotation

Climatic fluctuations dominate changes in the distribution of ice and water on the Earth's surface, which in turn affects climate itself. Continental ice accumulation and ablation and the accompanying changes in sea level result in the deformation of the solid Earth, a process termed glacial-isostatic adjustment (GIA). The resulting changes in surface topography and bathymetry affect the spatial pattern of sea-level change, which again influences deformation. The redistribution of ice and water, along with the mass redistribution in the Earth's interior also induce perturbations in the Earth's gravitational field and rotational characteristics. The wander of the rotation axis in turn induces variations in the centrifugal force and thus additional variations in sea level and surface deformations. Taken together, this means that the determination of sea-level change coupled with polar wander due to changes in ice-water mass is a complex geophysical and mathematical problem.

Assuming that the deformation in the Earth is small, the movement of the rotation vector can be described by the linearized Liouville equation. The numerical integration of it requires us to specify the temporal perturbation of the inertia tensor. The approach presented here is based on the MacCullagh formulae and derives this perturbation from the time-dependent variation of the second-degree spherical harmonics of the induced changes in the gravitational potential.

Once the Liouville equation is solved, the temporal variability in the centrifugal force is established. This driving force is then considered in the linear-momentum and Poisson equations governing GIA to compute the surface-deformation and gravitational-potential changes. This rotational feedback, called the rotational deformation, is mathematically described by particular terms in the field equations for GIA. We will present the effects of individual terms on surface deformation and sea-level variation. The rotational deformations are treated in the time domain, which eliminates the need to apply the traditional Laplace-transform method and allows the conventional approach based on load Love numbers to be extended to the case of a 3-D viscoelastic earth model.

The influence of initial condition and plate history on geodynamical predictions of thermochemical structures

One conceptual mantle model that attempts to explain the large, low seismic velocity regions beneath Africa and the Pacific involves large thermochemical piles in the lowermost mantle. Using geologically recent plate motion history as surface boundary conditions, geodynamical studies have been performed to predict the present day location and shape of an intrinsically more-dense, primitive lower mantle reservoir. One shortcoming of this approach is that we only have reasonable plate history data for the past 120 million years, and the geologic record is less complete for earlier times. We have investigated the role of initial condition and plate history, and it was found that initial condition does play a large role in the prediction of present-day thermochemical structures. We also find that plate history is important, meaning that using present day plate motions is not enough. Reasonable, yet somewhat unsatisfactory predictions occur if a Pangea configuration is assumed from Permian times until 120 million years ago. Strangely, we find that the best prediction, as compared to tomography, occurs when we use the artificial initial condition of a ubiquitous dense layer. These results lead to several subtle inferences about the state of thermochemical convection, if it exists in the lower mantle.

The Spreading of Two-phase Viscous Gravity Currents

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Viscous gravity currents involve the spreading of viscous fluid being driven by its own weight. Its theory has numerous applications in geosciences, from small scale emplacement of lava flows or glaciers, to large scale flow of mantle plume heads, deformation of weak continental crust under its own weight and flow of ice polar caps. Gravity currents in real geological settings are, however, very complex and are comprised of a mixture of several components: lava and gas or crystals for lava flows, matrix and melt for plume heads, ice and liquid water for glaciers etc... The general equations for the spreading of a two-phase mixture composed of matrix and fluid, for which the matrix has a much higher viscosity than the fluid, are developed. A loss of fluid phase through the upper boundary of the current is considered when the density of the fluid is smaller than the density of the matrix. We consider both constant volume and constant volume rate flows.

A particular focus is given to lava flows containing a gas phase and to the effects of degassing on the spreading of the current. But results can be applied to spreading of mantle plume heads below the lithosphere, as they contain some melt. As the current spreads, its surface increases and degassing becomes easier, which, in turn, increases the density of the flow and facilitates the spreading. When the loss of fluid becomes significant, the thickness evolution diverges significantly from the single-phase evolution. It returns to it when degassing is complete. We derive the characteristic time for complete degassing of lava flows as a function of gas and lava physical properties. We also find a characteristic thickness for degassing to become significant and a characteristic radius for complete degassing. The shape of a two-phase viscous gravity current does not differ significantly from the shape of a single-phase flow.

2D Numerical modelling of double subduction process

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Double subduction is a complex geodynamic process in which two plates following each other are synchronously subducted in the same direction. Double subduction episodes are characteristic for both modern and ancient plate tectonics and are, in particular, inferred in the history of the Himalayan collision zone. However, our knowledge about this process is limited by conceptual schemes and double subduction remains unexplained in terms of physical factors controlling its initiation, duration, dynamics as well as its relation to magmatic activity. We present first results on numerical simulation of double subduction process. Our current highresolution 2D coupled geochemical-petrological-thermomechanical numerical model employs visco-plastic rheology of rocks and allows simultaneous treatment of heat, mass and water transport, metamorphic phase transformation, partial melting and melt extraction. We studied the influence of different physical factors on initiation, duration and dynamics of the process. In particular we explored the effect of varying convergence rate (0.0 - 7.0 cm/yr), age of the slab (10 – 100 Myrs), water propagation velocity (0-10 cm/yr) and dislocation creep activation volume (0.6 - 1.0 J/bar). Depending on these physical parameters (primarily on dimensionless ratio between convergence rate and water percolation velocity) numerical experiments show large variations in double subduction dynamics characterized by (i) different amount of shortening/extension in two simultaneously developing subduction zones, (ii) strong spatial and temporal oscillations of magmatic productivity (separated magmatic episodes) within two parallel volcanic arcs, and (iii) different modes of interaction of two subducting slabs (penetrating/non-penetrating) with the 660 km discontinuity. We compare numerical results with two geologically and geophysically investigated examples of double subduction: the past Karakoram and Kohistan Arcs and the active Izu-Bonin-Marianas and Ryukyu Arcs. Numerical predictions show important similarities with geological information and shed new light in interpreting the natural case stories. In particular, they allow deciphering magmatic and structural/kinematic interplays during double subduction tectonics.

Key Words: numerical modelling, double subduction, vage hydration, melt extraction

Mantle convection, plasticity and plate kinematics

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Convection models combined with a simple picture of material plasticity have proven to be very useful in describing some aspects of the coupled system of plate motions and mantle flow. In this talk I will review recent developments in this area and then address ways in which we might use our knowledge of the kinematics of plate boundary evolution to improve plasticity models.

In the context of viscous deformation, we normally formulate plastic deformation as the sum of a viscous (or viscoelastic) strain rate, ε^{ve} and a plastic strain rate, ε^{p} which becomes active at high stresses

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{\text{ve}} + \dot{\varepsilon}_{ij}^{\text{p}} \tag{1}$$

The plastic strain rate is a general function of the applied stress which ensures that the yield conditions (on the stress tensor) are satisfied.

$$\dot{\varepsilon}_{ij}^{\mathrm{p}} = \lambda \Lambda_{ijkl} \tau_{kl} \tag{2}$$

where Λ captures the form / symmetry of the plastic deformation and λ determines its magnitude; τ is the deviatoric stress.

If the deviatoric stress is expressed in terms of the strain rate we obtain

$$\tau_{ij} = 2\eta \dot{\varepsilon}_{ij} - \beta \Pi_{ijkl} \dot{\varepsilon}_{kl} \tag{3}$$

in which $2\eta\dot{\varepsilon}_{ij}$ is a hypothetical stress predicted from the viscous (or viscoelastic) constitutive law and $\beta\Pi_{ijkl}\dot{\varepsilon}_{kl}$ is a correction. As before, Π represents the form / symmetry of the stress correction relative to the deformation rate, β is the magnitude of the correction.

Commonly, the plastic deformation is determined mathematically from the yield condition on the stress together with some simplifying assumptions which ensure consistent deformation at the yield stress. The symmetry of plastic deformation is therefore implicit in the yield criterion and consistency assumptions.

However, for plate tectonics, we have a very successful kinematic description of plate boundary evolution and a relatively poor understanding of the stress field and yield strength. For this reason it may be worthwhile to instead constrain the symmetry of deformation at yield (Λ) directly to satisfy the observed behaviour. I will show how to develop simple kinematic flow rules for each of the principal plate boundary types, and how to construct a corresponding visco-plastic constitutive model (Π) and yield criterion. I will also discuss the limitations of this approach.

Mantle plumes and superswells.

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If the Pacific "Ring of Fire" has been operating essentially in place since the breakup of Pangea (migrating only slowly as the Pacific closes in response to the growth of the Atlantic and Indian oceans), the downward motion of the near-continuous Pacific "belt" of subduction can drive/push the upwelling flow (plumes) toward the "poles" of this belt (Africa and the central Pacific). This pattern of mantle flow could enhance upward flow in these superswell regions — over time this could change the geotherm from what it is in "normal" regions. Our poster explores consequences of such a mode of mantle convection.

Planetary Scale Simulations of Geodynamics with Multipole Boundary Elements

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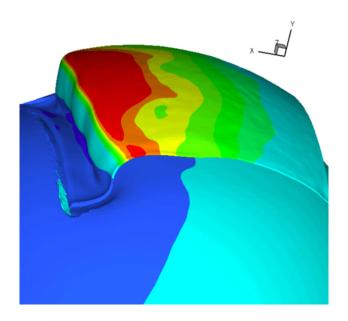


Figure 1: Subduction of a giant slab in spherical coordinate and plot of the interaction with the 660km discontinuity. Colors represent horizontal velocities in the subduction direction (x).

We present a novel computational approach for modeling geodynamics in a spherical setting using a fast multipole acceleration of the boundary elements method. The technique makes it straightforward to run models of plate tectonics at the planetary scale with great computational efficiency. We analyze the effect of size, earth curvature, and slab-slab interaction for large subducting plates, in order to extract general laws for the collective behavior of tectonic plates.

The numerical approach is based on a fast multipole method (FMM) for the evaluation of the integrals, which scales as $N \log(N)$, which is far more tractable and still allows the use of a Generalized Minimized Residual method (GMRES) or any Krylov space based method that does not rely on the storage of the full matrix. We show that the code scales linearly with the problem size for large sizes (more than 10^3 elements) and shows a very good parallel behavior that is promising for larger systems.

In order to appropriately model subduction, an adaptive mesh algorithm has been newly developed, which adapts the shape of the earth surface to the free-surface to the lithospheric topography. Consequently the density difference between the mantle and ocean self-consistently sustains the unsubducted lithosphere while the lithosphere deforms in a full free surface setting. Exploiting this innovation, for the first time FMM-BEM has been employed for modeling subduction of planetary sized plates in spherical coordinates.

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Intraoceanic volcanic arc development: insights from numerical modeling

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We have created a new 2D coupled geochemical-petrological-thermomechanical numerical model of retreating intraoceanic subduction associated with volcanic arc development. The model includes spontaneous slab bending, subducted crust dehydration, aqueous fluid transport, mantle wedge melting and melt extraction resulting in crustal growth. This model allows us to study influence of melt extraction intensity on the dynamics of subduction, mantle wedge plumes development and magmatic arc growth and displacement. In our numerical experiments subduction nucleates across the weak transform fault separating two oceanic plates different age. Subduction rate strongly varies with time. In all studied cases there is a deceleration period of a few Myr after the beginning of subduction, during this period subduction rates decrease from ~ 7 cm/yr to ~ 4 cm/yr. Subsequently, two scenarios can be distinguished: (1) decay and, ultimately, the cessation of subduction, (2) increase in subduction rate (to up to ~12 cm/yr) and stabilization of subduction. In the first case the duration of subduction correlates positively with the intensity of melt extraction: the period of continued subduction increases from 15,4 Myrs to 47,6 Myrs with the increase of melt extraction threshold from 1% to 9%. In scenario 1 the magmatic arc crust includes large amounts of rocks formed by melting of subducted crust atop the thermally relaxing slab. In contrast, in case of stable subduction, magmatic rocks produced by partial melting of hydrated mantle wedge clearly dominate the crust. In several numerical experiments an intra-arc extension is observed during subduction. This process results in splitting of previously formed magmatic arc crust by a newly formed spreading center. The loci of magmatic activity and intensity of crustal growth is strongly dependent on the dynamics of hydrous partially molten upwellings (cold plumes) rising from the slab.

Insights into the Properties of the Deep Earth from Computational Mineral Physics

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Knowledge of material properties at conditions of the Earth's deep interior is necessary for meaningful interpretations of seismological data and for realistic geodynamical modelling. In the recent years, computational mineral physics has made major advances, some of which will be discussed in this talk:

- 1. Finite-temperature calculations of the elastic constants, and their applications for the interpretation of seismic tomography maps [1].
- 2. Calculations of mineral phase diagrams from first principles, and their implications for Earth's composition, structure and dynamics [2-4]. One particular example here is the post-perovskite phase of MgSiO₃, the predicted stability field of which has guided its experimental synthesis, and has important geophysical consequences [4].
- 3. Novel approaches for studies of mineral plasticity, which have clarified the origin of seismic anisotropy in the deep mantle [5].
- 4. Novel evolutionary methodology for the prediction of stable crystal structures at given pressure-temperature conditions, which has resulted in the prediction of several new mineral phases at conditions of the deep interiors of the Earth and terrestrial planets [6,7].
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Isotopic Constraints on Archean Mantle Dynamics

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Radiogenic isotopes provide powerful constraints on the evolution of the Earth because they record time. More than any other observational method, geochemistry allows us to ask the question 'When?' This ability has lead to an extremely detailed understanding of how the Earth's crust has evolved physically and chemically, and has allowed us to probe even its earliest beginnings as zircons as old as 4.4 Ga have been identified [1]. One of the primary results of this research has been to quantify the distribution of crustal ages. The fundamental observation is that not all ages are equally represented. In particular, there are four time periods that are grossly overrepresented: 1.2, 1.9, 2.7 and 3.3 Ga [2, 3]. These are the ages of the cratons.

While the observation is clear, its interpretation is not. One possibility is that these peaks in area versus age record pulses of continental crust (CC) growth [4]. Such CC production events would imply large dynamic events in the mantle. However, another interpretation is that erosion destroys most CC, and that the peaks are artifacts of preservation and the cratons just the scraps that have randomly escaped destruction by plate tectonics [5]. In this case, there is no direct evidence about mantle dynamics in the CC age spectrum. At some level, the CC data will always be ambiguous as it is both the data and the means of recording the data. Thus gaps in data can either be real or just when the recording was erased. What is required is an independent record of crust production, preferably one from the mantle itself.

Based upon their trace element composition, it is clear that the CC was extracted from the mantle by melting [6], and so should have left an isotopic fingerprint of its extraction in the mantle. But evidence for such a fingerprint has remained elusive. In general, asking 'When?' has not been very successful in the mantle. Subduction and mixing seems to have been very efficient at erasing the early isotopic record of Earth evolution in standard isotopic systems such as Sr, Nd and Pb. These systems have not yielded very clear answers to the questions about the timing of mantle depletion [7]. However, there are two, relatively new isotopic systems (He and Os) that, due to their distinct chemical behavior, offer hope of unlocking the early melting history of the mantle.

In this talk I will review the He and Os records of mantle melting and how they relate to the early geodynamics of the planet. In particular, both isotopic systems appear to preserve abundance peaks at the same ages as the CC area peaks. There are a number of ways to interpret this correspondence (including random coincidence) and even the data themselves are controversial. However, an attractively simple hypothesis that relates all three data sets is that there were global melting events in the mantle at those times [8]. These events would have produced large volumes of melt (recorded as pulses of CC growth) and proportionally large volumes of melt-depleted mantle (recorded in mantle He and Os isotopes). This hypothesis suggests a very catastrophic (as opposed to uniformitarian) evolution of the Earth, one dominated by a few large events. Given the size of the events, their ultimate cause would have to have been related to mantle dynamics. Geodynamic models of mantle convection have produced such episodic behavior under a range of conditions [9]. Whether or not this idea is eventually confirmed, the He and Os isotopic systems provide fundamental information about early mantle dynamics.

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More Evidence for a Plume-Fed Asthenosphere Jason Phipps Morgan, Cornell University, Ithaca NY (jp369@cornell.edu) W. Jason Morgan, Harvard University, Cambridge MA

There is increasing evidence for a well-developed asthenosphere existing between ~80-250km depths beneath the relatively thin lithosphere found in the ocean basins and younger continental regions, and a ~100km deeper and moreviscous 'asthenosphere' (if we want to use the same term) found beneath ~200+km-thick continental cratons. Sub-oceanic seismic velocity and attenuation observations are most easily explained if the sub-oceanic asthenosphere is hotter — at least in terms of potential temperature — than underlying mesosphere (cf. Phipps Morgan et al., JGR, 1995; Yamamoto et al., 2007)). If the sub-oceanic asthenosphere is fed by concentrated upwelling from regions hotter than typical mantle (e.g., thermal plumes), then sub-oceanic asthenosphere should typically be hotter than underlying mantle. If so, the asthenosphere layer will resist downwards entrainment by subducting slabs, resulting in its consumption through accretion into overlying oceanic lithosphere that eventually cools, densifies, and subducts into the deeper mantle. The well-known geochemical differences between MORB and OIB can also be explained as a consequence of small amounts of OIB melt-extraction from the lower-melting components of a plum-pudding mantle that first melts a small amount above plumes and later melts to a much larger degree beneath mid-ocean ridges (cf. Phipps Morgan and Morgan, EPSL, 1999). We show recent numerical experiments of the anticipated flow patterns in a plume-fed asthenosphere (cf. Phipps Morgan et al., 2007; Yamamoto et al., 2007). One prediction of these experiments is that the mantle wedge will have partial recirculating flow in the sub-arc region as the asthenosphere resists being subducted, as well as the potential for strong trench-parallel flow.

Surface deformations during the earthquake cycle for a layered visco-elastic crust

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Prediction of the vertical deformation of the surface near the faults may help in evaluation of the earthquake hazard. We examine using finite element method nonlinear effects during crustal block movements. The numerical models employ finite strains and the generalised linear viscoelastic constitutive relations.

In particular, we examine predicted surface displacements of layered crustal blocks under loading that simulates the earthquake cycle considering different relaxation times of the materials.

Anisotropic rheology of a cubic medium and implications for geological materials

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Dislocation creep, which is the dominant deformation mechanism in the upper mantle, results in a non-Newtonian anisotropic rheology. The implication of non-Newtonian rheology has been quite extensively studied in geodynamic models but the anisotropic aspect remains poorly investigated. In this paper, we propose to fill this gap by (1) introducing a simple mathematical description of anisotropic viscosity and (2) illustrating the link between plastic crystal deformation and bulk material rheology. The study relies on the highest symmetry of the anisotropic tensor, a cubic symmetry, for which anisotropy is characterized by one parameter only, . First-order implications of anisotropy are quantitatively explored as a function of . The effective rheology of the material is described as a function of the orientation of the crystals and of the imposed stress and the validity of the isotropic approximation is discussed. The model, applied to ringwoodite, a cubic crystal with spinel-type structure, predicts that the dynamics of the transition zone in the Earths mantle is going to be strongly affected by mechanical anisotropy.

All Bent Out of Shape: The Dynamics of Thin Viscous Sheets

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Although the earth's lithosphere is thermally, chemically and rheologically complicated, one can understand some important aspects of its dynamics by modeling it as a thin sheet of very viscous fluid. The key to the dynamics of viscous sheets is the competition between two distinct modes of deformation: stretching and bending. The partitioning of the deformation between these modes depends in a complicated way on the sheet's shape and on the distribution of the load applied to it. A simple way to quantify this is to calculate the deformation of a "shallowly" curved sheet with thickness h and principal curvatures κ_1 and κ_2 due to a load with wavelength λ applied normal to the sheet's midsurface. One thereby obtains the "rule of thumb" that stretching (bending) is dominant when $\lambda^2(\kappa_1^2 + \kappa_2^2)^{1/2}/h \gg 1$ ($\ll 1$) (Ribe 2002.)

Because the resistances of a sheet to stretching and bending scale with the sheet thickness h in different ways ($\sim h$ and $\sim h^3$, respectively), loaded sheets exhibit a rich dynamics characterized by structures of boundary-layer type whose thickness is intermediate between h and the sheet's characteristic lateral dimension L. A remarkable example known to all amateur cooks is the periodic folding instability of a viscous sheet falling onto a surface (fig. 1.) As the height from which the fluid falls increases, the instability traverses four different dynamical regimes: a "viscous" regime in which folding is driven kinematically by the imposed fluid flux; a "gravitational" regime in which the viscous forces that resist folding are balanced by gravity; an "inertio-gravitational" regime in which the upper part of the sheet behaves as a swinging pendulum in resonance with the folding portion; and an "inertial" regime in which the viscous forces are balanced by inertia. The same sequence of regimes is also observed in the closely related phenomenon of "liquid rope coiling" that occurs when the fluid has the form of a thin filament (Ribe et al. 2006.) Because inertia is negligible in Earth's mantle, the viscous and gravitational regimes are the geodynamically relevant ones.

While folding instabilities are most easily observed at solid surfaces, they can also occur at fluid interfaces where the density and/or viscosity increases. It is therefore natural to ask whether such instabilities might occur in the mantle when subducted lithosphere encounters the transition zone or the CMB. Tomographic images under subduction zones such as Central America and Java show that the subducted slab appears to widen rapidly beneath the transition zone to form a broad (up to 700 km wide) wedge-shaped anomaly. To test the hypothesis that this apparent widening is the result of a folding instability, we used a numerically determined universal scaling law (Ribe 2003) to predict the folding amplitude δ for parameters (lithospheric thickness, subduction rate, etc.) appropriate to Central America and Java. The results ($\delta = 460$ and 400 km, respectively; Ribe et al. 2007) match well the widths of the velocity anomalies just beneath the transition zone, suggesting that the folding mechanism may be viable. As for the CMB, the possibility of slab folding there has recently been proposed based on seismic observations of a 100-km offset in the depth of a reflective layer (Hutko et al. 2006.) Because the scaling law of Ribe (2003) breaks down when the viscosity of the sheet is not much larger than that of the fluid surrounding it, we have performed laboratory experiments to determine how the viscous ambient mantle influences the folding dynamics of a slab encountering the CMB. When the sheet/ambient mantle viscosity contrast $\gamma > 500$, the sheet folds as if the ambient mantle were not there. For more moderate contrasts $\gamma \approx 10$, however, folding is suppressed, and the sheet impinges on the CMB as a stagnation-point flow with superimposed



Figure 1: Periodic folding of a sheet of corn syrup (fall height 7 cm.)

small-amplitude oscillations, creating a periodic undulating topography on the top of the fluid spreading laterally over the boundary.

In addition to the insight they provide into folding instabilities, thin-sheet models are useful tools for studying the dynamics of subduction more generally. One promising approach for modeling the coupled dynamics of a deforming sheet and the flow around it is the boundary-integral method, wherein a Stokes flow in a given region of space is represented in terms of the velocities and tractions at its boundaries. I will present results of numerical models of subduction obtained using this method, focusing on how concepts from thin-sheet theory can be used to derive scaling laws for important subduction parameters such as the surface plate speed, the rate of trench rollback, and the geometry of the subducted slab.

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A two phase segregation model

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Various geodynamic situations involve simultaneously two phases interacting in the same convective medium. This is the case when partial melting is present and was the case when the iron and the silicates differenciated in the Hadean Earth. The attemps to handle such situations in numerical codes have not been very numerous. In addition to be intrinsically with lateral viscosity variations, non Boussinesq (as the difference between densities can be of the same order as the densities themselves), each phase must also be considered as compressible. We present the first results obtain with a code that solves the equations and formalism proposed by Bercovici et al. (2001). The applications to the formation of the core will be presented.

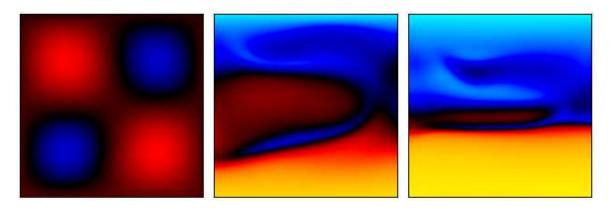


Figure 1: On left, initial metal-silicate proportion, the zones rich in liquid metal are in red. The flow corresponds to the superposition of an incompressible circulation (the iron rich zones are denser, the silicate-rich zone lighter) and a compressible flow (Darcy flow of liquid metal through solid silicates). After some time (middle and right panels), the metal (yellow) has segregated from the silicates (blue).

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Water induced convection and slab dehydration in the Earth's mantle transition zone

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Water enters the Earth's mantle at trenches by subduction of oceanic lithosphere. Most of this water immediately returns to the atmosphere through arc volcanism, but a part of it, retained in Dense Hydrous Magnesium Silicates (DHMSs) and Nominally Anhydrous Minerals (NAMs) like olivine, is expected as deep as the mantle transition zone (410-660 km depth). There, slabs can be deflected and linger before to sink into the lower mantle. Because it lowers the density and viscosity of the mantle minerals which may hold it at this depth (wadsleyite, ringwoodite) water is likely to affect the dynamics of the stagnant slab.

Here we investigate, the consequence of water presence on the dehydration of a stagnant slab. In particular, we focussed on the possible onset of small scale mantle convection despite the unfriendly thermal state of the studied area (mantle is cooled from below). The competition between the thermal and water effects on the density and thus on the convective stability of the top layer of the slab is questioned using numerical model including water dependent density and viscosity and temperature dependent water-solubility.

Depending on the value of the initial water content in the slab reaching the transition zone, convection occurs or not. Others important controlling parameters are the water dependence of density and viscosity. If small scale convection is taking place at the top a stagnant slab in addition to considerably enhance the speed of the process of slab dehydration (otherwise controlled by the slow diffusion of water) it provides an efficient way to heat up the slab. Our preliminary results suggest that young and wet stagnant slabs are unlikely to reach the lower mantle because they would thermally relatively quickly equilibrate with the surrounding mantle within the transition zone.

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Nanoscale properties of rocks and subduction zone rheology: Role of grain-boundary energy

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Nanoscale material properties may affect global geodynamic processes: It has been shown, e.g., that grain boundaries may serve as reservoirs of incompatible elements in the Earth's mantle. Segregation of incompatible elements results in a marked difference between the composition of the interiors and the boundaries of grains within the rocks that comprise the Earth's mantle (Hiraga et al., 2004). Grain boundaries are also the key for the understanding of mineral reaction kinetics. Nanometer scale structures in geological materials such as crystal defects, grain- and phase boundaries and small scale chemical zoning patterns provide, more generally, insight into processes that occur at the atomic level and that control in many respects the transport properties of rocks. Processes involved in breaking and establishing bonds at reaction sites determine how and at which rate bulk rock properties change in response to external tectonic forcing and possibly feed back into various geodynamic processes.

In order to include detailed kinetics into thermo-mechanical modelling of convergent plate margins, reliable kinetic data of high-pressure mineral phase transformations is required. However, the measurement of grain-boundary energies is a difficult problem. Methods of grain boundary surface tension measurement include (a) equilibrium angles at triple junction (b) rotating ball method (c) thermal groove method, and others (Gottstein & Shvindlerman, 1999).

Here I will discuss a new method how measured (in-situ) kinetic data at the laboratory time scale can be used to extract grain-boundary energies for the specific kinetic mineral reaction and how this can be used to extrapolate kinetic laboratory data to the geological time scale (Riedel and Karato, 1997). According to this approach, any given kinetic phase boundary measured at the laboratory time scale can be scaled to the corresponding critical isotherm at subduction zones, under experimentally "forbidden" conditions (Liou et al., 2000).

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comparing tomographic images to conceptual 3D velocity models. By applying \mathbf{R} , theoretical models are filtered to the spatial resolution of the tomographic model and the same image artifacts are introduced. We demonstrate how \mathbf{R} of the tomographic model S20RTS affects thermo-chemical and iso-chemical models of convection and how it may impact model interpretation. We discuss how tomographic filters can be applied to any theoretical model, particularly as a built-in module in the code "citcomS".

The resolution operator \mathbf{R} is a critical accompaniment to tomographic models of the mantle. Tomography offers a distorted view of the real Earth. One must account for the heterogeneous spatial resolution when

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3D Spherical modelling of the onset of convection within Iapetus: implications for the timing of its accretion.

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The Cassini spacecraft has observed Iapetus and found two spectacular characteristics. First, the equatorial radius is about 35 km larger than the polar radius, which suggests an equilibrium shape with a 16 hours rotation period whereas the present day rotation is synchronous (79 days). Second, a mountain range about 18 km high, is perfectly aligned with the equator. In order to explain these two striking observations, Castillo et al. (2007) proposes that Iapetus froze its shape as it de-span from a rapid orbital rate of a few hours to the present synchronous rotation. Such a despinning is possible if an additional heat component was present during its early history, including short-lived radiogenic elements such as ²⁶Al, and if heat transfer is inefficient to cool down the interior (i.e. if no thermal convection starts as the satellite heat up). In this context, we performed numerical simulations of thermal convection for fluids with large viscosity contrasts in 2-D cartesian and 3-D spherical geometries, using a 3-D code named OEDIPUS (Choblet, 2005). Comparisons between 2-D and 3-D simulations allow to constrain the onset time of convection and the cooling rate of the satellite interior during the early stage. In the 3D case, gravity is depth dependent. The results emphasize the importance of taking into account not only the 3D nature of the convection pattern but also the satellite curvature. A first result is that the onset time is shorter in 3D spherical geometry than in 2D Cartesian. When convection initiates, a large number of plumes form due to the large value of the Rayleigh number and the small thickness of the thermal boundary layer. Our results suggest that convection starts if the ice viscosity gets lower than 10¹⁶ Pa.s, which corresponds to a temperature of 250 K for pure H₂O ice. It puts limits on the time of formation of Iapetus after the formation of CAIs.

Dynamics of the deep Earth as seen by Seismology

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Seismic studies of recent years show that the lower mantle is far from simple homogeneity. Strong heterogeneities have been detected on many scale lengths spanning several orders of magnitude from a few to 1000's of km using a variety of seismic probes. Using modern data and improved imaging techniques current seismological studies are able to image finer and finer details in the deep Earth.

The seismic models of the lowermost mantle include a variety of features such as intermittent sharp horizontal discontinuities which show considerable topography, strong seismic anisotropy, thin ultra-low velocity zones (ULVZ) and large low velocity provinces that show sharp vertical boundaries between normal and low velocity mantle.

These structures indicate a highly dynamic and complicated region that can only be understood by combining results from various disciplines such as seismology, geodynamics, mineralphysics, and geochemistry. Current models to explain the seismological data include the recently detected solid-solid phase transition from perovskite to post-perovskite to explain the discontinuity atop of the D" layer and possibly other regional layers, partial melts to explain ULVZ and chemically distinct regions and enrichment to explain a variety of features from ULVZ to large low velocity provinces.

This presentation will highlight recent seismological results of the structure of the lowermost mantle and the D" region going from the large low velocity provinces beneath the Pacific and Africa, to the structure of the post-perovskite phase transition as the source of the D" discontinuity to the small-scale structure of ULVZ.

Shear localisation in mixed diffusion/dislocation regime

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We propose a new formalism on grain-size sensitive rheology in the mantle when the grain-size evolves with the deformation and we focus on how deformation can eventually be localised under shear-stress. This study compares some recent approches (Montesi & Hirth, 2003; Bercovici & Karato, 2003; Braun et al., 1999) based on high-pressure experiments (Van der Wal et al., 1993; Twiss, 1977; Rutter and Brodie, 1988) and show a way to generalise them. Our approach is in agreement with observations but also in agreement with the fundamental requirement of mass, energy conservation and positivity of entropy sources. The case of olivine-rich rocks have specially been taken into account because of its large implication on mantle convection, which isn't still well understood. We discuss the grain-size at equilibrium state when the diffusive coasening mechanisms are balanced by the grain-size reduction. A localisation criterium can be found in studying equilibrium states of the mean grain-size when two of them coexist under the same conditions.

Late syn-rift (65-55 Ma) uplift in the Voring Basin, Norwegian Sea - was it a 'hot' or a 'cold' event?

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The Voring Basin is a large sedimentary basin province in the Norwegian Sea and is commonly described as a volcanic end-member of rifted passive margins. A series of rifting events since Permian-Triassic times resulted in structurally complex basins. A striking feature of the Voering basin is a regional uplift event during the last rifting phase (65-55Ma). The geologic process responsible for this uplift remains, however, enigmatic. A common explanation for uplift is strong differential thinning and possibly magmatic underplating. While this mechanism is theoretically viable it requires very high mantle stretching/thinning factors resulting in a high basement heat flow into the sedimentary section. We explore an alternative scenario, based on studies by Podladchikov et al. 1994 and Kaus et al. 2004, in which metamorphic phase changes in the stretched lithospheric mantle results in lower mantle densities and uplift. In this scenario, parts of the thinning lithospheric mantle cross the phase boundaries from dense garnet peridotite to lighter spinel/plagioclase peridotite. This 'cold' uplift scenario can lead to uplift at much lower stretching factors and a thereby lower basement heat flow as in the 'hot' scenario described above.

In this study we will focus on the structural evolution of the Voring Basin close to the Gjallar Ridge and use numerical modeling techniques to explore which scenario is more consistent with the observables. A two-dimensional forward model combined with an inverse algorithm for automated stratigraphy fitting is used to reconstruct the thermal and structural evolution of the Voring basin. Different reconstruction case studies that fit the observed stratigraphy are tested against other observables like subsidence curves and vitrinite reflectance. Both, metamorphic phase transitions and very strong mantle thinning reduce the effective density of the mantle leading to uplift. The resulting uplift and subsidence pattern are, however, different with phase transitions leading to rapid subsidence when the mantle transforms back into dense garnet peridotite during thermal re-equilibration. This and vitrinite reflectance, being sensible to paleo heat flow, can further help to discriminate between the 'hot' and the 'cold' model.

Our reconstructions show that it is possible to discriminate between the 'hot' and 'cold' scenario on the basis of vitrinite reflectance data and subsidence curves. In addition, a comparison with available geological background and well data suggests that the 'cold' scenario is more likely than the 'hot' scenario.

Magma chambers: Convection with spherical particles Jan Verhoeven and Jörg Schmalzl

Abstract:

The dynamics of a convective magma chamber is driven by the presence of different concentrations of crystals and temperature gradients of the fluid. Crystal settling occurs because crystals are heavier than the fluid, leading to differentiation and layer formation. With our numerical model we investigate the characteristics of the crystals and want to find out whether they remain suspended or start to build a layered structure on the ground withing the convective lifetime of a magma chamber.

We present a newly developed algorithm that is a combination of a convection model by Trompert and Hansen and the Discrete Element Model (DEM) that describes the movement and acting forces in granular material. The interaction between the solid particles and the fluid is described on one hand by Stokes' law that influences particle movement and on the other hand by a particle concentration field that describes density variations in the fluid due to the presence of particles. The algorithm enables us to study crystal settling in non-dilute convective suspensions which are typical for magma chambers. The characteristics of settling are mainly controlled by the following two parameters: Rayleigh number and chemical Rayleigh number.

First results indicate that particles can influence convection in magma chambers considerably. We present an example of the behavior of a fluid that is cooled from above and heated from below with 2000 particles homogeneously placed in the whole area. The total number of sedimented particles is recorded over time. The settling velocity that is dependent on time can give hints whether the convection is driven by the particle concentration differences or by the temperature gradients.

Numerical Models of Continental Rifting with Melt Generation

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Active or passive continental rifting is always associated with thinning of the lithosphere and the ascent of the asthenosphere. Depending on the vigour of asthenospheric upwelling decompressional melting may occur. This melt may percolate within the partially molten source region, accumulate and be extracted via dykes. It is not very well known, at which depth levels and to which extent solidification takes place: near the solidus temperature at the top of the asthenosphere, at the base of the crust or at the surface after extrusion.

Two-dimensional numerical models of extension of the continental lithosphereasthenosphere system are carried out using an Eulerian visco-plastic formulation. The equations of conservation of mass, momentum and energy are solved for a multi-component (crust - mantle) and two-phase (solid - melt) system. Temperature, pressure and stress dependent rheologies based on laboratory data for granite, pyroxenite and olivine are used for the upper, lower crust and mantle, respectively. A typical extension experiment is characterized first by the formation of a weak boudinage structures followed by rapid strain localization and necking of the whole lithosphere (see Fig. 1). This necking phase is associated with a pronounced negative topography ("rift valley"), being the result of dynamic stresses and density and thickness variations within the rift zone. If melt is generated (Fig. 2) and extracted, basaltic lavers of a few km thickness can be formed with a maximum thickness near the rift flanks. Not all melt may be extracted, solidification at depth leads to basaltic enrichment in parts of the thinned lithospheric mantle. Comparing models with and without melting but with equal extension rates show, that the occurrence of melting accelerates thinning and stretching at the rift axis. Consequently, models with melting seem to show a slightly stronger subsidence in the rift axis. Once extension stops, partial melt might be present in the mantle beneath the rift for several tens of Mio years. Due to the absence of dynamic stresses the "rift valley" seems to become deeper, followed by further deepening due to cooling. These models demonstrate the importance of melting processes for the topography of extensional regions.

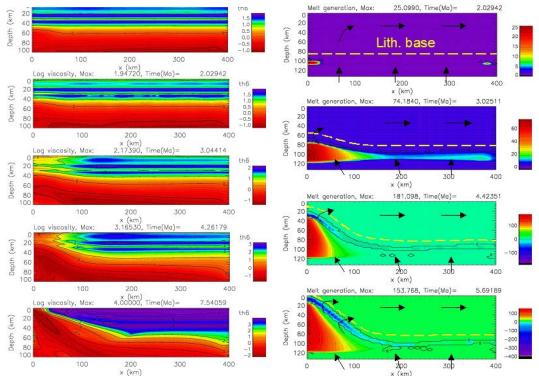


Fig. 1. Viscosity of the rift model

Fig. 2. Melt generation rate

Seismic Tomography: Methodology, Results, and the Latest Developments

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Determining the structure of Earth's interior is one of the most fundamental pursuits in Earth science. Seismic tomography is the premier tool in this endeavor, since seismic waves sample the Earth directly. Wave speeds yield valuable information about the structure, and by inference the composition, temperature, and evolution of Earth's interior. Using highresolution, accurate seismic images it is possible to shed light on such issues as the length scale of mantle convection, the mechanisms of heat transfer from the core to the surface, or the interaction between the deep Earth and surface processes such as plate motion and deformation. Does the mantle convect as a whole or is it layered? Do mantle plumes exist? What is their contribution in delivering Earth's heat to the surface? What are the origins and correlation length scales of mantle heterogeneity? What are the nature and role of geochemical reservoirs? Is there an undifferentiated reservoir in the lowermost mantle? Answering such questions requires a contribution from seismic tomography — a technique by which the three-dimensional distribution of wave speeds in the Earth is reconstructed from travel-time or waveform anomalies. In this presentation I will discuss the methods of seismic body and surface wave tomography, starting from first principles, parameterization schemes and inversion techniques, to ongoing developments such as finite-frequency sensitivity approaches and adjoint methods. As a method, seismic tomography is borrowed from medical tomography; there, as here, accurate reconstructions depend vitally on the even distributions of sources and receivers. I will devote attention to theoretical and practical approaches to evening out global ray path coverage, and discuss the implications of the current status of such efforts with regards to the uncertainty of our knowledge of the structure and the evolution of the Earth's deep interior.

Inference of mantle viscosity from geodynamic data: a genetic algorithm inversion method

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During the past two decades, considerable efforts have been dedicated to recover radial model of mantle viscosity from traditional inverse techniques, using two main sources: data related to the glacial isostatic adjustment of the Earth, and geophysical observables linked to the convection process. Indeed, radial variations in the viscosity of the mantle can in principle be determined from gravity measurements made at the Earth's surface by means of an analytical theory of mantle flow that provides geoid kernels relating density maps and viscosity profiles to the Earth's gravity field. A scaled global tomographic map of seismic wave speeds can be used as an estimate of the Earth's density distribution. A linear inverse problem can then be set up, with gravity observations as data, and the viscosity profile as unknown. Unfortunately, the solution to this problem is strongly non-unique, and a consensual radial model of Earth's viscosity has not been identified by traditional inverse techniques. The problem is further complicated by the existence of numerous tomographic models of seismic velocity, and by the fact that both thermal and chemical heterogeneities participate to the density variations, thus adding some difficulty in establishing an appropriate velocity-to-density scaling for the mantle.

We attempt to account for non-uniqueness in the inverse problem by exploring the solution space, formed of all possible radial profiles of Earth viscosity, by means of a non-deterministic global optimization method: the genetic algorithm. For each solution (radial viscosity profile), synthetic gravity anomalies are computed and tested against the gravity anomalies from GRACE. We experiment with different density models, based on competing tomographic images of the Earth.

Using the yin-yang grid to model thermo-chemical mantle convection with large viscosity contrasts in a 3-D spherical shell

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Here I report a new version of the old 3-D finite volume multigrid code Stag3D [1], recently adapted to spherical geometry using the "yin-yang" grid introduced by [2]. This grid allows the orthogonal staggered-grid primitive-variable discretization of the original code to be maintained, together with fast solution of the velocity-pressure system using a multigrid solver. Compared to the first implementation of this grid for the mantle problem [3], Stag3Dyy uses the minimum overlap yin-yang grid in order to avoid the possibility of differing solutions in the overlapping areas. Additionally, most features of the original code, implemented over many years, are retained, including: the compressible anelastic approximation, tracking of major- and trace-element variations using a tracers (marker-in-cell technique), multiple phase changes including both olivine and pyroxene-garnet systems, and a nonlinear visco-plastic rheology. The code can switch between spherical-shell, Cartesian, a single spherical patch or various 2D geometries by changing only one input switch. A multigrid solver allows efficient solution of large problems (e.g., > 1 billion degrees of freedom) on only modest-sized beowulf clusters (e.g., 64 CPUs). Recent improvements to the multigrid scheme allow large viscosity variations to be modelled, e.g., 13 orders of magnitude globally with 8 orders of magnitude between adjacent points, with only a moderate performance penalty. Performance, scaling, and scientific results will be presented.

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Compressible thermo-chemical convection and application to lower mantle structures

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A new finite element code for compressible thermo-chemical convection is developed to study the stability of a chemical layer at the base of the mantle. Using composition-dependent compressibility and a density difference between compositions at a reference pressure, a compositiondependent density profile is derived. Together with depth-dependent thermal expansion, this combination of parameters yields a wide range of dynamic evolutions for the chemical layer. The chemical structures are classified into five major categories, classical plumes, mushroom-shaped plume, domes, ridges, and continuous layers, and a few abnormal cases, such as hourglassshaped plumes and columnar plumes. Several models have a chemical structure morphologically similar to the African low V_S structure in the lower mantle, at least at a single time. Guided by our models, several dynamic scenarios are proposed for the dynamic nature of the lower mantle low velocity structures (a.k.a. superplumes), including plumes at an early stage, plume clusters, ridges, passive piles, sluggish domes, and high-bulk-modulus domes (Figure 1). We predict seismic velocity anomalies from these dynamic models. The thermo-elastic parameters used in the conversion are additional constraints. We compare the density structure with normal mode inversion, the predicted seismic signature observations, and the required thermoelastic parameters with mineral physics data. Among the proposed scenarios, only the scenario of high-bulk-modulus domes satisfies all constraints simultaneously. The implication on the geochemistry and mineralogy of lower mantle chemical structures is discussed. (This work is published on J. Geophys. Res., Vol. 112, B06304, doi:10.1029/2006JB004505, 2007)

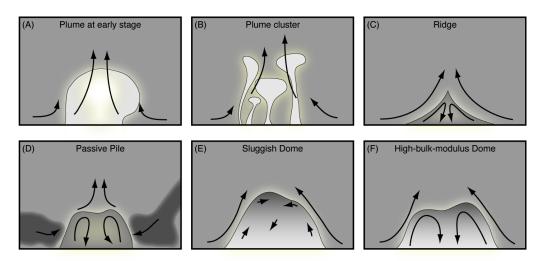


Figure 1: Various dynamic scenarios for the African low V_S structure. The gray scale indicates the density anomaly. Darker is denser. The arrows indicate the direction and speed of the flow. (A) A large, buoyant plume at early stage, (B) a cluster of small plumes merging together, (C) a stable ridge-shaped chemical structure, (D) a stable chemical pile passively displaced by dense slabs, (E) a stable chemical dome made of high-bulk-modulus material, and (F) a stable chemical dome made of high-viscosity material.

Dynamics and evolution of icy satellites

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The Galileo mission (1995-2003) and the Cassini-Huygens mission (2004-2010) in orbit around Jupiter and Saturn, respectively, have revealed that these two giant planets host several very active moons. The magnetic data returned by the Galileo mission suggest that deep salted water oceans are present within three of its biggest moon, Europa, Ganymede and Callisto. Europa exhibits very complex tectonic features, suggesting that liquid water has been recently exposed on its cold surface. Saturn's moon Enceladus also displays in some regions tectonic features similar to Europa. Even more surprising, this tiny moon (only 252 km in radius) is one of the rare solid objects in the solar system to be sufficiently geologically active for their internal heat to be detected by remote sensing. But in contrast to the Earth and Jupiter's volcanic moon Io, the endogenic activity on Enceladus is mainly localized at the South Pole, from which jets of water vapor and ice particles has been observed. The origin of this huge hotspot at Enceladus' South Pole still remains enigmatic.

One of the most intriguing world is probably Titan, Saturn's biggest moon. Titan is the only moon in the solar system hosting a massive atmosphere, mainly composed of nitrogen, methane, and a complex suite of organic molecules resulting from the photolysis of its main atmospheric compounds. Methane, which can be liquid at Titan's atmospheric conditions, plays a role similar to water on Earth, forming lakes and river networks that the Cassini-Huygens mission recently revealed. Measurements performed by the Huygens probe during its descent through Titan's atmosphere on Jan. 14 2005, provided circumstantial evidences that the atmospheric methane is recycled by internal outgassing processes, maybe still operating. More recently, data gathered by the Cassini spacecraft indicate that outgassing processes are probably also operating on other Saturn's moon, Dione, Tethys and Rhea, previously thought to be geologically dead. And this is probably not the last surprise of the Cassini-Huygens mission.

How these small icy worlds have kept such an activity more that 4.5 gigayears after their accretion is enigmatic. Radiogenic heating in these icy bodies is relatively low. Frictional heating owing to solid tides raised by their giant planet on the satellite is probably a major source of energy for several of these moons. Tidal heating associated with their eccentric orbit has long been suspected to play a major role in the thermal evolution of giant planet moons. The surprising activities of Io and now, of Enceladus are the most convincing evidence for tide-generated heat. I will show how the specific rheological properties of water ice make the satellite interior very dissipative, and hence provide a huge source of energy. The effect of tidal heating on the convective instabilities and on coupled thermal and orbital evolution of the satellites will be illustrated. The role of ice composition and grain size will also be discussed. I will expose how tidal heating and thermal convection are strongly coupled in these exotic. This strong coupling could explain the spectacular activity observed on Enceladus, could maintain a global liquid ocean below Europas icy crust and could help recycle Titans atmosphere.

Mechanical anisotropy of the lithospheric mantle and continental rifting: Observations and models

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Analysis of major rift systems suggests that the preexisting structure of the lithosphere is a key parameter in the rifting process. Rift propagation is not random, but tends to follow the trend of the orogenic fabric of the plates, systematically reactivating ancient lithospheric structures. Continental rifts often display a clear component of strike-slip deformation, in particular in the early rifting stage. Moreover, although the close temporal and spatial association between flood basalt eruption and continental breakup suggests that mantle plumes play an important role in the rifting process, there is a paradox between the pinpoint thermal and stress perturbation generated by an upwelling mantle plume and the planar geometry of rifts. These observations suggest that the deformation of the lithosphere, especially during rifting, is controlled by its preexisting structure. On the other hand, (1) the plasticity anisotropy of olivine single crystal and aggregates, (2) the strong crystallographic orientation of olivine observed in mantle xenoliths and lherzolite massifs, and (3) seismic anisotropy data, which require a tectonic fabric in the upper mantle coherent over large areas, suggest that the preservation within the lithospheric mantle of a lattice preferred orientation (LPO) of olivine crystals may induce a large-scale mechanical anisotropy of the lithospheric mantle.

We use multi-scale numerical models to investigate the effect of a preexisting mantle fabric on the continental breakup process. Model results show that a LPO-induced mechanical anisotropy of the lithospheric mantle may result in directional softening, leading to heterogeneous deformation. During continental rifting, this mechanical anisotropy may induce strain localization in domains where extensional stress is oblique to the preexisting mantle fabric. This directional softening associated with olivine LPO frozen in the lithospheric mantle may also guide the propagation of the initial instability that will follow the preexisting structural trend. The preexisting mantle fabric also controls the deformation regime, imposing a strong strike-slip shear component. A LPO-induced mechanical anisotropy may therefore explain the systematic reactivation of ancient collisional belts during rifting (structural inheritance), the plume-rift paradox, and the onset of transtension within continental rifts.

Low-degree gravity signature of short-wavelength models of subduction

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In the framework of the ongoing discussion concerning the importance of lateral viscosity variations (LVV) on geoid predictions, it is recognized that LVV of long wavelength (in the spectral domain, $\ell_{\rm max} \simeq 20$) such as those associated to a temperature-dependent viscosity derived from seismic tomography, do not significantly affect inversions of the low-degree geoid $(2 \leq \ell \leq 10)$. On the other hand, regional models of subduction zones generally fail to predict the correct high-degree geoid signal if LVV of sufficiently short-wavelength are not taken into account. Using a mixed spherical harmonic-finite element approach to model present-day mantle flow, we perform numerical experiments to investigate, in a spherical axisymmetric geometry, the effects of LVV on the low-degree geoid and gravity anomalies above a typical subduction zone. We present a systematic exploration of the parameters space, testing several combinations of density, viscosity and geometry of a subducted slab having a realistic lateral extent (~ 100 km), with the aim of predicting the characteristic broad positive highs that the low-degree geoid and gravity exhibit over major subduction zones.

Reduced oceanic seismic anisotropy by small-scale convection

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Seismic anisotropy has been proven a valuable tool to determine rheology and flow properties in the Earths asthenosphere. However, the relationship between flow and the nature of seismic anisotropy is complicated and depends on cumulative strain and rheological properties such as dynamic recrystallization, and even simple shear experiments show non-trivial fabric developments (e.g. Zhang & Karato, 1995; Wenk & Tome, 1999; Kaminski & Ribe, 2001). Several studies indicate that the amplitude of seismic anisotropy in the old Pacific is small compared to that in the young Pacific (Nishimura & Forsyth, 1989; Becker et al.,2003; Smith et al., 2004). This suggests that the built-up seismic anisotropy is somehow destroyed during ageing of the plate. Here we examine how small-scale sublithospheric convection (SSC) influences the amplitude fabric under older oceanic lithosphere. SSC has been suggested to occur below Pacific lithosphere older than \sim 70 Ma, although it might locally occur under much younger lithosphere when triggered by inhomogeneities, such as transform faults or melting events (Ballmer et al., 2007).

We investigated the importance of SSC on the disturbance of plate-motion aligned seismic anisotropy in oceanic lithosphere. Therefore, we output from our previous model calculations (van Hunen et al., 2005) the local deformation rate, from which we calculate accumulated strain and fabric using the numerical code D-Rex, provided by Edouard Kaminski (Kaminski, Ribe, and Browaeys, GJI, 158, 744-752, 2004). Our results show that on a 100-km lengthscale, SSC randomly reorientates previously build-up anisotropy over a given depth range. However, when smoothed over lengthscales of 500-1000 km (the typical seismic resolution of surface wave tomography in the Pacific) SSC appears to reduce the amplitude, not the azimuthal direction of anisotropy. These results are similar to the observed anisotropy amplitudes, and suggest SSC as a possible explanation for reduced anisotropy in the older Pacific lithosphere.

A community benchmark for compressible convection

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The silicate mantle of the terrestrial planets is slightly compressible and goes through a number of phase changes and a decrease in volume as pressure increases. The related physical properties of the silicates, such as density, bulk modulus, coefficient of thermal expansion and heat capacity, change therefore with pressure. Many existing mantle convection codes are based on the simplified Boussinesq or Extended Boussinesq approximations, which ignore the effects of compression. While this simplified approach has been useful in exploring mantle convection modeling, it is difficult to explicitly compare these models with models from seismology or mineral physics. A realistic Earth model for geodynamics, seismology, or mineral physics must take the compressibility and its effects on the mantle into account. With the advances made in high pressure mineral physics research, our knowledge of the physical properties of mantle rock at lower mantle conditions has greatly improved. It has become possible to construct a dynamic model with realistic mineralogical and thermodynamical formulation, where the model results can be readily compared with seismology and geodesy. To aid the further development of compressible convection modeling, a benchmark for compressible thermal convection is formulated by the community within the Computational Infrastructure of Geodynamics (CIG). The initial benchmark problem is 2-D thermal convection of a non-rotating anelastic liquid of infinite Prandtl number in a Cartesian, closed, unit cell. The governing equations are based on Truncated Anelastic Liquid Approximation. The benchmark consists of several cases: steady and timedependent, constant and variable viscosity, and bottom and internal heating. Several numerical and analytical codes participate in the benchmark. We welcome wider participation from the community.

URL: http://www.geodynamics.org/cig; www.geo.lsa.umich.edu/~keken/benchmarks/compr

Finite element meshing of three-dimensional faulted domains

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Meshing of 3-D spaces for finite element applications is often a complicated and time-consuming process. The introduction of internal boundaries in order to represent (subduction) faults further complicates the mesh generation process. We present two new tools which result in a significant simplification of the meshing process for geodynamic problems. The first is a mesh generator which uses a regular grid to rapidly generate a finite element mesh for a faulted spherical shell or spherical shell segment (figure 1). It includes radial mesh refinement, and iterative optimization of the finite element aspect ratio. The second is a graphical tool to facilitate the step from geodynamical maps to finite element meshes. Currently in the final stages of development, these tools will be applied to global and regional scale geodynamical modeling studies, using the large-scale mantle convection model of Geenen et al. (see poster "Large scale mantle dynamics modeling").

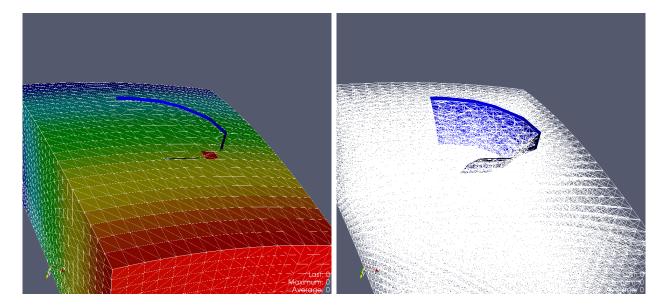


Figure 1: Finite element mesh including subduction fault.

3-D Interactive Visualization with ACuTEMan

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ABSTRACT

Mantle convection researchers at the University of Minnesota (UofM) have collaborated with members of the Laboratory for Computational Science and Engineering (LCSE) to implement a system capable of interactive exploration of large scientific model data sets rendering in near real time. Model data that is computed over hundreds of processors on a Linux cluster is sent over a local network to the LCSE lab on a periodic basis for visualization on an extremely high definition display. We describe the technical details involved in designing such a system and describe the specific application to the mantle convection simulation program, ACuTEMan.

Additional Keywords: 3-D volume visualization, mantle convection, interactive visualization, parallel computing.

1 Introduction

Our task has been to develop interactive visualization capabilities for high-resolution 3-D flows that are being computed in near real time on the Blade Cluster at the UofM. Here, we differentiate interactive from real-time visualization as possessing the ability to manipulate the visual representation of the data and having those changes available for assessment in a timely manner. In our case, we are viewing 3-D results from the ACuTEMan model in near real-time (very close to the actual computation time), and we also have the ability, through specialized software, to adjust the rendering of our image and the color spectrum to explore additional areas of geophysical interest. Here we discuss the techniques employed to allow for instant feedback in the form of visualization rather than having to manually post process our results.

2 Strategy

The AcuTEMan model [1], a multigrid-based mantle convection simulation code, has been modified to use LCSE's interactive rendering system. Model data that is initially calculated at the BladeCenter is transferred over a local network in the Brick of Bytes (BoB) format to the LCSE for visualization [2]. After the data is transferred, it is rendered and then

displayed over 13 million pixels on the LCSE's 10-panel PowerWall display. The transfer and rendering tasks operate in an automated fashion, allowing the ACuTEMan model to periodically and asynchronously send data over the local network for visualization. Figure 1. Shows the steps involved in the process of using the LCSE rendering system from the BladeCenter. Researchers, who have access to PowerWall, whether physically or by other means such as a Web Cam, can observe the temperature fields of the ACuTEMan evolving over time on the Blade system.

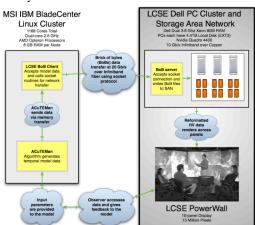


Figure 1. Model data is computed over N PEs at the Blad Center and is sent to a local BoB client where it is transferred to the LCSE. Once the data is received by the LCSE it is reformatted into the HV standard and is rendered as a three dimensional volume.

2.1 LCSE rendering system

To support interactive visualization, the LCSE has modified the rendering cluster to act as a data pipeline. Eleven visualization nodes are used to operate LCSE's PowerWall; each, a Dell workstation with 8 Gigabytes of RAM, an NVidia Quadro graphic board, and a high-speed connection to a multi-Terabyte striped disk system. To achieve fast transfer rates, incoming model data is stored on a ram disk and is periodically deleted; the speed of the disk writes is 125 MB/s, while the virtual ram disk allows for up to 1GB/ sec. When

model data reaches the LCSE, it is converted from the BoB files to a single HV file for volume rendering. A HV file contains a single time step of data restructured in a tree hierarchy [3]. After the HV file is created, a MPI program broadcasts this file to each of the visualization nodes over Infiniband so that rendering can begin. The time between model time steps can be used to manually explore data using the LCSE DSCVR software package, thus allowing for interactive visualization. The rendered image can either be displayed by the PowerWall (13 Megapixels.), sent back over the socket to DSCVR which is running on a Windows PC, or posted to a website. Some adjustments we make during this time are swapping colormaps, rotating the volume, and changing the opacity to view data that might otherwise be occluded.

3 DISCUSSION

The ACuTEMan code is a high-performance numerical tool, written for large-scale parallel computing in order to investigate the convective motions of the Earth's mantle [4]. ACuTEMan solves a set of linear elliptic equations for velocity and pressure using a multigrid method together with the smoothing algorithm named ACuTE. With this new capability, researchers using ACuTEMan have the ability to directly interact with live model data by rotating the volume, adjusting the color scale, and zooming into the data set for exploration of smallscale features. Undesired results due to incorrect model configuration can become visible to the researcher during the interactive visualization, thus allowing the calculation to be stopped preemptively, adjusted, and then restarted. In Figure 2 we show a series of camera snapshots of data being rendered interactively on the PowerWall. Shown in these images are red upwellings originating from the hot thermal layer at the bottom (roughly equivalent to 2700 km in depth inside the Earth) of the grid space. The blue areas are colder downwellings that provide the mass for a downward flow, thus initiating the convection

4 CONCLUSIONS & FUTURE WORK

Using ACuTEMan with interactive visualization, we can detect whether the model as been given insufficient input parameters and decide to terminate the execution of the model. This, in effect, allows the model results to be assessed more quickly, saves CPU hours and resources, and also minimizes wasted effort. Using these methods, we also learn a great deal by monitoring the evolution of 3-D mantle convection from the onset of the initial instabilities.

The interactive visualization system presented here offers a solution to support a variety of interactive supercomputing tasks both from the University of Minnesota and from remote sites. Currently, we have the ability to convert raw model data into an interpretable visualization, save the data in a variety of formats, and offer a service to both view and steer a computation. We are proposing a system that will offer these services in a web-based environment so that they can be accessed from outside the university.

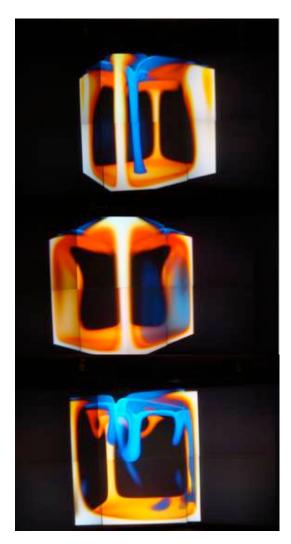


Figure 2. A series of camera snapshots taken of the LCSE PowerWall showing a three-dimensional temperature field from the ACuTEMan evolving in real-time with a Rayleigh number of 10⁶.

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We show that three-dimensional spherical shell mantle convection with realistic mantle viscosity structure, convective vigor and internal heating rate is characterized by either spherical harmonic degree-1 planform with a major upwelling in one hemisphere and a major downwelling in the other hemisphere when continents are absent, or degree-2 planform with two antipolar major upwellings when a supercontinent is present. We propose that due to modulation of continents, these two modes of mantle convection alternate within the Earth's mantle, causing the cyclic processes of assembly and breakup of supercontinents including Rodinia and Pangea in the last 1 Ga. Our model explains Africa and Pacific antipolar superplumes for the present-day mantle. Our model also explains the basic features of the true polar wander (TPW) for Rodinia and Pangea including their equatorial locations and large variability of TPW inferred from paleomagnetic studies. Our model also suggests that TPW is expected to be more variable and large during supercontinent assembly, but small after a supercontinent acquires its equatorial locations and during supercontinent dispersal.