9th INTERNATIONAL WORKSHOP ON NUMERICAL MODELING OF MANTLE CONVECTION AND LITHOSPHERIC DYNAMICS

25th COURSE OF THE INTERNATIONAL SCHOOL OF GEOPHYSICS

Ettore Majorana Foundation and Centre for Scientific Culture
Erice, Sicily
September 8-14, 2005

Director of the School	**Enzo Boschi**	Dipartimento di Fisica, Università di Bologna, Italy
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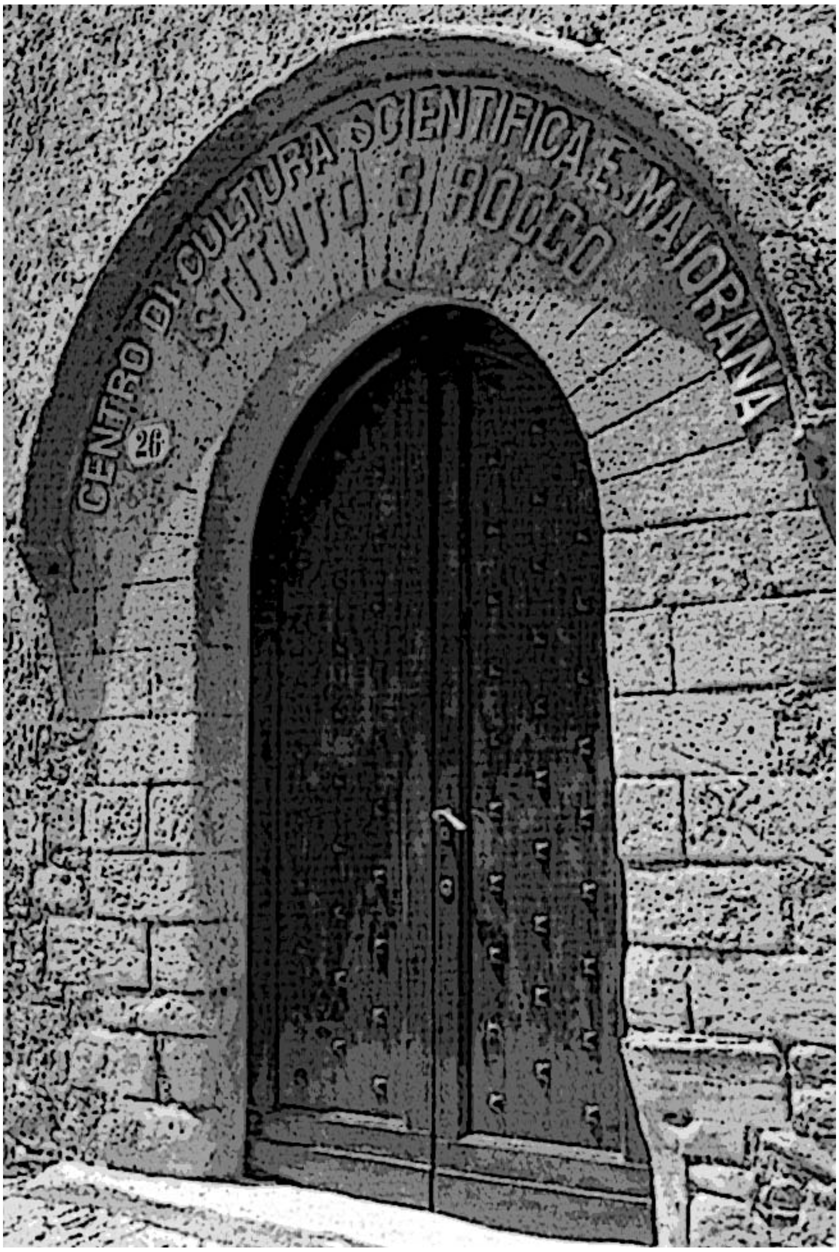

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INVITED LECTURES & TUTORIALS

Friday, September 9

Yanick RICARD
Cnrs-Ensl-Université de Lyon, Lyon, France
Successes and Future Challenges of Mantle Modelling

David SANDWELL
Scripps Inst. of Oceanography, La Jolla, USA
Lithospheric Dynamics - Can Plate Cooling and Shrinkage Explain Everything?

Kurt LAMBECK
Research School of Earth Sciences, Canberra, Australia
Earth Rheology from Glacial Rebound Analysis

Patrick CORDIER
University of Lille, Villeneuve d'Ascq, France
Rheology: the Crystals Behind the Flow

Saturday, September 10

Ondrej CADEK
Charles University, Praha, Czech Republic
Constraints on Global Mantle-Flow Models from Geophysical Data

Jeroen RITSEMA
IPG Paris, Paris, France
Seismological Constraints on Earth's Structure

Albrecht HOFMANN
Max-Planck-Institut für Chemie, Mainz, Germany
Tutorial on Geochemical Constraints on Mantle Evolution and Plume Structure

Monday, September 12

Marc HIRSCHMANN
University of Minnesota, Minneapolis, USA
Distribution of H_2O in the Mantle: Constraints on Mantle Circulation

Greg HIRTH
WHOI, Woods Hole, USA
The Role of Melt on the Dynamics of the Upper Mantle

Joerg SCHMALZL
University of Münster, Münster, Germany
Numerical Modeling of Chemical Heterogeneities in the Earth's Mantle

Tuesday, September 13

Jun KORENAGA
Yale University, New Haven, USA
Thermal History of Earth and the Modes of Mantle Convection

Alessandro BONACCORSO
Istituto Nazionale di Geofisica e Vulcanologia, Catania, Italy
Volcano Ground Deformation: Search for Magma Storage and Modelling of the Intrusion Process

Malcolm SAMBRIDGE
Research School of Earth Sciences, Canberra, Australia
Nonlinear Inverse Problems and Model Space Search

PROGRAM

Thursday, September 8

12:00	Registration
20:30	Icebreaker party

Friday, September 9

Chairpersons: D. Bercovici
S.-I. Karato

08:30	Opening of the workshop
08:45	**Invited lecture:** Y. Ricard
09:45	**Invited lecture:** D. Sandwell
10:45	— coffee break —
11:15	**Invited lecture:** K. Lambeck
12:15	Discussion
13:00	— lunch —
14:45	Poster presentation
15:30	Poster Session
17:00	— coffee break —
17:30	**Tutorial:** P. Cordier
18:30	Discussion

Saturday, September 10

Chairpersons: C. Bina
T. Becker

09:00	**Invited lecture:** O. Cadek
10:00	**Invited lecture:** J. Ritsema
11:00	— coffee break —
11:30	Discussion
12:15	Poster presentation
13:00	— lunch —
15:00	Poster Session
17:00	— coffee break —
17:30	**Tutorial:** A. Hofmann
18:30	Discussion

Sunday, September 11

09:00	Trip to Segesta and S. Vito Lo Capo
20:30	Social dinner

Monday, September 12

Chairpersons: H. Schmeling
N. Ribe

09:00	**Invited lecture:** M. Hirschmann
10:00	**Invited lecture:** G. Hirth
11:00	— coffee break —
11:30	Discussion
12:15	Poster presentation
13:00	— lunch —
15:00	Poster Session
17:00	— coffee break —
17:30	**Tutorial:** J. Schmalzl
18:30	Discussion

Tuesday, September 13

Chairpersons: S. Labrosse
C. Hieronymus

09:00	**Invited lecture:** J. Korenaga
10:00	**Invited lecture:** A. Bonaccorso
11:00	— coffee break —
11:30	Discussion
12:15	Poster presentation
13:00	— lunch —
15:00	Poster Session
17:00	— coffee break —
17:30	**Tutorial:** M. Sambridge
18:30	Discussion & Meeting Summary

Wednesday, September 14

09:00	Departure from Erice

Poster Session, Friday, September 9

Lithosphere and Mantle-Lithosphere Interaction Posters

P1	Caroline Dumoulin	3-D numerical simulations of mantle flow beneath mid-ocean ridges separated by transform faults
P2	Ritske Huismans	Effect of lithospheric stratification on extensional styles and rift basin geometry
P3	Jeroen van Hunen	On the viability and style of subduction in a hotter Earth
P4	Laurent Husson	Propagation of tectonic waves
P5	Margarete Jadamec	Lithospheric deformation and 3D mantle flow in the Pacific-North American plate boundary corner in southern Alaska
P6	Boris Kaus	Effects of elasticity on the Rayleigh-Taylor instability: implications for large-scale geodynamics
P7	Gabriele Morra	Far interaction in the upper mantle through 3D-BEMFEM
P8	Anton Popov	A new 3D finite strain elastoviscoplastic code for lithospheric scale modeling

Geoid and Post-glacial Rebound Posters

P9	Andrea Antonioli	3D numerical modeling of glacial isostatic adjustment with lateral heterogeneities
P10	Giulio Dal Forno	FE modelling of postglacial rebound and the microphysical approach
P11	Kevin Fleming	Low-degree geopotential changes due to past and present-day ice-load changes: comparisons with GRACE observations
P12	Luce Fleitout	Post-glacial rebound, lateral viscosity variations and transient creep
P13	Yann Krien	Long-wavelength geoid anomalies and dynamic of subduction zones: effects of a layering at 660km
P14	Karen Niehuus	Temporal geoid variations as constraint in global geodynamics
P15	Tõnis Oja	Postglacial rebound in Estonia: constraints from the measurements of Estonian geodetic networks
P16	Nicola Piana Agostinetti	Post-glacial rebound in North America: ice load parameters from inverse problems
P17	Paolo Stocchi	Holocene sea-level changes in the Mediterranean: the role of remote and near-field ice sheets
P18	Hugo Schotman	Shallow low-viscous Earth layers in flat 3D finite-element models of glacial isostatic adjustment

Poster Session, Saturday, September 10

Rheology and Mantle Dynamics Posters

P1	Shun-ichiro Karato	Variation of olivine fabrics with thermo-chemical environment: an interdisciplinary study
P2	Shun-ichiro Karato	Large-strain deformation experiments under deep mantle conditions using a rotational Drickamer apparatus (RDA)
P3	William Landuyt	Two-dimensional convection with a two-phase damage rheology lithosphere
P4	John Sheehan	Rheology and the Porcupine Basin

Global Mantle Convection Posters

P5	Gaël Choblet	Modelling convection with large viscosity gradients in the cubed sphere
P6	Rebecca Farrington	Entrainment in 2-D and 3-D numerical models of thermochemical convection
P7	Cécile Grigné	Effect of continents on mantle dynamics for various mantle rheologies
P8	Catherine Hier-Majumder	Finite Prandtl convection
P9	Giampiero Iaffaldano	A global coupled model of the lithosphere and mantle dynamics
P10	Stéphane Labrosse	The thermal evolution of the Earth
P11	Einat Lev	Mixing of differentiated oceanic crust in a convecting mantle with depth and temperature dependent properties
P12	Benjamin Phillips	The aggregation and dispersal of supercontinents in global mantle convection models
P13	Guillaume Richard	Slab dehydration and fluid migration at the base of the upper mantle
P14	Kai Stemmer	Numerical simulation of mantle convection: 3D, spherical shell, temperature- and pressure-dependent viscosity
P15	Nicola Tosi	Spectral-finite element approach to present-time mantle convection
P16	Joost van Summeren	Composition-dependent viscosity in evolutionary models of thermo-chemical mantle convection

Seismology Posters

P17	Thorsten Becker	Seismic anisotropy in the Western US as a testbed for advancing combined models of upper mantle geodynamics and texturing
P18	Marie Běhounková	Synthetic travel-time tomography: resolution tests for models with regular and irregular parameterisation
P19	Jules Browaeys	Spatial coherence of seismic anisotropy and interpretation of shear wave splitting - *Hawaiian upper mantle case*
P20	Eric Debayle	Global distribution of seismic heterogeneities and azimuthal anisotropy in the upper mantle
P21	Francesco Pio Lucente	Mapping the long route of the Tyrrhenian slab through the mantle
P22	Dmytro Malytskyy	Mathematical modeling for seismology problems
P23	Gaia Soldati	Global P velocity models and resolution analyses: increasing grid density
P24	Lev Vinnik	S velocity reversal in the mantle transition zone

Poster Session, Monday, September 12

Melting and Melt Extraction Posters

P1	Mark Behn	The effect of magmatism on faulting and axial morphology at mid-ocean ridges: modeling the transition from rift valley to axial high
P2	Saswata Hier-Majumder	Influence of grain boundary wetting on migration and retention of melt
P3	Edouard Kaminski	An experimental study of melt circulation in a poroviscous matrix
P4	Shun-ichiro Karato	Some new experimental constraints on the transition-zone water filter model
P5	Richard Katz	Melt localization and the rheology of the partially molten mantle under shear
P6	Kei Kurita	Melt segregation and textural evolution of partially molten system
P7	Kristian Müller	Generation and evolution of channels due to the melt channel instability
P8	Michael Riedel	Permeability-porosity relationship in a stochastic model of partial melting
P9	Ondřej Šrámek	Melting and compaction in deformable two-phase media

Slab Dynamics Posters

P10	Magali Billen	Deformation of subduction lithosphere in the upper mantle
P11	Craig Bina	Slab stagnation depth: buoyancies, bending moments, and seismic structure
P12	Fabio Capitanio	Effects of continental buoyancy on subduction dynamics
P13	Erika Di Giuseppe	Modeling the subduction process using 3D laboratory and numerical tools
P14	Alwina Enns	The influence of the plate properties on the dynamics of subduction
P15	Francesca Funiciello	Mapping the flow during retreating subduction: laboratory models analyzed by Feature Tracking
P16	Jörg Hasenclever	Investigating the Earth's upper mantle structure: numerical and laboratory experiments on mantle flow and entrainment processes
P17	Ritske Huismans	Factors controlling slab roll-back and back-arc extension: insights from numerical models
P18	Laurent Husson	Dynamic topography above subduction zones: evidence from theory, seismic tomography and gravity
P19	Claudia Piromallo	3D numerical instantaneous flow models induced by subduction
P20	Neil Ribe	All bent out of shape: buckling instabilities of viscous sheets and slabs
P21	Leigh Royden	Trench motion, slab geometry and viscous stresses in subduction systems
P22	Karin Ruckstuhl	Dynamic consequences of slab edges in the Calabrian subduction region
P23	Harro Schmeling	What is the cause for trench roll back?

Poster Session, Tuesday, September 13

Mantle Plumes and Thermo-Chemical Convection Posters

P1	Anne Davaille	On the zoology of mantle upwellings: fluid mechanics constraints
P2	Huw Davies	Splash plumes - plumes rooted in mid-mantle
P3	Christoph Hieronymus	Thermal convection and mantle plume dynamics with grain-size dependent viscosity
P4	Garrett Leahy	Structure and dynamics of a hydrous melt layer above the transition zone
P5	Tanya Lubetskaya	Composition of Earth's mantle and its variance
P6	Gabriele Marquart	A mantle flow model for the North Atlantic and its relation to seismic anisotropy and geochemical signature
P7	Eric Mittelstaedt	Ridge jumps associated with plume-ridge interaction: 1. Off-axis heating due to lithospheric magma penetration
P8	Henri Samuel	Oscillatory vs. stagnant plumes in the Earth's lower mantle
P9	Judith Vatteville	The transient nature of mantle plumes

Faults, Dykes, Crust & Lithosphere Deformation Posters

P10	Andrey Babeyko	Thermal and compositional control on deformation distribution along the Central Andean foreland
P11	Andrey Babeyko	Hidden tectonic shortening: a numerical model of coupled erosion and deformation at plateau margin
P12	Susanne Buiter	Discussion on designing a plasticity benchmark experiment
P13	Susanne Buiter	Comparison of sandbox-style numerical extension experiments
P14	Rosie Fletcher	Geodynamic modelling of the Tertiary development of the Faroes-Shetland Basin: a failed continental breakup basin?
P15	Boris Kaus	A parameterized rheology for creating lithospheric-scale shear zones
P16	Rocco Malservisi	Effect of lithospheric model assumption on the interpretation of geodetic data
P17	Gabriele Marquart	A detailed model for accretion of crust in Iceland
P18	Alexey Petrunin	Thermo-mechanical modelling of a pull-apart: approaching 3D
P19	Eleonora Rivalta	Analytical 2D modeling of a strike-slip fault in a viscoelastic space
P20	Eleonora Rivalta	Relation between deformation and cumulative seismicty as a possible tool for monitoring dike stability
P21	Catherine Robin	Visco-elastic models of greenstone belt formation by diapiric density inversion and magmatic intrusions
P22	Alexander Rozhko	Vent modeling
P23	Lars Rüpke	Towards dynamic basin inversion: motivation, approaches, and some results
P24	Dani Schmid	Buckling of elastic layers: wavelength selection, strain rate
P25	Stephan Sobolev	How to make the Andes?
P26	Elisa Trasatti	Numerical inversion and modeling of 1993-97 GPS data at Mount Etna, Italy

SUBMITTED ABSTRACTS

3D numerical modeling of glacial isostatic adjustment with lateral heterogeneities

Giorgio Spada[1] , **Andrea Antonioli**[2,3] , **Spina Cianetti**[3] **and Carlo Giunchi**[3]

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Analytical spherically layered models are commonly employed to study the response of the Earth to the melting of the late–Pleistocene ice-sheets in order to predict postglacial deformations and gravity variations. To overcome the limits of analytical approaches, numerical models have been developed to keep into account lateral varying rheological structures that may significantly affect various geophysical quantities related to Glacial Isostatic Adjustment (GIA), and particularly postglacial relative sea level (RSL) variations and horizontal deformations. We develop 3D spherical finite element models with lateral variations of lithospheric thickness and Newtonian upper mantle, and we directly compare the outcomes of these models with RSL data selected from published and available global data set. This differs from previous investigations, that have mainly focused on extensive sensitivity analysis or have considered a very limited number of RSL observations pertaining to the formerly glaciated regions or to their periphery. In our study the lithospheric thickness is constrained to mimic the global structure of the cratons based on geological evidence, and the upper mantle includes a low–viscosity zone beneath the oceanic lithosphere. We use two distinct global surface loads, based upon the ICE1 and ICE3G deglaciation chronologies, respectively. Our main finding is that using all of the available RSL observations in the last 6000 kyrs it is not possible to discern between homogeneous and heterogeneous GIA models. This finding, that holds for both the ice chronologies employed here, suggests that the cumulative effects of laterally varying structures on the synthetic RSL curves tend to cancel out globally, thus providing signals that do not significantly differ from those based on the traditional radially stratified models. We have also considered specific subsets of the RSL database, selecting sites sharing similar geographical settings and distances from the main centers of deglaciation. In the regions where the disagreement between predictions and observations is particularly evident, further investigations will be needed to improve the geometry of the deep heterogeneous structures and of the surface ice sheets distribution.

Thermal and compositional control on deformation distribution along the Central Andean foreland

Andrey Babeyko[1] **and Stephan Sobolev**[2]

[1] *Institut für Meteorologie und Geophysik, J.W.Goethe Universität Frankfurt, Germany*
[2] *GeoForschungsZentrum Potsdam, Germany*

The Central Andean orogen was built during the last 30 Myrs as a result of tectonic shortening of the South American margin between the subducting Nazca plate at the west and indenting Brazilian shield at the east. The corresponding deformation pattern varies both in space and time. Along the strike, tectonics at the plateau foreland changes from thin-skinned in the Altiplano foreland (north to 23 S) to thick-skinned in the Puna foreland (south of 23 S). On the other hand, Altiplano shortening demonstrates an abrupt switch from pure- into simple-shear mode in Late Miocene.

Using 2-D thermo-mechanical numerical simulations we show that spatial and temporal variations of the shortening pattern might be well controlled by the two main parameters: strength of the foreland uppermost crust and temperature of the foreland lithosphere. Mechanical weakening and failure of the thick Paleozoic sediments overlying the cold lithosphere in the Altiplano foreland at 13-9 Ma explains the transition from pure to simple shear shortening accompanied by broad thin-skinned thrusting. On the other hand, at the Puna foreland, the high strength of the uppermost crust combined with relatively warm lithosphere results in the thick-skinned shortening. Failure of Paleozoic sediments in the Altiplano foreland significantly reduces the force required to shorten the lithosphere, which may well be the reason for the increase of bulk shortening rate in the Late Miocene.

Hidden tectonic shortening: a numerical model of coupled erosion and deformation at plateau margin

Andrey Babeyko[1] , **Stephan Sobolev**[2] **and Tim Vietor**[2]

[1] *Institut für Meteorologie und Geophysik, J.W.Goethe Universität Frankfurt, Germany*
[2] *GeoForschungsZentrum Potsdam, Germany*

The idea that high fluvial erosion rates at the plateau rim can influence the dynamic behavior of the plateau/foreland system is directly tested with our thermo-mechanical 2D parallel lagrangian explicit material-point code LAPEX-2D. The code incorporates highly nonlinear visco-elasto-plastic rheology as well as surface processes in form of fluvial and landsliding erosion. Model setup represents converging plateau/foreland system.

At low erosion rates tectonic shortening is unevenly distributed among the plateau and the foreland, depending on their relative effective stiffness, which is a function of thermal history, lithology and height of the plateau. In contrast, when the erosion rate is high, such as in areas with monsoon climate, the overall tectonic shortening could be almost completely hidden by a single exhumational shear zone at the plateau rim. In this case the apparent tectonic shortening might strongly underestimate the real one. Our numerical experiments suggest a way to estimate the amount of hidden shortening based on two observables: denudation and convergent rates. Thus, high denudation rates in Hymalayas may be responsible for more than 50 percent of hidden shortening.

High erosion and exhumation rates at the plateau margin have an overall dynamic weakening effect in the converging plateau/foreland system. Mass removal through the erosion process may, to a large part, compensate tectonic influx into the plateau and, thus, effectively prevent further uplift of the plateau. If this occurs, resistance of the convergent system to shortening will not increase with time.

Seismic anisotropy in the Western US as a testbed for advancing combined models of upper mantle geodynamics and texturing

Thorsten W. Becker[1] , **Vera Schulte-Pelkum**[2] **and Donna K. Blackman**[3]

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Observed seismic fast axes are popularly equated with directions of mantle flow. In order to substantiate this assumption, we present improved models of mantle flow, derived lattice preferred orientation (LPO, fabric) anisotropy, and predicted seismic anisotropy. Results include global models, where we compare surface wave based seismologic inversions with predictions from large-scale mantle circulation computations. For body wave anisotropy, we focus on a regional model of the western United States, a relatively simply-parameterized region where a wide range of seismic data is available. Our work addresses the three stages needed to connect mantle flow and anisotropy: flow, LPO fabric development, and wave propagation in a heterogeneous upper mantle and lithosphere. For the flow models, we explore lateral variations in viscosity, improved rheologic realism, and joint regional/global convection computations. In terms of mineral physics, we compare predictions from finite strain (FS), lower-bound (LB), and kinematic (KR) fabric formation theories. The seismological modeling includes computing apparent splitting from spatially variable, not necessarily hexagonal anisotropic elastic tensors. We also evaluate the potential role of the crust in partly obfuscating the underlying dynamic processes. Preliminary results indicate that FS, LB, and KR models are similar except in regions of large spatial variations in flow, as expected. Mantle circulation models that take the inferred Farallon slab density anomalies at depth into account show a return flow roughly opposite to the surface motion of North America. Those models tend to fit the data better, indicating a possible avenue to better constrain tectonic processes in the study region over time.

The effect of magmatism on faulting and axial morphology at mid-ocean ridges: modeling the transition from rift valley to axial high

Mark D. Behn[1] and Garrett Ito[2]

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[2] *School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu HI, USA*

Traditionally the differences in axial morphology and faulting at fast- and slow-spreading ridges have been attributed to variations in spreading rate between these environments. Fast-spreading ridges are characterized by a narrow axial high that is 5-10 km wide and 200-400 m high, while slow- spreading ridges typically display a 1-2 km deep and 20-30 km wide axial rift valley. However, recent observations along the Galapagos Spreading Center, the Southeast Indian Ridge, and the Juan de Fuca Ridge show that dramatic changes in axial morphology can occur over short along-axis distances on an individual ridge without large changes in spreading rate. In these regions, it appears that variations in the rate and distribution of magma to the crust are the dominant influence on axial morphology and faulting. Yet, while previous studies have focused on the effects of magma supply and spreading rate on ridge-axis thermal structure and morphology, few have integrated the thermal as well as mechanical effects of diking on lithospheric stress and faulting. In this study, we develop a thermo-mechanical model of diking in an extending 2-D elastic-viscoplastic layer using the Fast Lagrangian Analysis of Continua (FLAC) technique. Dike injection is simulated by widening a vertical column of model elements located within the crust and adding heat in proportion to the rate of dike opening. For cases in which the rate of dike opening is equal to the far-field spreading rate a narrow axial high develops. The height and width of the axial high are proportional to both the lithospheric thickness and the ridge-perpendicular variation in lithospheric thickness, which are in turn controlled by the spreading rate and the rate of conductive cooling. For cases in which the rate of dike opening is less than the spreading rate a rift valley develops. The width and depth of the rift valley as well as the height and spacing of the abyssal hills are again found to be proportional to the lithospheric thickness. Our calculations suggest that the magmatic accommodation of lithospheric extension associated with dike injection plays a greater role in controlling axial morphology and faulting than does the addition of heat to the ridge axis via magmatic accretion.

Synthetic travel-time tomography: resolution tests for models with regular and irregular parameterisation

Marie Běhounková[1,2], Hana Čížková[1] and Ctirad Matyska[1]

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We perform tomographic inversion of synthetic data in order to study the ability of seismic tomography to reveal structures created by mantle dynamic processes (Bunge and Davies, 2001). The synthetic input velocity model is based on the density heterogeneities obtained from 3D model of thermal convection, P and pP arrival-times are used in the inversion. We assess the sensitivity of the inverse problem to parameterisation, explicit regularisation (damping) and data error.

We use both irregular cell parameterisation (based on Spakman and Bijwaard, 2001) and regular cell parameterisation (equi-surface area). Due to uneven distribution of sources and receivers, we found substantial differences between inversion output for models with regular and irregular cells. For the irregular parameterisation, the cold-downwellings are resolved quite well. However the resolving power decreases with increasing depth. In the areas, where upwellings occur, the distribution of rays is very sparse and the parameterisation cells are big there. Therefore the upwellings can not be resolved due to high parameterisation error. The explicit regularisation is not necessary, if data errors are not included. For the regular parameterisation on the other hand, the inverse problem is very unstable and oscillation occur, hence the explicit regularisation is necessary.

Further, we compare the power spectra of input seismic velocity anomalies and inversion output for both regular and irregular parameterisations. In case of irregular parameterisation, the spectra of input model and inversion output are rather similar except for the layer above the core-mantle boundary, where the spectrum of input is steeper than spectrum of output. This effect is probably caused by lack of resolution near core-mantle boundary. This problem can be solved by including other seismic phases. Output of inversion with regular parameterisation produces much flatter spectra (high degree oscillations) and damping is needed to produce reasonable power on higher degrees. The anomalous layer above the core-mantle boundary is even more clear than in the case of irregular parameterisation.

We also investigate decrease (slope) of log-log power spectra for degree 20-40. The decrease of input model spectra is stronger than decrease of output model for both regular and irregular parameterisation. For regular parameterisation without damping (or with small value of damping coefficient), the spectrum can even increase, especially in the top layer of mantle with very uneven distribution of rays is the largest. Including the data error causes further flattening of spectra.

References

Bunge H.P. and J.H. Davies. Tomographic Images of a Mantle Circulation Model. Geophysical Research Letters, 28, 78–80, 2001.

Spakman W. and H. Bijwaard. Optimization of Cell Parameterization for Tomographic Inverse Problems. Pure and Applied Geophysics, 158, 1401–1423, 2001.

Deformation of subduction lithosphere in the upper mantle

Magali I. Billen[1] and Greg Hirth[2]

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Observations of the geometry of slabs provide strong constraints on the dynamic evolution of subducted lithosphere in the upper mantle. Slabs generally have shallow dip in the upper mantle (30–45°), steepening sharply at 200–350 km depth, and the dip of the deeper portion of the slab (just above the 670 km discontinuity) may shallow with time (Jarrard, 1986). Analytic models of corner flow and kinematic models with rigid slabs predict that slab geometry should depend strongly on convergence rate and age of the subducting lithosphere, due to the strong low pressure region that develops in the mantle wedge, which acts to pull the slab upwards (Stevenson & Turner, 1977; Tovish et al., 1978). The evolution of slabs likely depends on both a local balance of forces due to the buoyancy of the slab and slab-induced flow, as well as trench roll-back and large-scale mantle flow. However, both numerical and laboratory dynamic models of subduction with a moderate viscosity increase across the slab often develop steeply dipping slabs unless trench roll-back or other large-scale flow is included (e.g., King, 2001). In this study, we examine how slab shape depends on the local balance of forces, in the absence of trench roll-back and mantle-scale flow, in order to determine how rheology affects the evolution slabs.

We present 2D simulations of subduction using a visco-plastic rheology constrained by laboratory experiments for olivine with temperature-, pressure- and stress-dependent viscosity (Hirth & Kohlstedt, 2003; Goetze & Evans, 1979). Internal deformation of the slab can strongly influence the force balance on the slab, leading to time-dependent evolution of slab geometry with feed-backs on the mantle flow surrounding the slab. The interaction of the subducting plate with the non-Newtonian upper mantle leads to the generation of isolated low viscosity regions in the wedge and a halo of low viscosity surrounding the slab. The low viscosity regions diminish internal deformation and thickening of the slab. The model results demonstrate that stiff slabs (high yield stress) and a non-Newtonian viscosity produce shallow dipping slabs at shallow depths (<200 km). Slab dip increases rapidly through a hinge-like deformation of the slab, which occurs when stresses due to the buoyancy of the deeper slab exceed the yield stress. In addition, interaction of a stiff slab with an increase in viscosity and change in rheology (Newtonian) at a depth of 670 km stabilizes the evolution the slab and produces a slow shallowing of the deep slab. This shallowing of the deep slab can propagate up-dip and cause the shallow portion of the slab to flatten under the overriding plate. Subduction rate also affects the early evolution of the slab, but lithosphere age has only a minor influence. These models demonstrate that while roll-back and large-scale mantle flow certainly influence the shape of slabs, if slabs are strong, the local balance of forces may exert strong controls on the evolution of slabs through time.

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Slab stagnation depth: buoyancies, bending moments, and seismic structure

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We have constructed kinematic thermal models of subducting slabs [Negredo et al., 2004] for both stagnant (non-penetrative) and deep-mantle (penetrative) slabs [cf. Fukao et al., 2001]. For these cases, we have determined equilibrium phase assemblages (olivine polymorphism), along with the resulting buoyancy forces and seismic velocity anomalies. Beyond the well-known thermal dependence upon subduction rate, dip angle, and lithospheric age [Kirby et al., 1996; Yoshioka et al., 1997; Tetzlaff and Schmeling, 2000; Bina et al., 2001], we focus on the role of stagnation depth (of the base of the slab), neglecting the effects of trench roll-back and viscosity contrasts [Christensen, 2001].

Upon calculating slab bending moments (and bending moment gradients) about the trench axis, we find that thermo-petrological buoyancy forces yield extrema in bending moment gradients near 700 km depth whose sign is consistent with a decrease in dip angle (i.e., stagnation) at the base of the transition zone. Furthermore, bending moment gradients exhibit extrema near 400 km depth whose sign is consistent with the increase in dip angle (i.e., drooping) sometimes observed below depths of 300 km [e.g., Chen et al., 2004]. Incorporation of potential metastable persistence of lower-pressure phases [e.g., Green and Zhou, 1996] further enhances stagnation to the extent that the bending moments themselves (and bulk slab buoyancy [Bina et al., 2001]) become positive near 700 km depth, inhibiting direct slab penetration in such cases.

Variations in stagnation depth (z_{stag}) yield significant changes in calculated bending moments (and bending moment gradients) about the stagnation axis. While z_{stag} of 660 km yields small negative buoyancy anomalies in the recumbent portion of the slab (giving a bending moment gradient that promotes downward deflection), a z_{stag} of 700 km yields small positive buoyancy anomalies (giving a bending moment gradient that promotes upward deflection), and a greater z_{stag} of 750 km yields even larger positive buoyancy anomalies (hence stronger upward deflection).

These patterns suggest the existence of an equilibrium stagnation depth governed by the thermal state of the slab. Because of the simple geometric dip-dependence which generates larger buoyant bending moments at smaller dip angles, subducting slabs may overshoot their equilibrium z_{stag} before subsequently rebounding. Furthermore, potential continuation of metastable persistence into the recumbent slab yields bending moment gradients that promote strong upward deflection, but this effect decays (due to thermal equilibration) over 600-700 km of lateral travel, thereafter yielding bending moment gradients consistent with downward deflection.

Both the vertical and lateral extent of downward deflection of the equilibrium $rw \rightarrow pv + mw$ transition (associated with the “660-km” seismic discontinuity) also exhibit dependence upon stagnation depth. Small values of z_{stag} (e.g., 660 km) yield shallow and broad depressions of the phase boundary, while larger values (e.g., 750 km) produce deep and broad depressions, and still larger values (e.g., 820 km) yield deep and narrow depressions similar to those expected for direct slab penetration. Stagnation depth further controls the seismological visibility of these effects through superposition of broad negative (vertical) velocity gradients upon the sharper $rw \rightarrow pv + mw$ transition.

Such effects may be important beneath Japan, where an apparently stagnant slab gives rise to deep and narrow depression of the “660-km” seismic discontinuity [Kawakatsu, 2005].

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INVITED

Volcano ground deformation: search for magma storage and modeling of the intrusion process with application to recent Mt. Etna eruptions

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The pattern and rate of surface deformation reveal the final ascent mechanisms of the magma inside the upper crust. Different sources can characterize the uprising of the magma which can be stored at different depths in pressurized reservoirs and successively penetrates into the volcano edifice through fast dike intrusions or violent explosions at main conduits.

In general, ground deformation monitoring techniques (terrestrial geodesy, GPS, tilt, SAR) together with appropriate source modeling can provide the interpretation of the eruptive phenomena. In particular, the study of the ground deformation associated with the numerous and spectacular recent eruptions of Mt. Etna volcano (1981, 1983, 1989, 1991-93, 2001, 2002-03) furnished the opportunity to observe different behaviors related to the eruptive activity, and suggested different feeding and magma penetration mechanisms.

The results and principal conclusions suggested by modeling the recorded deformation clearly enlighten that different precursors are associated to different styles of eruptions. Implications for both the internal volcano dynamics and its structure are discussed.

Spatial coherence of seismic anisotropy and interpretation of shear wave splitting - *Hawaiian upper mantle case*

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Seismic anisotropy observations at surface, as shear wave splitting of SKS waves, are usually interpreted as a result of the Lattice Preferred Orientations of minerals in the underlying upper mantle induced by the deformation of rocks. We investigate the case of a three dimensional forward model for seismic anisotropy in the Hawaiian hotspot upper mantle and the related synthetics of shear wave splitting at surface. We have calculated the deformation of olivine polycrystals undergoing dislocation creep and dynamic recrystallization in a numerical model of the upper mantle flow for Hawaii. The polycrystal deformation model is D-Rex (Kaminski & al., 2004) and the three dimensional steady state flow has been produced by a hybrid spectral/finite difference code (Ribe & Christensen, 1994). The result of this coupling is a three dimension distribution of olivine crystals orientation. The corresponding seismic anisotropy model of hexagonal symmetry is obtained by decomposing the average elastic stiffness tensor at each location (Browaeys & Chevrot, 2004). We convolve this model with the sensitivity kernels (Favier & Chevrot, 2003) for typical SKS wave to produce synthetics shear wave splitting parameters. An heterogeneous distribution of seismic anisotropy decreases the time delay and increases the variability of the detected azimuth. Heterogeneity can be important both vertically and laterally and have an effect depending on its length scale and the one of the Fresnel zone of the wave. Vertical heterogeneity close to the plume conduit leads to a small time delay at Hawaii.

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Comparison of sandbox-style numerical extension experiments

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We directly compare results obtained with different numerical codes to results of analogue experiments from different laboratories with the aims to (1) test the code-independence of tectonic structures predicted by different numerical codes, (2) evaluate how closely various numerical solution methods can reproduce analogue model conditions, and (3) test the similarity of numerical and analogue models, in order to help establish robust features of tectonic models on the scale of the upper crust.

Our extension experiment was designed to reflect a setup often used in the study of upper-crustal processes with laboratory experimental models. It examines the influence of a weak, basal viscous layer on normal fault localisation and propagation in overlying brittle materials. Extension is achieved by moving one wall with an attached basal sheet outwards. Six numerical codes (using finite element or finite difference techniques) were used in our comparison: Abaqus/Standard, LAPEX-2D, I2ELVIS, Microfem, SloMo and Sopale.

Our results show that the overall evolution of all numerical codes is broadly similar. Shear zones initiate at the tip of the basal sheet, which acts as a velocity discontinuity. The asymmetric evolution of the models as the basal sheet is pulled out from underneath is similar for all numerical codes. In detail, differences exist in the number of shear zones that form and shear zone dip angles. We find that resolution of the calculation grid affects strain localisation and the number of shear zones that develop in strain-softening brittle material.

Comparison to equivalent analogue experiments show that the overall dynamic evolution of the numerical and analogue models is similar, in spite of the difficulty of achieving an exact representation of the analogue model conditions with a numerical model. We find that for this setup the degree of variability between individual numerical results is smaller than between individual analogue models. Differences among and between analogue and numerical results exist in predictions of number of shear zones that develop and their spacing and dip angle. Our results show that numerical models using different solution techniques can to first order successfully reproduce structures observed in analogue sandbox experiments.

Our results emphasize the importance of the following issues for numerical sandbox-type studies: (1) the ability to model large deformation structures; (2) the ability to represent boundary friction, velocity discontinuities and a free surface; (3) the representation of a composite (elasto)-visco-plastic rheology; (4) calculation with a relatively high resolution; (5) minimisation of numerical diffusion; (6) consensus on the procedure for quantification of modelling results. These are important for studies in which numerical and analogue models are used in combination, but reflect at the same time requirements for study of Earth tectonic processes.

As the initial setup and material properties of analogue models can be relatively well constrained, their results can form a useful test for numerical models. Numerical models may, therefore, benefit from future studies focussing on the differences between analogue and numerical modelling results. Our results indicate that future experiments should preferably (1) choose a simplified setup, which reduces the effects of boundary conditions and especially abrupt changes in boundary velocities, (2) prescribe resolution and time step size, (3) use material behaviour which is as similar as possible, and, (4) if possible, quantify results in an unambiguous manner.

Discussion on designing a plasticity benchmark experiment

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Deformation of the lithosphere is characterised by elastic, non-linear viscous and plastic material behaviour. The representation of this complex rheology is a challenge for numerical models of tectonic processes and it is important, therefore, to test rheology assumptions and implementations. A comparison of results run with different codes for a well-defined and constrained setup may help to establish code-independent results and improve codes by learning from any differences. Mantle convection codes, for example, can be validated against the results of convection benchmarks [Blanckenbach et al. 1989; Van Keken et al. 1997]. Recent initiatives also exist for code testing and comparisons for models of the thermal structure and dynamics of subduction zones [Schmeling et al. 2005; van Keken et al. 2003]. However, no comparison exists to date of Earth science codes for plasticity implementations.

We propose to design a tectonic Mohr-Coulomb plasticity experiment for comparing results of different numerical codes. The experiment should be (1) simple, (2) implement the same plasticity law, (3) use prescribed resolution and time step sizes, and (4) yield unambiguous quantitative numbers for comparison. During the workshop we will discuss possible experiments, including, but not limited to: (1) Circular inclusion in pure or simple shear [Schmid and Podladchikov 2003]; (2) GeoMod2004 viscous-plastic extension but with free basal slip [Buiter et al. in press]; (3) Compressional and extensional wedges [Zhao et al. 1986; Xiao et al. 1991] (4) Horizontal inward translation of a retaining wall [Roscoe 1970]; (5) 0D and 1D shear [Vermeer 1990].

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INVITED

Constraints on global mantle-flow models from geophysical data

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The flow in the Earth's mantle is usually studied via the numerical solution of the partial- differential equations that govern thermal convection. This approach allows the study of first-order effects such as the role of phase transitions, generation of lithospheric plates and chemical mixing, in a self-consistent manner by forward modeling. In this lecture, we will discuss another possible approach in investigating mantle convection, based on inverse modeling. This method employs available geophysical and geological data to determine the most probable values for the parameters that are included in the mantle-flow equations, and which are independent of mineral-physics experiments. During the last twenty years, most attention has been paid to determining the viscosity structure of the mantle from gravitational data (non-hydrostatic geoid and free-air gravity) and models of seismic-velocity anomalies provided by seismic tomography. These inversions, known as the "inferences of viscosity from the geoid", have led to the robust conclusion that viscosity increases with depth by 1-2 orders of magnitude. The successful prediction of the geoid, however, has raised new questions concerning the style of mantle flow. The best fit to the data has been obtained for whole-mantle flow models with a free-slip surface-boundary condition and a relatively weak lithosphere. Such a model, however, is not fully consistent with the observed velocities of plate motion, gives too-large strain rates in the lithosphere and usually also predicts excessive amplitudes of the long-wavelength dynamic topography. These points are better satisfied by layered- flow models and/or the whole-mantle flow model with imposed plate velocities that, nonetheless, fail to predict the observed gravitational signal. This apparent paradox can be reconciled by introducing a new formal parameter characterizing the partial layering of mantle flow. We discuss definitions of partial layering used by different authors, and demonstrate that the basic data are best satisfied by a mantle-flow model with imposed plate velocities in which the vertical velocity at the 660-km depth is reduced by 65% in comparison with the whole-mantle flow model.

Another issue that has been discussed in recent years is the effect of lateral-viscosity variations. This issue was not considered in the first generation of mantle-flow models, and their effect on the geoid was assumed to be of a second-order nature in comparison with radial changes in viscosity. We analyze the effect of lateral-viscosity variations on predictions of the geoid and other data, and show that small-scale lateral-viscosity variations, related to slabs and plumes, are significantly less important for predicting long-wavelength gravitational data than large-scale viscosity anomalies that are likely to exist in the boundary layers of the mantle. We present a model of lateral-viscosity variations in the asthenosphere, reflecting the viscosity contrast between continental roots and the low-viscosity zone beneath young oceans (Cadek and Fleitout, GJI 2003). This model can significantly improve the prediction of the geoid and free-air gravity data, provided the viscosity beneath young oceans is of a value of 10^{18}-10^{19} Pa.s, thus by 2-3 orders of magnitude lower than beneath continents. The model predicts the dynamic topography with a significant degree-1 pattern, showing a maximum long-wavelength elevation located in South-east Asia. The feasibility of such a pattern is discussed. The lateral- viscosity variations in the asthenosphere significantly influence the flow-velocity field in the upper-most few hundred kilometers of the mantle. The predicted velocity field can be compared with observed 'fast' directions of seismic anisotropy, representing an integrated record of mantle flow (Kaminski et al., GJI 2004). By comparing our predictions of seismic anisotropy with those recently published by Becker et al. (GJI 2003), we find that models with partial layering and strong lateral- viscosity variations in the asthenosphere predict the observed anisotropy somewhat worse than whole- mantle flow models without lateral-viscosity variations. Another problem in predicting seismic anisotropy is that the predicted anisotropy is significantly larger than that observed, suggesting the importance of composite rheology and/or small-scale convection in the upper mantle. The difficulties in explaining the observed pattern of seismic anisotropy indicate that, despite the significant progress made over the last decade, mantle-flow models obtained from the inversion of geophysical data are still far from perfect, and require a great deal of future development.

Effects of continental buoyancy on subduction dynamics

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At some point during their evolution, most trenches encounter continental lithosphere. Because average continental lithosphere is positively buoyant, collision is often the result. However, there is evidence that some continental crust and lithosphere does get subducted. For example, CW Mediterranean kinematic reconstructions show that Cenozoic subduction consumed a highly heterogeneous lithosphere including small oceanic basins and substantial portions of the flanking continental lithosphere, which had undergone various degrees of extension.

Here we study how continental lithosphere can affect the subduction process in general, and to what extent it can be responsible for the complexities of Cenozoic Mediterranean subduction in particular.

We model a visco-elastic slab, which subducts without external forcing into a passive viscous mantle. We find that lithospheric buoyancy is the primary control on continental subductability. Only if a significant amount of upper crust is stripped off, and the mantle lithosphere is not strongly melt depleted, does continental lithosphere become negatively buoyant. In the Mediterranean orogens, there is ample evidence of large amounts of upper crustal detachment. If in addition, the lower crust is eclogitized, continental lithosphere can even be as negatively buoyant as old oceanic lithosphere. Oceanic slab pull has a minor effect on continental subductability. It defines, with rheology, how much continental material is subducted to which depth (usually between 100 and 400 km) before subduction stalls, but can not change whether sustained continental subduction occurs or not. The influence of rheology is complex. For example, when buoyant lithosphere arrives at the trench, not only does slab pull reduce, but lowered convergence velocities give more time for viscous relaxation making slab pull less efficient at driving further subduction.

We investigate how the combination of continental buoyancy, slab pull and rheology can influence subduction velocities, depth and amount of continental subduction, and stress concentration in the slab, which may lead to detachment.

Modelling convection with large viscosity gradients in the cubed sphere

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A numerical method solving thermal convection problems with variable viscosity in a spherical shell is presented. Several features of earlier programs solving the same problem in Cartesian geometry are adopted because of their efficiency and robustness: finite volume formulation, multigrid flow solver, parallel implementation. A recent composite mesh gridding technique for a spherical surface, termed the cubed sphere has proven to be successful in solving other partial differential equations in geophysical problems. It is used here because of its various advantages: absence of geometrical singularities, same metric on each block, simple coupling of adjacent blocks. In addition, it is a mesh where grid-based methods proven efficient in the Cartesian context can be implemented, since it is reasonably close to uniform. Although as in the Cartesian case, convergence rates decrease with increasing viscosity gradients, global contrasts up to 10^6 are obtained at a reasonable cost.

FE modelling of postglacial rebound and the microphysical approach

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When modelling postglacial rebound the value of the rheology-controlling parameter - either the viscosity η or the pre-exponential parameter of the power-law creep A - is sometimes assumed as known on the basis of rough estimates or is often treated as a free parameter to be determined by the inversion of adequate data sets. We here derive the value, as a function of depth, of the pre-exponential parameter of the nonlinear-creep component A of a mixed linear-nonlinear rheology (Gasperini et al., 2004) through the knowledge on the microphysics of crystal deformation. This is done by extrapolating to mantle conditions theoretically established, and when possible experimentally controlled, creep equations, for relevant mantle materials (Ranalli, 2001). The depth-profile of A thus derived is implemented in the finite-element simulation of postglacial rebound and its performance is tested on North American Relative Sea Level (RSL) sites and also compared to previous homogeneous-mantle models (Dal Forno et al., 2005).

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On the zoology of mantle upwellings: fluid mechanics constraints

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Our image of mantle upwellings is still dominated by plumes issued from a steady point source of buoyancy. In a fluid whose viscosity depends strongly on temperature, this set-up generates steady “cavity plumes” with large heads and thin trailing conduits. So traps could be produced by impingement under the lithosphere of 1000 km heads and long-lived hot spot tracks by impingement of 100 km conduits. This model has been successful in explaining quantitatively a number of hotspots features such as the dynamic swell or the volume ratio between head/flood basalts and stem/island chain for a number of prominent hot spots. On the other hand, a growing body of observations shows that neither intraplate volcanism, nor seismic images, can entirely be explained by what has become the classical “mantle plume” model.

However, in an heterogeneous viscous fluid like the mantle, several kinds of upwellings may develop, from the classical, mushroom-shaped, thermal plume to more complicated thermo-chemical structures. A broad terminology involving “superplumes”, “mega-plumes”, “plume clusters”, “diapirs”, “cavity plumes”, “domes”, “piles”, “ridges” or “anchored plumes” has been developed in order to differentiate observations made either in seismic images or in convection experiments from “the” mantle plume model. Fluid Mechanics studies give definite constraints on the necessary conditions for these upwellings existence, characteristics (spacing, recurrence time, temperature anomaly, . . .), ability to reach the lithosphere, and geophysical signatures (superswells, volcanism, geochemistry, seismic anomalies, . . .).

This poster will first review these constraints and then used them to identify: 1) what types of upwellings could develop in the Earth’s mantle; 2) what observations, if any, CAN be explained by a mantle upwelling; 3) what observations can NOT be explained by a mantle upwelling.

Splash plumes - plumes rooted in mid-mantle

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A new class of thermal upwellings have been discovered in mantle convection simulations. The important point is that they are not rooted in thermal boundary layers, but are rooted at varying depths in the mantle and could explain minor hot spots.

These are high resolution, Earth-like vigour thermal convection calculations in three-dimensional spherical geometry. The models are for compressible convection, with decreasing coefficient of thermal expansion with depth, as observed in laboratory experiments. The models have $\sim$ chondritic (spatially uniform) rates of internal heating; and varying bottom heating that straddle estimated Earth values. Some of the models have included transition zone phase transitions. The models have depth dependent viscosity; with a viscous lithosphere and a lower mantle approximately 40 times more viscous than the upper mantle. The plate motion history of the past 120 Myrs is applied as a surface velocity boundary condition.

Passive, localised and shallow upwellings are generated beneath the spreading ridges. The planform of downwellings is linear at the surface and become cylindrical as they descend into the mantle. Similarly upwellings at the base of the mantle start linearly but become more cylindrical rising from the junctions of the linear features. In the simulations described here these features are rare and weak.

There are also upwellings that are not rooted at the base of the mantle. They develop as follows. Regions which have not suffered recent subduction become hotter than average and tend to form horizontal sheets that rise passively and slowly. Downwellings from the surface fall onto the sheets and make them into bowls as the hot material is forced up around the sides. The rims of the bowls can become unstable producing cylindrical upwellings (plumes). Since they look a bit like water droplet splashes, I have abbreviated “plumes not rooted in thermal boundary layers” as “splash plumes”. The splash plumes originate at a range of depths. In fact the downwellings can push the sheets all the way to the core mantle boundary in certain cases where it is then difficult to tell splash plumes from “traditional plumes”.

The sorts of hot-spots that “splash plumes” might be an explanation for, include magmatism behind arcs on continents; e.g. Korea and NE China; magmatism beneath slow-moving continental plates; e.g. Tibesti, Hoggar and Darfur in Africa; Eifel and Massif Central in Europe; and magmatism around lake Baikal beneath Asia.

Other models have been run which are similar in all respects, except for different upper boundary conditions. These models have a comparatively small number of very strong and stable plumes arising from the thermal boundary layer at the core mantle boundary and no splash plumes. This shows that a proper understanding of the relationship between the surface and convection will be critical for evaluating the importance of splash plumes for the actual mantle.

The best test for splash plumes will be seismic imaging. Their thin plumes and narrow bowls very near fast downwellings will require high resolution. These “plumes” also have implications for fixity, temperature contrast, and lifespan which can all be tested.

Global distribution of seismic heterogeneities and azimuthal anisotropy in the upper mantle

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Surface wave tomography is the only approach to provide constraints on the upper mantle structure at global scale, including regions where there are no seismic stations. We discuss a global upper-mantle tomographic model of Sv-wave heterogeneities and azimuthal anisotropy as a function of depth, constrained from the analysis of over 100,000 fundamental and higher mode Rayleigh waveforms. The selected waveforms are mostly associated with epicenter-station paths shorter than 6000 km. Compared to the longer R1 and R2 paths classically used in global tomography, these short paths are associated with thinner Fresnel zones and are less likely to be affected by spurious effects such as multipathing or focusing/defocusing. Our original dataset provides a global coverage of the Earth that allows us to resolve horizontal structure with wavelengths smaller than 1000 km, comparable to what is usually achieved at regional scale.

A good overall agreement is found at long wavelengths and at asthenospheric depths between fast anisotropic directions and present day plate motion for the fast-moving plates.

In oceanic regions this is especially clear beneath the Pacific although upwelling seems able to locally disturb this simple long wavelength pattern. We observe that azimuthal anisotropy does not correlate with plate driven flow over small anomalous regions of the northern Pacific that are systematically located westward of the hotspots associated with mantle plumes by Montelli et al. (2004). A broader anomalous anisotropic region is also observed in the vicinity of the Pacific Superswell, where seismic heterogeneities suggest a thinner lithosphere.

In continental regions, the fast-moving Australian plate appears to be the only continent for which basal drag on the lithosphere is sufficient to cause azimuthal anisotropy aligned with plate motion. Beneath other continents, azimuthal anisotropy vanishes near 150 km depth and supports a frozen-in origin within the lithosphere with no evidence for a deeper layer. This is compatible with a delay time of about 1 s, as typically observed in SKS studies. The weak azimuthal anisotropy observed at depth greater than 150 km for continents other than Australia is compatible with simple shear leading to anisotropy with a plunging axis of symmetry.

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Modeling the subduction process using 3D laboratory and numerical tools

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Laboratory and numerical models of the subduction process can provide a detailed and complementary description of the subducting lithosphere behavior. Laboratory models yield naturally a three-dimensional reproduction of compositional layering, and brittle process such a faulting and fractioning. Moreover, the research of materials with temperature-dependent viscosity reproducing the Newtonian and visco-elastic properties of subducting plate could lead to a more exact description of subducting process and to get over the limitations of the previous analogue models. Numerical models offer a means to study complex large scale processes such a phase transition, power-law rheology or temperature-dependent viscosity and buoyancy and allow for extensive and reproducible parameter studies. We present the preliminary results obtained combining the two methods, through the application of analogue material to study the subduction process with temperature dependent viscosity and density and dynamical full three-dimension numerical models performed with the finite element code Citcom, solving the equations for conservation of mass, momentum, composition and energy for an incompressible viscous Cartesian box. Besides, our first calibrations of the new materials allows us to make a preliminary restriction of the material research field on the basis of the suitable Earth's parameters scaling.

3-D numerical simulations of mantle flow beneath mid-ocean ridges separated by transform faults

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Several observations on Earth, such as short-wavelength geoid undulations lined up in the seafloor spreading direction (Haxby and Wessel, 1986) or complex pattern of seismic anisotropy in the uppermost mantle that do not correlate simply with plate motions (Leveque et al., 1998; Becker et al., 2003), suggested the presence of small-scale convection at the base of oceanic lithospheres.

The development of thermal instabilities under a moving boundary layer has already been widely studied (Marquart, 2001; Van Hunen et al., 2003). In the present study, we focused on the influence of ridge geometry on the development of instabilities and its impact on the large-scale flow. Two different 3D numerical codes have been used (Albers, 2000; Choblet and Parmentier, 2001). In the first part of this study, the ridge is separated by numerous transform faults into pieces perpendicular to the plate motion, but with a mean orientation strongly oblique to plate motion. In the second part, we used a unique transform fault, in order to study with more details the impact of the coexistence of two lithospheres of different ages on small-scale convection, large-scale flow and surface observables.

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The influence of the plate properties on the dynamics of subduction

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In the subduction dynamics the following factors play an important role: mantle flow, viscosity structure of the mantle, buoyancy forces, different rheologies. In a systematic study we investigated the influence of the plate properties such as thickness, density contrast between the subducting plate and mantle, plate viscosity and pore pressure factor in the Byerlee law on the subduction process. For the modelling we used the 2D finite difference code FDCON. The visco-plastic plate is described by the density and viscosity contrast between the plate and the mantle, and the mantle is stratified with a constant viscosity of the upper and lower part. The different rheologies and densities in the model are advected with a tracer method.

The low value of the pore pressure factor in the Byerlee law leads to the low viscosity of the slab bending region in the case of plates of different viscosity. This causes insensitivity of the subduction and trench retreat velocities to the variation of the plate viscosity. The trench tends to retreat at all subduction stages for all viscosities and plate thicknesses.

The high value of the pore pressure factor in the Byerlee law leads to strong bending region. For thick plates, the increase of plate viscosity by a factor 20 results in the decrease of subduction and retreat velocity by about 30%. At the late subduction stage we observe trench advance for the slabs with a strong bending region.

Entrainment in 2-D and 3-D numerical models of thermochemical convection

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Thermochemical convection problems frequently arise in geodynamics including, for example, the entrainment of the chemically dense D'' layer at the base of the mantle. Understanding the behaviour of these processes through both experimental and numerical models is an ongoing area of interest with implications for geodynamics, geochemistry, and geomagnetism.

Laboratory experiments are often used to study thermochemical convection. Experimental studies (Jellinek & Manga, 2002; Davaille, 1999; Gonnermann et al, 2002) which investigate mantle stratification with a dense layer atop the core-mantle boundary illustrate the importance of entrainment within these systems. Even small chemical variations may profoundly influence the dynamics of upwelling plumes including excess temperature (Farnetani, 1997), both stability and longevity (Jellinek & Manga, 2002) and possibly pulsations (Lin & van Keken, 2005). Many seismological observations point to such chemical heterogeneity existing in D$''$. However the recent discovery of a post-perovskite phase transition (Oganov & Ono, 2004) which leads to destabilisation of the thermal boundary layer may require an increase in the negative buoyancy arising from compositional densities (Nakagawa & Tackley, 2004).

Thermochemical convection can be simulated numerically using many different techniques, including tracer, marker chain, tracer ratio, filter and field methods as discussed in (van Keken et al, 1997; Tackley & King, 2003; Lenardic & Kaula, 1993). These methods, while meeting the requirements of the established thermochemical benchmark outlined in (van Keken et al, 1997), produce wide ranging behaviour for entrainment. It is possible to calculate the entrainment rates in laboratory experiments and develop scaling relationships as outlined in (Jellinek & Manga, 2004). The question remains how well numerical models capture the entrainment observed and measured in the laboratory models published for example by (Jellinek & Manga, 2002; Davaille, 1999; Gonnermann et al, 2002).

Resolving the density interface and entrainment rates in numerical thermochemical convection therefore remains a major issue. The methods currently used either over- or under-estimate (Tackley & King, 2003; Lenardic & Kaula, 1993) the entrainment observed in the laboratory experiments, but the extent to which has not been examined in detail. These difficulties, in particular over-estimation, may become amplified with the move from 2-D to 3-D geometry, leading to a growing need to quantify entrainment rates in numerical models.

We have studied the time evolution of the buoyancy number, density interface and entrainment for 2-D and 3-D numerical models of thermochemical convection. We have measured entrainment rates across a range of Rayleigh numbers. Continued study of these models will be pursued investigating effects such as model resolution, particle density, thickness of dense layer, viscosity contrast, aspect ratio and boundary conditions including lid-driven systems.

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Post-glacial rebound, lateral viscosity variations and transient creep

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Post-glacial rebound models often involve a layered viscosity and a Maxwell viscoelastic rheology. The inverted lithospheric thickness is found to be of the order of 100km. However, there is a thick cratonic lithosphere below the areas of Holocene glaciation. Assemblages of Maxwell solids do not behave like Maxwell solids and the mantle is expected to be heterogeneous at various scales: At a millimetric scale, it is made of minerals with different viscosities. At larger scale, variations of water content or of temperature should induce viscosity variations. Therefore, a Maxwell rheology may not describe appropriately the macroscopic properties of the mantle. Here, post-glacial rebound is modeled with lateral variations of the mechanical properties associated with cratonic roots and a Voigt-Reuss rheology, using a 3D spherical finite element code. The short wavelengths observed in the present-day rate of uplift, in particular in North-America, are compatible neither with a too stiff cratonic lithosphere neither with a very low average viscosity in the upper mantle. Dissipation in the lower part of the cratonic roots can explain the long time-scale associated with the relaxation of the short wavelengths. The transient rheology helps to have a long-term viscosity compatible with the stability of the cratonic roots. It also allows a larger viscosity contrast (100) between the sublithospheric upper mantle and the lower mantle. The asthenospheric viscosity below oceans and young continents is poorly constrained but can be as low as 3×10^{19} Pa.s, in agreement with models of heat transfer at the base of the plates. The total amount of ice over the various areas providing the best fit to sea-level data has been determined. It is larger over Scandinavia and Canada and thus lower over Antarctica for Burger models.

Low-degree geopotential changes due to past and present-day ice-load changes: comparisons with GRACE observations

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Rates of change in the low-degree geopotential coefficients ($\dot{J}_l, l = 1$ to 8) have been inferred by various observational methods over the past few decades (e.g. SLR, VLBI). Extensive studies have at the same time been carried out to determine the contribution to $\dot{J}_l$ of past and present-day ice-load fluctuations. $\dot{J}_l$ estimates have also been used to place constraints on these ice-load changes and the Earth's viscosity structure (e.g. Mitrovica and Peltier, 1993; Tamisiea *et al.*, 2002; Tosi *et al.*, 2005).

This work will discuss the sensitivity of $\dot{J}_l$ to various aspects of glacial-isostatic adjustment, especially the Earth's viscosity structure. Two ice models describing the last glacial cycle are used, and the contribution from changes in the present-day ice masses of Greenland, Antarctica, Patagonia and Alaska are examined. Our predictions are then compared with $\dot{J}_l$ values inferred from the Gravity Recovery and Climate Experiment (GRACE) space mission.

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Geodynamic modelling of the Tertiary development of the Faroes-Shetland Basin: a failed continental breakup basin?

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Continental breakup is often thought of as the extreme end member of continental lithospheric stretching and thinning where the lithosphere is stretched to zero thickness by pure shear deformation. However, this hypothesis has proved to be difficult to reconcile with observations of crustal structure and subsidence histories of rifted margins. We present a new model of continental lithosphere thinning leading to breakup and seafloor spreading initiation. In this model, lithospheric rupture is achieved by an upwelling and divergent flow-field acting within continental lithosphere and asthenosphere, rather than by pure shear.

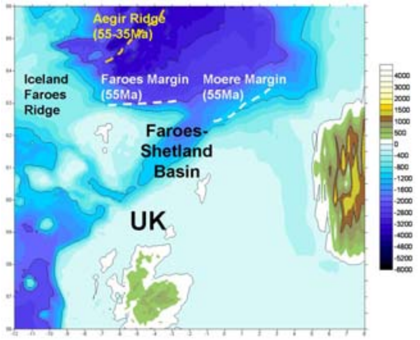

Figure 1. Map of region around the Faroes-Shetland Basin. The Moere and Faroese Margins began seafloor spreading close to 55Ma. We propose a model where the Faroes-Shetland Basin underwent most of the continental breakup process, but failed to initiate seafloor spreading.

The model predicts lithospheric structure and subsidence histories that can account for the observations at rifted margins and sites of incipient seafloor spreading. We show that the Faroes-Shetland Basin (NE Atlantic) can be successfully modelled as a site of failed continental lithosphere breakup. The Faroes-Shetland Basin lies to the North of the UK, coaxial with the Moere Margin which formed by seafloor spreading initiation on the Aegir Ridge at ∼55 Ma (Figure 1). A successful geodynamic model for the formation of the Faroes-Shetland basin must satisfy the present day structure of the basin, as well as paleobathymetric constraints, including subaerial indicators at ∼55 Ma. Intracontinental rifting type models for the basin usually assume formation by large scale Mesozoic and Paleocene pure-shear stretching and subsequent thermal relaxation. However, fault heave estimates and the subsidence history of the basin derived from flexural backstripping and paleoenvironmental mapping do not support this model. At ∼55 Ma, the Faroes-Shetland Basin lay at the propagating tip of the Aegir ridge. Post-Paleocene subsidence has been successfully modelled by thinning of the continental lithosphere due to an upwelling divergent flow- field propagating upwards within continental lithosphere and asthenosphere. Unlike at the Aegir ridge, where the flow-field successfully ruptured the whole lithosphere, the flow-field under the Faroes-Shetland Basin appears to have thinned the lithosphere and lower crust only, failing to initiate seafloor spreading. Subsequent thermal re-equilibrium has caused the basin to subside to the present day.

Mapping the flow during retreating subduction: laboratory models analyzed by Feature Tracking

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Three-dimensional dynamically consistent laboratory models are realized to model the large-scale mantle circulation induced by subduction of a lateral migrating slab. A laboratory analogue of a three layer linearly viscous slab-upper mantlelower mantle system is established in a silicone putty, glucose syrup, tank experiment. The circulation pattern is continuously monitored and quantitatively estimated using a Feature Tracking (FT) image analysis technique. The effects of plate width and mantle viscosity/density on mantle circulation are systematically considered. The evolution of the experiments shows that rollback subduction generates a complex 3-D time-dependent mantle circulation pattern characterized by the presence of two distinct components: the poloidal and the toroidal one. Spatial and temporal features of mantle circulation are carefully analyzed. Implications of these models include that (1) poloidal and toroidal mantle circulation are both active since the beginning of the subduction process. The poloidal component is the answer to the viscous coupling between the slab motion and the mantle. The toroidal component is produced by the lateral slab migration. (2) Mantle circulation is episodic. (3) Plate width influences mantle circulation. (4) The description of mantle flow in subduction zones cannot be correctly approached by models assuming a 2-D steady state process.

Effect of continents on mantle dynamics for various mantle rheologies

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Continents can be seen as passive rafts at the surface at the mantle, while the oceanic lithosphere is continuously recycled through subduction, and can be considered as the upper thermal boundary layer for mantle convection.

Continents however participate in mantle convection by imposing specific thermal and mechanical boundary conditions, whose effects are studied here with two-dimensional numerical experiments. We study the influence of the rheological parameters of the mantle on its response to the boundary conditions set on top of the mantle.

These preliminary results indicate that the lateral heterogeneities in the temperature field, induced by the presence of continents, can help generating plate tectonics.

Investigating the Earth's upper mantle structure: Numerical and laboratory experiments on mantle flow and entrainment processes

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The physical and compositional structure of the Earth's mantle is still a controversial issue. This is apparent in the ongoing debate whether whole-mantle convection or a separate evolution of upper and lower mantle are consistent with seismic observations and geochemical data from mid-ocean ridges and hotspots. Based on current evidence for a relative low density and low viscosity layer ($\eta \sim 10^{18-19}$ Pa.s) sandwiched between the overlying strong oceanic lithosphere ($\eta \sim 10^{25}4$ Pa.s) and underlying more viscous mantle material ($\eta \sim 10^{21}$ Pa.s), Phipps Morgan et al. (1995) and Phipps Morgan and Morgan (1999) considered the idea of a weak and buoyant asthenosphere layer that is fed by upwelling mantle plumes. In this scenario the asthenosphere layer is hotter than 'normal' underlying mantle, thus less dense and less viscous.

Based on this scenario we investigate mantle flow in response to forced plate motion and possible entrainment processes at subduction zones. We use a two-dimensional numerical model that solves for viscous flow in the Boussinesq-approximation (FE-solver) and for temperature (Smolarkiewicz FD-solver). Flow and entrainment of a 200 km thick asthenosphere layer are tracked by a tracer particle advection scheme. Speed of the oceanic plate, asthenosphere viscosity, and age of the subducting slab are varied (19 to 95 km/Ma, 10^{18} to 10^{20} Pa.s, 20 to 160 Ma, respectively), while the angle of subduction (45°) and the initial viscosity of the deeper mantle (10^{21} Pa.s) are held constant. Both sides of the subducting plate are modeled in separate numerical experiments, processes related to melting, slab-dehydration, or phase transitions are not implemented in the numerical model.

We find the lower (hot) side of the slab to entrain a 10-30 km-thick downdragged layer of asthenosphere, whose thickness depends upon the subduction rate and the asthenosphere viscosity and density. The upper (cold) side entrains as much by thermal 'freezing' onto the slab's top as by mechanical downdragging. Underneath the oceanic plate a relative pressure high at the subduction zone tilts the asthenosphere bottom and drives a return flow within the deeper asthenosphere towards the mid-ocean ridge. This flow pattern has been observed in all calculations, even in those having low viscosity contrasts (factor of 10) between asthenosphere and underlying mantle. Furthermore the low viscous asthenosphere acts as a lubrication layer that completely decouples plate motion from deeper mantle flow, at least down to the 410 km- or 670 km-discontinuity where asthenosphere viscosity may increase. In the mantle wedge a recirculation forms whose shape, extension, and circulation speed depend on the asthenosphere viscosity and the slab's speed and age.

In order to verify the numerical code we conducted laboratory experiments for the oceanic side of the slab. In each experiment, a corn-syrup + water mixture was placed on top of a denser and more viscous pure corn-syrup layer. Plate motion was simulated by a sheet of mylar moving along a fixed lithosphere-slab geometry (angle of subduction 45°). Illuminated glass beads were used to track the motion of the 'asthenosphere' and to quantify the amount of entrainment. The laboratory experiments evolve very similar to the numerical counterpart showing a tilted asthenosphere bottom, a return flow in the deeper asthenosphere, and entrainment at the slab's bottom. Numerical calculations using the measured densities and viscosities of the laboratory fluids and the dimensions of the experimental setup reproduce the lab observations in all aspects.

A boundary layer theory was developed to estimate the maximum entrainment at the base of the subducting slab. This simple theory neglects conductive heat loss into the slab. It is found to be in good agreement with the numerical results for moderate to large asthenosphere viscosities (which are numerically best resolved) and moderate to high plate speeds, due to the growing relative importance of conductive heat loss with decreasing subduction speed.

Laboratory and numerical experiments as well as the analytical boundary layer solution imply that slab entrainment is relatively inefficient at removing a buoyant and low viscosity asthenosphere layer. The entrained downward flux is roughly 20-40% of the flux within the slab itself which is composed of former asthenosphere that has been accreted to the oceanic lithosphere during its aging. Thus, most asthenosphere returns to the deeper mantle by accretion into and subduction of lithospheric plates, not being directly downdragged by subducting slabs. In our numerical experiments we found entrainment rates to be in accord with the maximum rates predicted by the analytical model only if the numerical grid-spacing is less than about 4-8 km. If the grid-spacing is larger, the numerical experiments tend to improperly entrain too much asthenosphere.

Current work focuses on the implications of the "plume-fed asthenosphere"-Earth model for mid-ocean ridge melting processes, emphasizing plume-ridge interaction. First steps cover the incorporation of melting related geochemical processes into a mantle convection model. Tracking the partition of trace element and isotope ratios between melts and residues within a convection mantle will help to constrain potential mantle compositions. In addition feedback mechanisms between the melting behavior (in response to geochemical composition) and viscous flow of the mantle may affect both geodynamic processes significantly.

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Finite Prandtl convection

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Convection in fluids with Prandtl numbers of order 10^4 is important in a wide variety of planetary situations such as the partially molten ice plumes of Europa or the magma oceans of early planetary interiors. Convection in fluids with Prandtl numbers above 10^3, have previously been modeled numerically using the infinite Prandtl approximation. This is the same approximation used for the Earths mantle, which has a Prandtl number of 10^5. It was assumed that by Prandtl numbers of order 10^3, the inertial terms no longer contributed significantly towards the convection behavior. This assumption, however, had not been previously tested numerically due to the fact that the inertial terms in the finite Prandtl equations become very stiff as Prandtl number increases requiring increasing grid sizes. We conducted studies of 2-D plumes with Prandtl numbers up 2×10^4. We found that these plumes tend to be hotter and to grow much faster than those modeled using the infinite Prandtl approximation.

Influence of grain boundary wetting on migration and retention of melt

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We employ the theory of two-phase flow to investigate the influence of grain boundary wetting during segregation of magma in a partially molten aggregate. Tensions on grain-grain and grain-melt interfaces in the partially molten aggregate play an active role in the dynamics of melt migration. The 'disaggregation melt fraction', the volume fraction of partial melt at which grain boundaries are completely wetted, is crucial in determining the total interfacial force per unit volume. Tensions on both grain-grain and grain-melt interfaces contribute to the total interfacial tension at melt fractions less than the disaggregation melt fraction. In contrast, only grain-melt interfaces contribute to the total interfacial tension when melt fraction exceeds the disaggregation fraction and grain boundaries are wetted.

Strong tension on grain-grain interfaces tend to homogenize melt distribution by capillary action. Buoyant magma ascends as solitary pulses in a compacting partially molten column. Capillary action arising from grain-grain interfacial tension in the matrix drains melt away from these ascending discrete magma pulses. As a consequence, a fraction of the melt is retained as a wake consisting of small melt tubules along grain edges behind an ascending pulse of magma. Thus surface tension reduces the efficiency of gravity-driven melt extraction, even in well-connected and highly buoyant melt networks.

Thermal convection and mantle plume dynamics with grain-size dependent viscosity

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Using a numerical model, the effect of grain-size dependent (GSD)-rheology is tested on thermal convection in a two-dimensional box. The mantle viscosity is determined by a combination of diffusion creep, which is enhanced at small grain size, and dislocation creep. In order to examine in detail the effects of grain size and dynamic recrystallization, other effects on viscosity such as temperature- and pressure-dependence are neglected. It is well-known that the equilibrium grain size is dependent on the applied shear stress. Combined with the GSD-rheology, the viscosity of diffusion creep effectively becomes stress-dependent with a stress-exponent of about 5. Diffusion creep is thus potentially more strongly non-linear than dislocation creep. However, the GSD-viscosity probably has an equilibration timescale similar to the timescale inherent in mantle convection, resulting in an interesting non-linear feedback as the relative importance of dislocation to diffusion creep changes.

One of the more puzzling results is that, when (using common notation) A_{diff} is increased relative to A_{disloc}, which should result in a strengthening of diffusion creep relative to dislocation creep, the exact opposite is what is observed. The explanation of this surprising finding is probably that grain-size diminution is caused only by dislocation creep; hence, when dislocation creep is reduced, the timescale of grain-size equilibration increases such that the non-linearity of the GSD-rheology is never fully activated. The result seems to turn upside-down the expectation of where in the mantle the flow is dominated by diffusion creep and where it is governed by dislocation creep.

Other observations of convection with GSD-rheology include: stronger time-dependence with periods of fast mantle overturning interspersed between quiescent periods characterized by large grain size; regions of the mantle with large grain size which over relatively long timescales do not participate in active convection and which may thus alter the mixing behavior of mantle convection; pulsating mantle plumes; plumes that stagnate mid-way in the mantle; and plumes that are anchored quite stably directly on a dividing line within the thermal boundary layer with large grains on one side and smaller grains on the other. It is clear that the present model has only limited applicability to mantle convection because of the simplifying assumptions. While especially the pressure-dependence of the two competing viscosities is not well known, the results indicate that convection and plumes may display an even richer dynamical behavior due to the GSD-rheology (not that we really needed yet more types of mantle plumes...).

INVITED

Distribution of H_2O in the mantle: constraints on mantle circulation

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The distribution of H_2O in the mantle is both an expression and an influence on the dynamics of mantle convection, but the total H_2O stored in Earths mantle remains highly uncertain. Estimates vary by approximately an order of magnitude, from less than a quarter of the mass of H_2O in the worlds oceans to ~ 4 ocean masses. Furthermore, the distribution of H_2O in the mantle may be heterogeneous on a large scale, but apart from the upper mantle above 410 km, there are considerable uncertainties regarding concentrations of H_2O in various regions of the mantle. Resolving these conflicts and narrowing the uncertainty in inventory of H_2O in the different portions of the mantle remain among the chief challenges to understanding the global deep H_2O cycle.

Constraints from basalt geochemistry indicate that the upper mantle reservoir sampled by mid-ocean ridges has 50-200 ppm H_2O. If this abundance applies to the whole mantle, then the total H_2O in the mantle is 1/6 to 1/2 of the water in the oceans. However, the transition zone may contain much greater concentrations of H_2O and different lines of evidence suggest that the lower mantle could be either much wetter or much drier than the upper mantle.

A wet transition zone?

The large H_2O storage capacity of transition zone minerals, combined with stability of dense hydrous magnesian silicates (DHMS) to great depths in subducting slabs, gives strong appeal to the hypothesis that appreciable amounts of H_2O are stored between 410 and 670 km. However, because the 410 km discontinuity is not thought to be a barrier to convection, the upper mantle and TZ may be well-mixed and have similar H_2O contents. The water-filter hypothesis of Bercovici and Karato (2003) posits that pervasive hydrous melting at 410 km may produce a TZ with dramatically enhanced H_2O and trace element inventories relative to the upper mantle. A critical component of the model is that the dehydrated residue must have a H_2O content (50-200 ppm) equal to that observed in the upper mantle. Present understanding of the H_2O storage capacity of upper mantle minerals suggests that residues would be much more H_2O rich, though experimental data are as yet incomplete. A key point, however, is that the upper mantle water concentration places a stringent limit to the possible hydration state of the transition zone.

Water, the lower mantle, and the source of plumes

Geochemical constraints show that the source regions of oceanic island basalts are H_2O-rich, having on the order of 300-1000 ppm H_2O. Combined with geochemical arguments that the sources of plumes reside in the deep mantle, this may suggest that regions of the lower mantle are H_2O-rich. In contrast, recent experimental results indicate that the H_2O storage capacities of the principal minerals in the lower mantle are very low on the order of a few 10s of ppm. This conflict may have one of three resolutions (1) plumes do not originate from the lower mantle (2) dry plumes from the lower mantle entrain H_2O rich material as they pass through the transition zone, or (3) the lower mantle hosts high H_2O storage capacity minerals that have not yet been identified.

INVITED

The role of melt on the dynamics of the upper mantle

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The processes that control the formation of oceanic crust, migration of melt to hot spots and volcanic arcs, and the dynamics of flow beneath oceanic spreading centers and the mantle wedge of subduction zones all depend on the mechanical and transport properties of partially molten mantle rocks. Our understanding of these regions is predominantly shaped by investigations of remotely collected geophysical data (e.g., seismic velocity) and geochemical analyses of the products and residues of melting. The interpretations of both types of data require an understanding of the relationships among deformation, melt topology and melt migration.

The effect of melt fraction on the viscosity of partially molten mantle rocks has been quantified through extensive deformation experiments in both the diffusion creep and dislocation creep regimes (e.g., Cooper & Kohlstedt, 1984; Hirth & Kohlstedt, 1995; Zimmerman & Kohlstedt, 2004). The effect is rather modest at low melt fractions, but a decrease in viscosity of approximately an order of magnitude is observed with an increase in melt content to $\sim 5-8\%$. These observations are well described by theoretical analyses that specifically account for the characteristics of melt topology observed from microstructural studies. The experimental data are also well fit by an empirical relationship in which the viscosity of the partially molten aggregate decreases exponentially with increasing melt fraction.

The mechanisms of melt migration in the upper mantle depend on the permeability and rheology of partially molten peridotite, which in turn, depend on both the amount and topology of the melt phase. Numerous theoretical studies have explored the effects of rheology and fluid mobility on melt migration processes in the upper mantle. These coupled processes have now been experimentally quantified in compaction experiments on partially molten dunite (Renner et al., 2003). The results of these experiments indicate that the permeability of partially molten aggregates is well described by a power law at melt contents between $\sim 3-20\%$ and that rheological properties under isostatic conditions are similar to those under deviatoric stress states.

The application of experimental data to natural conditions requires extrapolation in both time and scale. Experimentally based predictions for the rheology of the upper mantle compare well with both analyses of microstructures in naturally deformed rocks and geophysical estimates of mantle viscosity. However, for partially molten regions of the mantle, the scale of melt migration/melt redistribution may also play an important role on dynamics. For example, experimental studies indicate that melt rich channels form in response to pressure gradients arising from imposed deformation (Holtzman et al., 2003). In addition, significant changes in rheology may arise owing to variations in melt pressure during deformation (e.g., Renner et al., 2000; Evans et al., 2004; deMartin et al., 2004 (abs.)). Progress in these areas requires further quantification of transient deformation processes that arise owing to melt redistribution at scales ranging from ~ 1 mm (i.e., individual melt pockets) to 0.1 to 10 km (i.e., the "compaction length" in the upper mantle). Finally, analyses of the effects of melt on the dynamics of the upper mantle must also incorporate our understanding of how melting changes other important properties; changes in water content and grain size are particularly important.

INVITED

Tutorial on geochemical constraints on mantle evolution and plume structure

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Geochemists sample the mantle by analyzing peridotite outcrops, mantle xenoliths in erupted rocks, and melts produced in the mantle. The latter approach, although it has the disadvantage that we must understand the melting process before we can say something meaningful about the mantle, has the enormous advantage that melts sample the mantle very extensively along ocean ridges, on ocean islands and seamounts, as well as on continental rifts and above subduction zones. This tutorial will concentrate on the data and interpretation obtained from basalts erupted along ocean ridges (MORB) and ocean islands (OIB), primarily in order to avoid the complications arising from crustal contamination common in subduction and many continental settings.

Global chemical evolution of the Earth

Accretion from primitive meteoritic (chondritic) material starting 4.57 Ga ago required several tens of millions of years. Therefore, the "age of the Earth" cannot be sharply defined, but is now often taken to be the age of the "giant impact" of a Mars-sized impactor, which melted and partly volatilized the proto-Earth, produced the moon and completed terrestrial core formation approximately 4.53 Ga ago. Subsequently, the silicate portion of the Earth (the "primitive mantle") was further differentiated by melting, which formed various types of crust through segregation and upward movement of low-density partial melts. It is possible that at the base of the mantle, silicate melt may be denser than its residue. In that case, a dense and (at least initially) partially molten layer may have formed at the base of the mantle, now known as D''.

Crust-mantle budget

Continental crust is thicker and less dense than oceanic crust. Its formation probably requires the presence of water liberated from subducted lithosphere. The mean age of the preserved continental crust is 2 to 3 Ga, several times greater than the mean age of preserved oceanic crust. Separation of the continental crust (about 0.5% of the total silicate mass) had no measurable effect on the major- element (SiO_2, Al_2O_3, CaO, FeO, MgO) composition of the mantle, but it did change the abundances of the so-called incompatible trace elements (e.g. Th, U, Cs, Rb, Nb, Ta, La etc.) in the mantle dramatically, because roughly half the total terrestrial budget of Th and U resides in the present- day continental crust. This leaves the residual mantle severely depleted in these elements. The magnitude of this effect depends on the bulk partition coefficient between mantle minerals and melt, which in turn depends on the ionic properties (radius and charge) of the various elements, which determine their "goodness of fit" in the silicate minerals. Quantitative modeling shows that the incompatible-element budgets of mantle and crust are approximately, though not perfectly, complementary (Hofmann, 1988; Hofmann, 2003).

Mantle reservoirs

The above relationships also explain the complementary parent-daughter ratios of radioactive decay systems found in continental crust and mantle, i.e. high Rb/Sr and Re/Os, and low Sm/Nd and Lu/Hf, leading to high $^{87}Sr/^{86}Sr$, $^{187}Os/^{188}Os$, and low $^{143}Nd/^{144}Nd$, $^{177}Hf/^{176}Hf$ in the crust, with the respective opposite ratios in the mantle. Since the isotope ratios in mantle- derived basalts reflect the respective ratios in the source region of these melts, they also indicate the degree of incompatible-element depletion (or enrichment) in the source region of these basalts.

For noble gases, the radiogenic species are alpha-particles (^{4}He) from the decay of U and Th, and ^{21}Ne from nuclear reactions of neutrons and alpha-particles with Mg and O. The relative compatibilities of He and Ne compared with U and Th are controversial. Nevertheless, mid-ocean ridge basalts (MORB), representing the most depleted mantle reservoir, have higher $^{4}He/^{3}He$ and $^{21}Ne/^{22}Ne$ ratios than most OIB. This is consistent with the interpretation that the MORB-source portion of the mantle has been degassed at some time in the past, leading to high (Th,U)/(He,Ne) and thus causing the $^{4}He/^{3}He$ and $^{21}Ne/^{22}Ne$ ratios to increase with time. In addition, the complex systematics of Xe isotopes requires the existence of at least two Xe reservoirs in the mantle.

Mantle heterogeneity

The above trace element and isotope systematics is the basis of most of mantle geochemistry. Beyond this, one of the main questions is: What is the cause and the spatial distribution of the many isotopic and trace element heterogeneities observed in mantle-derived basalts? It is a wide-spread misconception that mid-ocean ridge basalts (MORB) represent isotopically and chemically homogeneous source regions, whereas ocean island basalts (OIB) represent much more heterogeneous mantle sources. Although it is true that MORB are on average more depleted with a somewhat lower variability than OIB, it is not clear to what extent the lower variability of MORB is the result of mixing in magma chambers rather than a greater homogeneity of the MORB sources. Such a mixing mechanism is indicated by the study of microscopic melt inclusions in magmatic olivines, which invariably show much greater variability than do the host basalts. A much better understanding of the true nature of mantle heterogeneity, as well as higher resolution of convection studies, will be needed to relate the two types of studies and understand the true nature of the scales and spatial distribution of convective stirring and magmatic redifferentiation in the mantle.

Reservoir sizes and locations

An important specific question is which portion of the mantle is occupied by the above-mentioned depleted reservoir. Classical geochemical thinking postulated two primarily (though not perfectly) isolated mantle reservoirs with a chemical boundary at 660 km depth. Recent geophysical evidence increasingly favors vertical transport through this boundary, creating an apparent conflict with geochemical constraints, which continue to require preservation of a relatively primitive mantle reservoir *somewhere*. Tolstikhin and Hofmann (2005) have proposed that the D'' layer at the base of the mantle is sufficiently large to satisfy the geochemical constraints for a reservoir containing primitive noble gases and a significant portion of terrestrial heat production, and they proposed that this reservoir was generated by subduction of a primordial mafic crust shortly after solidification of the early magma ocean. Boyet and Carlson (2005) have provided dramatic new evidence for mantle reservoir containing very ancient mafic crust. They showed that the relative abundance of ^{142}Nd in nearly all terrestrial rocks is about 20 ppm higher than in chondritic meteorites. ^{142}Nd is produced by decay of the extinct nuclide ^{146}Nd ($t_{1/2} = 100 \times 10^6$ yrs). This requires the existence of a very ancient, hidden reservoir with a Sm/Nd ratio lower than the chondritic value, in other words, a reservoir of ancient hidden crust, since crustal rocks invariably have lower Sm/Nd ratios than the mantle rocks from which they originate.

Sources and anatomy of plumes

Another question of great interest to mantle geochemists concerns the origin and internal compositional variation of mantle plumes. Such plumes are compositionally heterogeneous, and because melting is the dominant mechanism for creating chemical heterogeneity, the idea that plumes contain significant amounts of recycled crustal or lithospheric material has gained wide acceptance. Even the alternative, so-called "metasomatic", hypotheses call on melt migration to generate geochemically enriched lithosphere, which is thought to be subducted and preferentially recycled in mantle plumes. The specific isotopic "flavors" found in various plume-derived OIB (usually called HIMU, EM-1, and EM-2; Zindler and Hart, 1986) are all thought to be created by such crustal or lithospheric material, including the possibility of (generally minor amounts of) continental material. Questions of interest to the geophysical "mantle community" include the mechanism for segregating and storing such crustal material for sufficiently long periods of time in the mantle, spatial scale and evolution of heterogeneities introduced by subduction in response to convective stirring, and the internal structure of plumes including the role of entrainment by plume heads and plume stems. Entrainment by the plume stem is expected to lead to a concentric compositional structure of plumes, and evidence for such variations has been suggested in the literature on the Hawaiian plume. However, recent results from high-resolution Pb isotopic studies of the Hawaiian plume indicate a very different plume structure, which is consistent with the transport of laminar, stretched, large-scale and small- scale heterogeneities from the base of the plume through its conduit, without any evidence for concentric zoning (Abouchami et al., 2005). This is consistent with the most recent numerical results of Farnetani and Samuel (2005) and tank experiments of Kerr and Mériaux (2004). Such results are to be expected if the outer, entrained zones of mantle plume stems are too cool to undergo melting beneath the thick, N-Pacific lithosphere. Consequently, these outer zones are likely to remain "invisible". These results are also consistent with the observation that erupted melts sample the Hawaiian plume only over a radius of about 50 km, although the total plume radius is expected to be considerably greater.

Melting process and melt extraction

There remains the question how melts are actually sampling mantle compositions, both in ridge and in plume settings. Are the melts being formed in the mantle actually in chemical and isotopic equilibrium with the source rocks? Is the melting process fractional in nature? Are melts extracted by mechanisms of porous flow, or do they quickly collect in fractures and are thus prevented from chemically interacting with the solid phases? Answers to these questions require experimental studies of diffusion and reaction kinetics, solid-melt interface properties, and theoretical work on melt extraction. New insights have come from the study of microscopic melt inclusions in magmatic crystals, particularly olivines. These melt inclusions often show extreme compositional heterogeneities. Originally, these were believed to be caused by fractional melting processes, where successive melt parcels progressively deplete the residue in all incompatible trace elements. However, it is now clear that much of this heterogeneity actually reflects the heterogeneity of the source rocks. This raises new questions, e.g. how such compositional heterogeneity can be introduced into single olivine crystals, which sometimes contain melt inclusions of grossly different compositions, even though these olivines crystallized in relatively shallow magma chambers. Sorting out these problems leaves many theoretical and experimental problems for future research.

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Effect of lithospheric stratification on extensional styles and rift basin geometry

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Plane-strain thermo-mechanical finite element model experiments of lithospheric extension are used to investigate the effects of strain softening in the frictional-plastic regime and the strength of the lower crust and mantle lithosphere respectively on the style of extension. Crust and mantle lithosphere strength are varied independently. A simple scaling of wet-quartz and dry olivine rheologies is used to examine crust and mantle lithosphere strength variations. Cases are compared where the crust is strong ($\eta_{wet\ quartz}$ x 100), weak ($\eta_{wet\ quartz}$), or very weak ($\eta_{wet\ quartz}$ / 10), and the mantle lithosphere is either strong ($\eta_{dry\ olivine}$) or weak ($\eta_{dry\ olivine}$ / 10). Strain softening takes the form of a reduction in the internal angle of friction with increasing strain. Predicted rift modes belong to three fundamental types: 1) narrow, asymmetric rifting in which the geometry of both upper and lower lithosphere is approximately asymmetric; 2) narrow asymmetric upper lithosphere rifting concomitant with narrow symmetric lower lithosphere extension; 3) wide symmetric crustal rifting concomitant with narrow mantle lithosphere extension. The different styles depend on the relative control of the system by the frictional-plastic and ductile layers, which promote narrow, localized rifting in the plastic layers and wide modes of extension in the viscous layers, respectively. A weak ductile crust-mantle coupling tends to suppress narrow rifting in the crustal layer. This is because it reduces the coupling between the frictional-plastic upper crust and localized rifting in the frictional-plastic upper mantle lithosphere. The simple strength variation may be taken to represent end-member thermal and/or compositional conditions in natural systems and the relevance for rifting of old, strong, and cold cratonic lithosphere as compared to young, standard, and moderately weak Phanerozoic lithosphere is discussed.

Factors controlling slab roll-back and back-arc extension: insights from numerical models

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Although subduction is a first order plate tectonic process, the factors controlling the dynamics of slab roll-back and back-arc formation are still not very well understood. The major driving forces for subduction and slab roll-back are well established as the slab pull and ridge push forces, their relative importance and the relative importance of forces resisting these driving forces is, however, not very clear.

We use thermo-mechanical models to study oceanic subduction, slab retreat, and back arc formation. We focus on two aspects of the subduction process: 1) factors that control retreat of the subduction zone, and 2) those that control the opening of the back arc.

The model evolution is calculated using 2D plane strain thermo-mechanical finite element techniques for the finite element solution of incompressible viscous-plastic creeping flows (Fullsack, 1995). The models extend from the surface to 660 km depth. The upper surface of the model is free to move. Upper mantle rheology is linear viscous, whereas the rheology of the subducting slab is either linear viscous or combined linear viscous and von Mises plastic. Reflective and periodic boundary conditions are used.

We investigate interaction of the subducting slab with the overlying plate and focus on factors that may control the opening of a back-arc basin. The down going plate is driven by a kinematic boundary condition, far from the zone of subduction. After an initial stage of far-field driven contraction, the negative buoyant down welling of the mantle lithosphere may drive continued formation of the subduction zone leading to mature subduction. The models suggest that two primary factors are required for slab retreat and the formation of an extensional back-arc system: 1) Processes weakening the back arc, and 2) the ability of material below the slab to flow out of the model.

Dynamic topography above subduction zones: evidence from theory, seismic tomography and gravity

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Can we decipher any systematic trend in the morphology of the upper plate of subduction zones, and why should we? Since modern candidates are not numerous, and because the morphology above subductions is often obscured by irregular features linked to the nearby location of continental units and arc volcanoes, the answer is not straightforward. Mass heterogeneities in the mantle characterize subducting slabs and rising plumes. Because these masses tend to sink in the embedding asthenosphere, they not only induce a current in the asthenosphere but also a vertical surface tension at the Earth surface. We know that the surface warps up above plumes, it should therefore be deflected above subductions.

Intra-oceanic subductions and particularly back-arc basins provide good conditions for this study since less parameters affect the bathymetry than in continental settings. Back-arc basins are correlated to retreating subducting slabs of finite width, typically less than a 1000 km. Bathymetric profiles along the ridges of the oceanic back-arc basins which are the less affected by pre-opening dynamics (east Scotia and Mariana) show that the bathymetry increases towards the center of the basin by a several hundred meters. In the East Scotia sea, when corrected for age / thermal subsidence, the bathymetry shows a striking deepening towards the center of the basin, which is deeper by more than 750-1000 m than the edges. In addition, the Aegean sea -which is not a back-arc basin- also shows an important increase in the bathymetry beneath the Cretan sea, which is probably non isostically compensated, according to the crustal thickness. All three basins therefore suggest that their bathymetry is at least partly non isostatic.

A convenient way to understand the Stokes flow around a body of random shape is to discretize it into elementary bodies approximated as small spheres, for which the Stokes stream function is known. This in turn provides an estimate of the tensional stresses normal to the surface of the Earth. Because the lithosphere is not absolutely rigid, this tension can be counterbalanced by a deflection h giving rise to an outward tension of magnitude ρgh. The results suggest that the maximum deflection is located 100 km to 400 km away from the trench, depending on the dip of the slab, and can reach several thousands of meters, depending on the density contrast between the mantle and the asthenosphere. This depression vanishes towards the edges of the slabs.

Seismic tomography data acknowledge the presence of bodies of variable density in the asthenosphere. I converted the ΔV_P data from Van der Hilst and, assuming a linear relationship with density, I evaluate the deflection of the Earth surface. In all three reference areas (East Scotia, Mariana, and Aegean Sea), well defined deflections appear, that I fit by selecting the best conversion factor $\partial\rho/\partial\Delta V_P$. The deflections not only matches the prediction of the theoretical models, but also fit the observed bathymetry. Maximum deflections of $\sim$1000-1500 m are predicted at 170 km, 230 km, and 280 km from the trenches, respectively for the East Scotia, Mariana, and Aegean subductions.

Last, the free air anomaly is positive and reveals the presence of the underlying dense slabs. However it is rather low for such high density bodies ($\sim$30-50 mGal). In addition, it is almost uniform or even decrease towards the center of the basins while it is expected to increase towards the center of mass of the slab, *i.e.* towards the center of the basin. The primary anomaly due to the slab is lowered by a secondary free air anomaly, due to the deflection of both the surface level and the Moho, which is lower in magnitude, of opposite sign, and of shorter spatial wavelength than the primary anomaly.

On the basis of theoretical models, seismic tomography, and gravity, I therefore conclude that the bathymetry of upper plates at the proximity of subduction zones is dynamically lowered by up to 1500-2000 m by the subducting slabs. In chosen areas like the East Scotia sea, the Mariana basin, and the Aegean sea, the bathymetry reflects such dynamic process.

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Propagation of tectonic waves

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Mountain building depends on the disequilibrium between boundary stresses, either at the base of the deforming lithosphere or its lateral boundaries, and buoyancy stresses arising form lateral density variations within the lithosphere itself. On the basis of the thin viscous sheet approximation, we propose a model which accounts for both crustal and lithospheric thicknesses variations. The deformation is controlled by the sum of the moments of density anomalies (i.e. density anomalies times depth) of compositional and thermal origins. The transport of the compositional moment is obtained from the continuity equation while the transport of the thermal moment is obtained from the heat equation. The resulting set of equations controls the coupled behavior of the crust and lithosphere. It shows that various type of solutions can exist. When the crust dominates the system, the composite lithosphere tends to get back to a stable situation, when the lithosphere mantle dominates, it is unstable and the system ultimately reaches a convective mode. A third situation may occurs, where none of the two components dominate but the heterogeneities propagate laterally, i.e., the deformation of the lithosphere migrate in an undulatory mode. When propagation occurs, the crustal and the lithospheric thickness variations are out of phase. The tectonic waves propagate with velocities around 5 mm/yr that increase with the crustal thickness and decrease with the lithospheric viscosity. We found that continents may in large part be in a domain of propagating tectonic waves. We show that the propagating mode can explain the progradation of deformation in high plateaus. Crustal thickening in the Central Andes or Tibet may have initiated in the convergence zone, then gradually migrated away form it, independently from the original source of stresses at subduction zones.

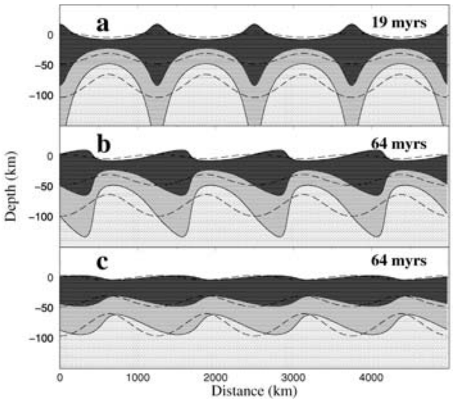

Figure 1. Evolution of the crust and lithosphere with time. The initial sinusoidal interfaces are depicted with dashed lines, the final interfaces with solid lines. The crust, mantle lithosphere and asthenosphere are shaded (darker, intermediate and lighter shades). The initial wavelength is in the domain of unstable (a), propagating (b), and stable (c) regime. For clarity the surface topography has been multiplied by a factor 5. The final solutions have been computed after 19 myrs, (a), and 64 myrs, (b) and (c).

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A global coupled model of the lithosphere and mantle dynamics

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Understanding the dynamics of global lithospheric motion is one of the most important problems in geodynamics today. Mantle convection is commonly accepted as the driving force for plate motion but, while the kinematics of plate movement is well known from space geodetic and paleomagnetic observations, we lack a rigorous description of the coupled mantle convection-plate motion system. Here we present first results from a combined mantle convection-global lithosphere motion model. Our plate motion code is SHELLS, a thinsheet FEM code developed by Bird which computes global plate motion and explicitly accounts for faults. The global mantle convection code is TERRA, a high-resolution 3-D FEM code developed and parallelized by Bunge and Baumgardner. We perform simple modeling experiments in which the shear tractions applied to the bottom of the lithosphere arise directly from two different mantle circulation model, in which the amount of heat coming from the core-mantle boundary is respectively 5% and 45% of the radiogenic heat. Our mantle circulation model includes a history of subduction and accounts, among others, for variations in mantle viscosity. We find that our results are sensitive to the amount of core heating, an inference that has received renewed attention lately.

Lithospheric deformation and 3D mantle flow in the Pacific-North American plate boundary corner in southern Alaska

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The pattern of 3D material flow in a continuum is one proxy used to characterize continental deformation and can yield insights into the physics of convergent margin deformation, specifically the interplay between plate boundary forces, the viscosities of the materials within the tectonic plates, and possibly the importance of plate margin geometry. Two-dimensional analytic and numerical models of thin sheet viscous deformation demonstrate that the long-term (10^6 years) deformation of the lithosphere can be modeled as that of a highly viscous (10^{23} Pa s) fluid [e.g., England, Houseman, and Sonder, 1985]. These models predict a regular pattern of diffuse deformation such that the magnitude of material flow in an indented sheet will decay exponentially with the perpendicular distance from the sheet edge and with a characteristic length scale proportional to the wavelength of the indenter.

The characteristic length scale of decay predicted by 2D viscous deformation models does not explain the formation of the central Alaska Range, a young (5–6 Ma) localized region of uplift that hosts North America's tallest peak, Denali (6194 m), located approximately 500 km inland from the plate boundary between the North American and Pacific plates. This corner-shaped plate margin contains a northwest-southeast striking transform plate boundary to the east and to the west of the corner is a northeast-southwest striking subduction zone. The topographic profile from the plate boundary northward through the central Alaska Range is punctuated by basins and mountain ranges with the tallest peaks in the central Alaska Range, as opposed to a concentration of the tall mountains only near the plate boundary.

We use 3D spherical-geometry, finite-element, viscous flow models of the plate boundary system in southern Alaska to test competing hypothesis for the uplift of the central Alaska Range: (1) slab geometry and the degree of interplate coupling may increase the transfer of stress inland to the central Alaska Range, (2) the varying composition, age, and temperature of the accreted terranes in Alaska may result in long wavelength lateral strength variations that may in turn enable discontinuous deformation of the overriding lithosphere, (3) the Denali Fault system is a weak zone in the overriding plate that localizes deformation (uplift) far from the plate boundary, and (4) the ongoing collision of a small terrane (the Yakutat block) is required to initiate uplift.

We present here initial results of models from the first phase of our investigations, that is for models that investigate the influence of the slab geometry on deformation patterns in the overriding lithosphere. The pattern of seismicity at depth indicates that beneath central Alaska Range the slab orientation changes [Ratchkovski and Hansen, 2002] and that south of the eastern Alaska Range there is either a cusp in the slab and/or the slab contains a gap below 45 km [Page et al., 1989]. The spatial correlation of the central Alaska Range with a change in the geometry of the subducted slab implies that features in the subsurface, such as slab shape and/or mantle flow patterns generated therein, may be genetically linked to the uplift of the central Alaska Range. These first viscous flow models evaluate two end-member geometries of the subducted lithosphere, one with a continuous slab and the other with a slab that contains a gap. These end-member models are instantaneous and use a uniform temperature profile and viscosity structure for the overriding lithosphere. The slab is represented by a simplified density (and thermal) anomaly. The results of these 3D numerical models have general applicability to understanding the tectonic processes that occur at plate corners that contain a spatial transition between convergent and transform plate motion as well as how the mantle flows in response to the edges of slabs.

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An experimental study of melt circulation in a poroviscous matrix

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Partial melting and the consecutive circulation of melt in the upper mantle plays an original role in the dynamics of the Earth. First, the extraction of melt is the main probe of its chemistry at mid oceanic ridges. Second, because the presence of melt modifies both the rheology and the flottability of the material, it may locally change the characteristics of convection. The study of ophiolites and the geochemical signature of MORBs reveal that the extraction of melt from the mantle does not occur simply by a pervasive porous flow but rather by a channelized flow. The mechanism of formation of these channels is a matter of debate and has been the subject of several theoretical and numerical studies since the eighties. The difficulty of an accurate description of the physics of the two phase flow involved in melt extraction is due to the uncertainty on the actual interactions at the interface between fluid and solid. As a consequence, there is no definitive choice for the best macroscopic formalism that can account for the bulk characteristics of the flow. Experimental studies provide a suitable tool to try to solve such a problem but they remain relatively scarce. In order to fill the gap, we propose a first comprehensive analogical experimental study of the circulation of a liquid in a porous and deformable matrix. The preliminary results presented here show that one can actually define two regimes of extraction for a given set of liquid and matrix, a pervasive regime (corresponding to a classical Darcy's law) and a channelized one. The transition between the two regimes is defined as a function of the properties of the matrix and of the circulating fluid, and the transport properties in the channelized regime are established as well. Both the qualitative and quantitative results of this study bear fundamental implications for the understanding of two phase flows and of their consequences for the dynamics of the zones of partial melting in the Earth.

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Variation of olivine fabrics with thermo-chemical environment: an interdisciplinary study

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In the majority of studies of seismic anisotropy in the upper mantle, the experimental results published more than 30 years ago ([*Carter and Avé Lallemant*, 1970; *Nicolas et al.*, 1973]) have been used (e.g., [*Ben Ismail and Mainprice*, 1998]) with minor modifications to deformation geometry (for experimental studies [*Zhang and Karato*, 1995]; for numerical modeling see e.g., [*Tommasi et al.*, 2000]). Based on well-known physics of deformation fabrics and the known anisotropic role of water to enhance of olivine deformation ([*Mackwell et al.*, 1985]), [*Karato*, 1995] proposed that water might play an important role in deformation fabrics in olivine.

We have made extensive experimental studies to test this hypothesis ([*Jung and Karato*, 2001; *Jung et al.*, 2005; *Katayama et al.*, 2004; *Katayama and Karato*, 2005]) and investigated the deformation fabrics of naturally deformed peridotites ([*Katayama et al.*, 2005; *Skemer et al.*, 2005]). Experimental studies were performed in simple shear geometry under a range of water contents, strain-rates and temperatures. Laboratory studies are used to establish a functional relationship between fabric types and thermo-chemical conditions of deformation, and geological observations are used to pin down fabric boundaries at conditions that are impossible to reproduce in the laboratory (i.e., deformation at low temperatures and low stresses). We found that the laboratory data extrapolated to lower temperatures with a help of theoretical analysis ([*Karato*, 2005]) agree well with the geological observations, supporting that our laboratory data can be applied to Earth.

Our mineral physics results predict that (1) the B-type fabric is dominant in a cold region if some water is present and (2) in the asthenosphere of the ocean mantle, olivine E-type fabric (not the A-type fabric) will be dominant, although conventional A-type fabric should be dominant in the depleted lithosphere. The B-type olivine fabric is of particular importance since it predicts that the direction of the polarization of the faster S-wave is normal to the shear direction as opposed to parallel as in the case of A-, C- and E-type fabrics. Consequently, we have conducted a detailed numerical modeling to map out the regions where olivine B-type fabric might play an important role under the subduction zone environment ([*Kneller et al.*, 2005]). In this modeling, details of rheological properties are incorporated including linear and non-linear rheology as well as temperature and pressure sensitivity. We find that the olivine B-type fabric plays an important role in the cold corner of the mantle wedge which could explain an enigmatic shear wave splitting observed in many subduction zones (e.g., [*Smith et al.*, 2001]).

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Large-strain deformation experiments under deep mantle conditions using a rotational Drickamer apparatus (RDA)

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Rheological properties and deformation microstructures (lattice-preferred orientation, grain-size evolution) in deep mantle minerals are critical to our understanding of global dynamics but quantitative deformation experiments at high-temperatures were limited to $\sim$0.3 GPa. To extend this pressure at least by a factor of 50 (i.e., 15 GPa), we have spent last $\sim$10 years to develop new techniques of high-pressure deformation ([*Karato and Rubie*, 1997; *Xu et al.*, 2005; *Yamazaki and Karato*, 2001]). A rotational Drickamer apparatus (RDA) is a result of this effort by which quantitative deformation experiments have been performed to $\sim$15 GPa and $\sim$1800 K to shear strains to $\sim$2 ([*Xu et al.*, 2005; *Yamazaki and Karato*, 2001]).

The apparatus is composed of a pair of opposed anvils (with a gasket) inserted in a cylinder. A thin sample is inserted in a sample space together with heater and other materials. After pressurization and annealing (to eliminate unwanted defects), a sample is sheared by rotating one of the anvils. Both stress and strain are monitored by synchrotron X-ray: stress from X-ray diffraction and strain by X-ray imaging using the technique developed by Don Weidner and his colleagues. We have made a number of modifications to adopt synchrotron techniques with RDA. Important modifications include the process of making a disk heater and X-ray transparent electrodes. As opposed to D-DIA where deformation experiments are conducted by the radial motion of anvils ([*Wang et al.*, 2003]), anvils in a RDA are supported in a similar way as static experiments. Consequently, deformation experiments can be performed at much higher ($\sim$50%) pressures in RDA than in D-DIA if anvils with same material are used as demonstrated by the data ([*Xu et al.*, 2005]). In addition, the maximum strain achieved is much larger for RDA than for D-DIA that has two important consequences: (1) Microstructural development such as lattice-preferred orientation can be studied only at larges strains, and (2) steady-state rheological properties can only be determined when a sample shows steady-state rheology that is achieved (according to our results) only after several 10s%.

The RDA has been used to deform wadsleyite and olivine (in addition to Fe and (Mg,Fe)O). We have shown that a constant strain-rate experiment can be performed to P$\sim$15 GPa and T$\sim$1800 K, and the first stress-strain curves for wadsleyite and olivine were obtained under these conditions (for olivine to $\sim$11 GPa) ([*Nishihara et al.*, 2005]). We found: (1) there is a significant transient period (up to $\sim$20-40% strain) after which nearly steady-state deformation is achieved (this implies that results from low strain experiments significantly underestimate the steady-state strength), and (2) wadsleyite is somewhat stronger than olivine (a factor of 2-3) under the conditions so far explored.

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Some new experimental constraints on the transition-zone water filter model

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Partial melting plays an essential role in the geochemical evolution of a planet. In most of the previous models of chemical evolution of Earth, only partial melting near the surface (i.e., beneath mid-ocean ridges) is considered. However, recent mineral physics observations suggest that partial melting may also occur at ∼410 km if sufficient water is present in the transition zone. If the melt produced there is denser than the upper mantle mineral but less dense than the transition zone mineral, the melt will be trapped and hence a large amount of incompatible elements will be sequestered in the deep mantle [*Bercovici and Karato*, 2003].

We have conducted three sets of experimental studies to test this hypothesis: (1) the measurements of electrical conductivity of wadsleyite and ringwoodite as a function of hydrogen content to infer hydrogen (water) content in the transition zone [*Huang et al.*, 2005], (2) the measurements of density of hydrous ultramafic silicate melts to see if a melt produced at ∼410 km is trapped there and (3) the measurements of dihedral angles between silicate melt and olivine to obtain insights for the process of melt segregation.

Electrical conductivity and hydrogen [Huang et al., 2005]

Electrical conductivity of wadsleyite and ringwoodite was measured as a function of hydrogen content and temperature at transition zone pressures (∼14-16 GPa). The functional relationship between hydrogen content and temperature was determined and used to infer hydrogen content in the transition zone. We found that the electrical conductivity in these minerals is relatively insensitive to temperature but highly sensitive to hydrogen content. By comparing laboratory data with geophysically inferred electrical conductivity in the transition zone, the hydrogen content in the transition zone is estimated to be ∼0.1-0.2 wt% (in the Pacific). This exceeds an estimated critical value for partial melting in the upper mantle (∼0.05wt%), and suggests that partial melting occurs at ∼410 km in these regions.

Density of hydrous ultramafic melt [Matsukage et al., 2005]

The density of hydrous ultramafic melt was determined under the conditions equivalent to ∼400 km depth. The major element composition was chosen based on the study by [*Litasov and Ohtani*, 2002]. 5wt% of water was added (as brucite) and the density of melts was determined by the sink/float method. The addition of water reduces the melt density but the density of water is found to increase significantly with pressure and at ∼14GPa (∼2.5-3.0 g/cc), the influence of water to reduce the melt density is relatively small. After the corrections for the effects of oxygen fugacity, our results imply that hydrous ultramafic melts will be denser than the upper mantle minerals but less dense than the transition zone minerals in most cases (except for very high temperatures) and therefore the melts will be trapped at 410-km boundary.

Dihedral angle between olivine and silicate melts under high pressures

The dihedral angle between a melt and mineral controls the way in which melt is separated from solid and the way in which partial melting affects physical properties of materials. Under most conditions, the dihedral angles for silicate and silicate melts are between ∼30 to ∼100 degrees, and consequently, melt occurs either in isolated pockets (for >60 degree) or in a tubules (if angle is less than 60 degrees but non-zero). We have conducted an experimental study to determine the dihedral angle between hydrous silicate melts and olivine, and found that the dihedral angle decreases with pressure and finally goes to zero at ∼7-8 GPa. Above this pressure, the angle is zero and consequently, the melt will completely wet the olivine grain-boundaries.

Some consequences of these new results on the water filter model will be discussed.

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Melt localization and the rheology of the partially molten mantle under shear

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The emergence of patterns of melt distribution in experiments on partially molten aggregates under simple shear (8, 3) provide a rare opportunity to test magma migration theory (5, 6, 7) by directly comparing experiments and calculations. The fundamental observation is the emergence and persistence to large strains of bands of high porosity and concentrated deformation oriented at about 15-25° to the plane of shear (4). We report results from linear analysis and numerical solutions that suggest that band angle in experiments is controlled by a balance between porosity and strain rate-weakening mechanisms. Lower angles are predicted for stronger strain rate-weakening. For the specific model considered here, a power-law stress-dependent rheology, calculations with $n \approx 6$ are consistent with the observations. These results suggest that partially molten aggregates deforming under shear may have a greater sensitivity to strain rate than previously believed (1, 2).

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A parameterized rheology for creating lithospheric-scale shear zones

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Shear localization is a process of primary importance for the onset of subduction and the evolution of plate tectonics on Earth. Here we focus on a model in which shear localization is initiated through shear heating. The rheology employed is linear Maxwell viscoelastic with von Mises plasticity and an exponential dependence of viscosity on temperature. Dimensional analysis reveals that four non-dimensional parameters control the initiation of shear zones. The onset of shear localization is systematically studied with 0-D, 1-D and 2-D numerical models, both under constant stress and under constant velocity boundary conditions. Mechanical phase diagrams demonstrate that six deformation modes exist under constant velocity boundary conditions. A constant stress boundary condition, on the other hand, exhibits only two deformation modes (localization or no-localization). Scaling laws for the growth rate of temperature are computed for all deformation modes. Numerical and analytical solutions demonstrate that diffusion of heat may inhibit localization. Initial heterogeneities are required to initiate localization. The derived scaling laws are applied to Earth-like parameters. For a given heterogeneity size, stable (non-seismic) localization only occurs for a certain range of effective viscosities. Localization is inhibited if viscosity is smaller then a minimum threshold, which is a function of the heterogeneity size. The simplified rheological model is compared with a more realistic, and more complex model of olivine that takes diffusion-, power law and Peierls creep into account. Good agreement exists between the models. The simplified model proposed in this study thus reproduces the main physics of ductile faulting. Two-dimensional late-stage simulations of lithospheric-scale shear localization are presented that confirm the findings of the initial stage analysis.

Effects of elasticity on the Rayleigh-Taylor instability: implications for large-scale geodynamics

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Elasticity is typically ignored in numerical models of mantle convection, which has resulted in vigorous discussions in the previous two editions of this workshop. In order to continue the discussion, we have analyzed the Rayleigh-Taylor instability for a Maxwell viscoelastic rheology. Both an analytical thick-plate perturbation technique and direct numerical simulations have been employed.

Results for the 2-layer setup of a dense layer overlying a lower density material show that three different deformation modes exist: the 'classical' viscous mode, an intermediate viscoelastic mode and an elastic mode. Whereas elasticity has only a minor effect on the dominant wavelength, it may increase the dominant growth-rate significantly, compared to the purely viscous case. The transition between viscous and elastic deformation modes is dependent on the Deborah number, which is given in the present setup by $De = \Delta\rho g H/G$ (where $\Delta\rho$ denotes the density difference, g gravitational acceleration, H total height of the system and G elastic shear module). For typical Earth-like parameters, $De = 10^{-3}$–1. For the 2-layer system, with a free-slip upper boundary condition, the critical Deborah number for elasticity to be important is $\sim$ 1–10. If, however, a fast erosion/mass redistribution boundary condition is present, the critical Deborah number may decrease significantly for large viscosity contrasts. Under these conditions, elastic effects may influence lithospheric dynamics.

Additional results will be presented for a 3-layer setup with various upper boundary conditions (free-surface, free-slip, no-slip and fast erosion). It was previously demonstrated that elasticity may result in stress-enhancement in the lithosphere (*e.g.* Poliakov *et al.*, 1993; Vasilyev *et al.*, 2000), due to non-relaxed elastic stresses and plume-lithosphere interaction. We study this effect systematically for various boundary conditions and material parameters.

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INVITED

Thermal history of Earth and the modes of mantle convection

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Possible geodynamic regimes have may have prevailed in Earth's history are discussed on the basis of the energetics of plate-tectonic convection. Plate-tectonic convection, modulated by strong depleted lithosphere created at mid-ocean ridges, demands more sluggish plate tectonics when the mantle was hotter, contrary to commonly believed, more rapid tectonics in the past. This notion of sluggish plate tectonics can simultaneously satisfy geochemical constraints on the abundance of heat-producing elements and petrological constraints on the degree of secular cooling, in the framework of simple whole-mantle convection. The geological record of supercontinents back to 2.7 Ga is shown to be broadly consistent with the accelerating plate motion as predicted by the new model. Furthermore, the very fact of repeated continental aggregation indicates that thicker depleted lithosphere in the past needs to move more slowly to become negatively buoyant by thermal contraction and also needs to be strong enough to support resulting thermal boundary layer. The concept of many small plates covering Archean ocean basins is thus physically implausible. As a consequence of reduced secular cooling, mantle plumes were most likely weaker in the past. The chemical evolution of Earths mantle may have been encumbered considerably by sluggish plate tectonics and weak mantle plumes, maintaining its compositional heterogeneity at various spatial scales to the present day. Internal heat production probably played an important role in controlling plate dynamics in the early Archean, for which a different mode of mantle convection is suggested.

Long-wavelength geoid anomalies and dynamic of subduction zones: effects of a layering at 660km

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We investigate the effect of a layering at 660 km on the dynamic and surface observables (such as geoid) of a subduction zone, using a finite element code (Zebulon) which allows for a wide variety of rheologies. We have developed a two-dimensional non-newtonian viscoelastic flow model incorporating a fault, representing the interface between the rigid overriding and subducting plates. A low viscosity wedge is also included. The flow is driven by a body force imposed in the slab, corresponding to the negative buoyancy of the cold sinking part of the lithosphere.

Free slip boundary conditions are applied for the two vertical and horizontal boundaries. As the physical processes that may influence the flow across the 660-km boundary remain relatively unknown and difficult to quantify, we decided to apply surface anomalies at 660-km proportional to the mass anomalies needed to achieve a perfectly layered circulation. So, the efficiency of the transition is parameterized by a single coefficient, characterizing the reduction of mass exchange across the discontinuity with respect to the whole mantle flow (See *Cadek and Fleitout, 1999* for more details). Preliminary results point toward a significant influence of the 660 discontinuity on the observables, and may eventually provide sufficient resistance to limit the need for a large viscosity increase at 660 km.

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Melt segregation and textural evolution of partially molten system

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Partially molten state is one of the most typical examples which exhibit self-organized behavior in complex composite system. Tiny fluctuation in composition, temperature and stress fields leads drastic change in the internal structure, which in turn could modify composition, temperature and stress fields. The essential part of this system is fragile nature of the internal structure with respect to the external forcings. When partially molten system is considered in terms of packing state, three kinds of packing fraction of the solid phase characterize the system into 4 states; Fl, the loose packing fraction, Fc, the close packing fraction and Fp, the percolation threshold packing fraction. Below Fl solid phase looses continuous connection and only the melt phase is continuous. This state is called suspension state. The viscosity is mostly dominated by the melt phase. Between Fl and Fc both solid and liquid phases retain continuous connection and the system has low value of yield strength, which can be called as a fragile partially molten state. The rheological property of this state is complicated. It strongly depends on applied stress, strain rate, type of deformation, and even the history of deformation (memory effect). The solid skeletal frame which supports the externally applied stress can be easily deformed and broken, which results in drastic change of the internal structure. Between Fc and Fp also both phases retain continuous connection but the system has high to infinite yield strength. The solid skeletal frame is hard enough. This state can be called as a hard partially molten state. The rheological property of this state is dominated by that of solid phase modified by melt phase. Above Fp the melt phase looses connectivity. The system behaves as a solid. The most important and interesting state is the fragile partially molten state. Since this state is essentially unstable the life time is short so that temporal and spatial extent of this state should be quite limited. But through this state the system can easily switch between solid-like behavior and liquid-like behavior. The time-, and spatial scale of the formation/destruction of connectivity of solid phase critically controls evolutionary path of partially molten state as well as segregation of melt phase. As for this evolutionary path two representative cases are explained. One is the case for thermo-convective coupling. Ogawa,Yamagishi and Kurita (JGR 2003) modeled melting process of permafrost layer by intrusion of magmatic body in simulation for the water-outbursting phenomena on Mars. Progressive increase of the molten zone by conductive heating results in initiation of permeable convective motion in this zone. Strongly localized heat flux by convection enhances localized melting. This works as a positive feedback; localized convection promotes localized melting and localized melting concentrates and enhances convective flow. Because of this spatial extent of the molten zone is strongly controlled by convective fluid flow. The second example is viscous coupling. Since viscosity depends on the solid phase fraction, heterogeneity in the degree of melting causes heterogeneous distribution of viscosity and yield strength. Under stress-constrained system some parts increases degree of melting and other parts decreases it because of destruction of solid skeletal frame.

The thermal evolution of the Earth

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The problem of thermal evolution of the Earth is long standing and has sometimes been called “the missing heat paradox”. This problem arises because most cooling models of the Earth, based on parameterized convection, are unable to get a present–time heat flow at Earth’s surface that matches the observations, unless an unrealistically high value for the radiogenic heat production is used. In other words, the present Urey ratio of these models is higher than what is implied by geochemistry. In order to solve this problem, new scaling laws for heat transfer by mantle convection have been proposed, mainly decreasing the exponent β of the Rayleigh number in the a relationship of the form $q = ARa^{\beta}$, using arguments like temperature dependence of viscosity (Christensen, 1984) resistance of plates to bending (Conrad and Hager, 1999) or depth of melting (Sleep, 2000; Korenaga, 2003). The difficulty in such approaches is to ascertain the validity of such scaling laws for the Earth which may be influenced by other effects.

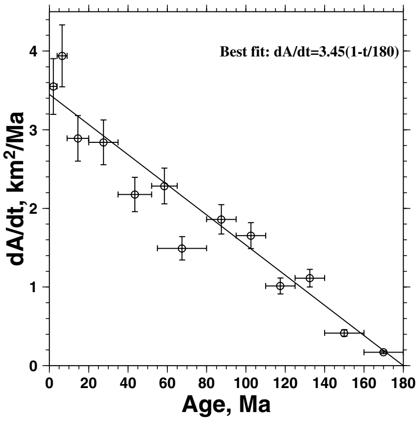

Figure 1. Distribution of seafloor age. Adapted from Sclater et al. (1981).

Instead, we use an empirical approach, based on the present observation of distribution of seafloor ages and a few assumptions. The total heat flow at the surface of oceans can be shown to be controlled only by the maximum age of oceanic lithosphere, the potential temperature of the mantle and the shape of the seafloor age distribution. The observed present time distribution (Fig. 1) shows that lithosphere of any age is subducted with equal probability, irrespective of its buoyancy. Even ridges can be subducted. This observation contradicts models of convection that assume a heat flux controlled by the boundary layer instabilities (Howard 1964).

Using the observed distribution, we find that the characteristic time scale for the thermal evolution of the Earth is about 10 Gyr so that an almost constant heat flow and a modest evolution of the temperature give a reasonable solution (Fig. 2). However, the smooth evolution heat flow curve should be modulated by variation due to changes in the shape of the distribution in seafloor ages. The amplitude of such fluctuations can be estimated as 25%, on the timescale of the Wilson cycle, about 500 Myr. Such fluctuations dominate over the long term evolution, at least since the establishment of plate tectonics.

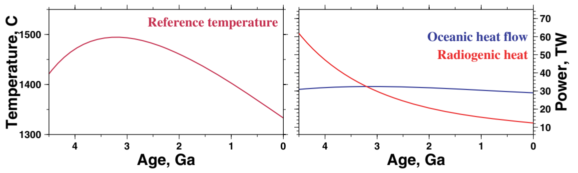

Figure 2. Thermal evolution of the Earth based on the observed distribution of seafloor ages.

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INVITED

Earth rheology from glacial rebound analysis

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The knowledge of the Earths mantle viscosity remains unsatisfactory despite the many laboratory and field studies that have been conducted. Is the viscosity depth dependent and does it vary laterally? Is it linear or is it non-linear? The rebound of the crust to the past ice loads has often been described as Natures own experiment in estimating the viscosity but, as is often the case with elegant experiments, reality is more complex and the viscosity estimates that have been inferred from rebound analyses are usually only as good as the assumptions made about the surface loading history of the ice sheets and analyses of rebound have to consider both the rheology and the ice history as imperfectly known functions. Thus strategies for the inversion of rebound data have to be developed that separate out earth- and ice-model parameters and that enable depth- spatial- and time-dependencies of the effective viscosity function to be determined.

Iterative solutions for earth-response and ice-load parameters have yielded some separation of parameters through focussing on (i) regional inversions of rebound data rather than global solutions, (ii) using differential methods to separate eustatic change from the rebound signal, (iii) using the responses observed on different time scales (e.g. geodetic versus geological), (iv) observing the response at different wavelengths, and (v) observing both radial and horizontal rebound responses. The results confirm that simple linear models for the viscosity function can provide an accurate response of the mantle to surface loading on time scales from decades to millennia. Depth dependence of the viscosity is important, with a marked increase from the average upper mantle to the average lower mantle, as well as increases within the upper mantle that correspond to the seismic transition zone. Lateral variability is also significant, with the viscosity variation following the seismic evidence for lateral variation in mantle shear-wave velocity and attenuation. Finally, there is evidence for a time dependence of the effective viscosity, with analyses based on observations of the recent response leading to higher upper mantle viscosity estimates than analyses based on geological data for past millennia.

Two-dimensional convection with a two-phase damage rheology lithosphere

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Plate tectonics is the unifying theory of geology, yet much remains to be understood about its development on Earth and absence on other planets. The generation of plate tectonics from mantle convection requires shear localization in order to form narrow, weak zones that separate the broad, strong plate interiors. Two-phase damage theory provides a theoretical framework to describe the failure and weakening that leads to shear localization. Two-phase damage theory allows for the development of damage to be manifested in two distinct ways: void generation associated with dilation of the matrix and increasing the fineness of the mixture (e.g. pulverization). This work will examine the application of two-phase damage theory to the problem of generating plate behavior from mantle convection. Our model will consist of a thin plate obeying a two-phase damage rheology overlaying a Newtonian mantle that is undergoing simple thermal convection in two dimensions. Our objective is to determine how successful the different manifestations of damage are at producing plate-like behavior in a more sophisticated simulation than previously examined.

Structure and dynamics of a hydrous melt layer above the transition zone

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The "transition zone water-filter"(Bercovici and Karato, 2003) model relies on the presence of a dense hydrous melt above the 410 km discontinuity that is formed by dehydration melting as wet wadsleyite undergoes a phase change to low-water-solubility olivine. Huang and Karato (2005) suggest that, particularly in the Pacific, there is sufficient water in the transition zone to cause dehydration melting to occur. In the original water-filter model, the melt layer is divided into two regimes: a melt production area, where wet upwelling material melts, and a slab-entrainment area, where slabs become a reservoir for water due to their cold temperatures. Here we consider an additional regime: the viscous entrainment area, where mantle is viscously entrained by slabs at ambient mantle temperatures. We propose a mechanism that allows for melt to spread from the production area to the viscous entrainment area and find that this mechanism drains the melt layer of water very efficiently. Additionally, we find that because melt recycled into the transition zone has a large (near saturation) water content and is therefore more buoyant (Angel et al. 2001), the recycling process disturbs the bulk convective circulation and may contribute to transition zone scale convective cells. This disturbance can become an important feedback, affecting both the rate of melt production and the entrainment efficiency.

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Mixing of differentiated oceanic crust in a convecting mantle with depth and temperature dependent properties

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The mixing of materials in the Earth's mantle is directly controlled by the style of convection, which is not fully understood. Geochemical and petrological studies of mantle-derived rocks reveal a wide variety of compositions, which implies a convection pattern capable of preserving distinct chemical reservoirs, often identified as layers convecting separately (e.g. Allègre, 1997). However, recent seismic tomographic studies resolve subducted slabs well into the lower mantle, arguing for a whole-mantle convection regime (Kárason and van der Hilst, 2001).

In this project we study the evolution of compositional heterogeneities created by recycling a differentiated oceanic crust, a popular approach for reconciling geochemical and geophysical observations (Lassiter, 1998). We focus on two major parameters likely to control the fate of a subducting slab - the thickness of the basaltic crust and its composition, both of which affect the slab's buoyancy. We utilize two-dimensional cartesian finite-element models (Zhong and Zuber, 2000) and investigate the eventual depth of subduction and the pattern of the chemical heterogeneity introduced by it into the mantle. In our models, the thermal expansivity and the density contrast between the compositional components vary with depth, and the viscosity depends exponentially on both depth and temperature. We find that the thickness of subducted crust, specifically its thickness relative to that of the surface thermal boundary layer, indeed changes the resulting structure of the mantle. We also include two mineralogical phase transitions, at 410- and 660- km depth. The inclusion of mineralogical phase transitions is found to have profound consequences for the behavior of the model, as it alters the shape of the subducted slab and its initially layered structure.

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Composition of Earth's mantle and its variance

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We present a new statistical method to construct a model for the chemical composition of Earths mantle along with its variance. Our fundamental assumptions are essentially the same as the so-called pyrolite approach; primitive mantle can be located by the melting trend exhibited by mantle peridotites, with cosmochemical constraints on the relative abundance of refractory lithophile elements. Though this pyrolite approach involves the least number of assumptions thus perhaps most satisfactory compared to other approaches, its previous implementations suffer from questionable statistical treatment of geochemical data, leaving the uncertainty of model composition poorly quantified. In order to properly take into account the influence of data variance (i.e., scatters in peridotite data) on this geochemical inference, we combine the following three statistical techniques: (1) modeling a nonlinear melting trend in the multidimensional compositional space through the principal component analysis, (2) determining the most primitive mantle composition on the melting trend by simultaneously imposing all of cosmochemical constrains with least squares, and (3) mapping scatters in original data into the variance of the final composition model through the Monte Carlo bootstrap resampling method. The new composition model is shown to be substantially depleted in refractory lithophile elements, compared to previous models. Revising global heat budget and noble gas budget with this new model indicates the large-scale homogeneity of Earth's mantle.

Mapping the long route of the Tyrrhenian slab through the mantle

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In the south-eastern corner of the Tyrrhenian basin, in the central Mediterranean Sea, a tight alignment of earthquakes along a well defined Benioff zone marks one of the narrowest active trenches worldwide, where one of the last fragment of the former Tethys ocean is consumed. Seismic tomography furnishes snapshot images of the present-day position of this slab, and seismic anisotropy allows to reconstruct the past kinematics of the subduction process. Using seismic anisotropy fast directions as a proxy for the present and past mantle flow, we look backward for the seismic traces of the slab motion through the Western-Central Mediterranean mantle, from the starting locus of subduction toward its current day position. The result of combining independent data sets provides a coherent pattern of anisotropy that illustrates an example of slab rollback from its initiation point to its present-day location.

Effect of lithospheric model assumption on the interpretation of geodetic data

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The use of geodetic measurements to evaluate the slip rate (thus slip deficit) along a fault during the interseismic period, is a very important tool for seismic hazards assessment. Unfortunately the geodetic measurement itself is only telling us the movement (or relative movement) of selected points and is not a direct measurement of the fault slip rate. In order to compute this value we need to introduce different assumptions on the behavior and the properties of the lithosphere surrounding the fault. The easiest assumption made in the analysis of geodetic data is the elastic half space assumption (e.g. Savage and Burfurd, 1973). This is directly derived from the elastic rebound theory and assumes that in the interseismic period the fault is locked to a defined depth and creep at a fixed rate beneath that level. Despite the oversimplify assumption this model in general can fit the geodetic data pretty well. Unfortunately, this model do not keep in account the earthquake cycle and the viscoelastic behavior of the lower crust/upper mantle. This effects can be very large in case that the recurrence of seismic event on the fault is very long respect to the relaxation time and can introduce big biases if we are interested in partitioning the strain among faults in different stages of their earthquake cycle (Dixon et al 2002). To solve this problem Savage and Lisowski (1998) introduced a model of an elastic layer over a viscoelastic half space loaded by an infinite number of earthquakes on an infinitely long fault that break through the elastic layer. Since this model is currently widely utilized we test here the effects of some of the assumptions in this model on the velocity field. In particular we analyze the effect of the assumption of the infinite number of earthquake that imply a quasi-steady state in the stress regime of the ductile material. We observe that if the material is relaxed before the event the relaxation is much more fast than expected by the model of Savage and Lisowski indicating that the local stress regime can have an influence on our estimation of the viscoelastic properties through interseismic data. We also analyze the effect of lateral heterogeneity in the elastic and/or viscoelastic material properties on the strain accumulation during the earthquake cycle.

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Mathematical modeling for seismology problems

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We obtain the exact solution for free surface displacements generated from a point source in a layered medium. The far-field results are given in cylindrical coordinates for moment tensor point sources:

$$\begin{pmatrix} u_r^{(0)} \\ u_z^{(0)} \end{pmatrix} = \sum_{i=1}^{3} \int_0^\infty k^2 \mathbf{j}_i L^{-1} \left[m_i \mathbf{G}_i \right] dk$$

$$u_\varphi^{(0)} = \sum_{i=5}^{6} \int_0^\infty k^2 j_i L^{-1} \left[m_i G_i \right] dk$$

The function of a source $\bar{u}(t)$ is modeling by Brune's model and we consider the r-th component of the displacement $u_r^{(0)}(r,\varphi,t)$ that contains $M_{zz}(t)$ (the zz-component of the seismic moment tensor M):

$$\begin{aligned} &\tilde{u}_r^{(0)}(r,\varphi,t) = \\ &\quad \frac{\sin 2\delta \sin\lambda}{2\pi\mu} \int_0^\infty \frac{k^2 J_1 dk}{2\pi j} \\ &\quad \int_{\sigma-j\infty}^{\sigma+j\infty} \frac{2\alpha\beta e^{-kh\alpha} - g e^{-kh\beta}}{4\alpha\beta - g^2} M_0(k\eta) e^{k\eta t} d\eta, \\ &\quad M_{zz} = M_0 \sin 2\delta \sin\lambda \end{aligned}$$

The last equation represents the complete displacement field on the free surface for the moment tensor point source $M_{zz}(t)$, including body and surface waves. Inner integral is the sum of residues in poles of the integrands (surface waves) and profile integrals (body waves). Surface waves in the sense of normal mode are related to poles of the integrands which follow from the dispersion equations. Thus, it is possible to calculate body or surface waves. But we are interested to calculate only for poles $\eta = 0$ and $\eta = -\frac{1}{k\tau}$ of the function $M_0(k\eta)$. We obtain for the r-th component of the displacement that contains $M_{zz}(t)$:

$$\begin{aligned} &\tilde{u}_r^{(0)}(r,\varphi,t) = \\ &\quad \frac{\sin 2\delta \sin\lambda A U_0}{2\pi} \int_0^\infty k^2 J_1(kr) \Big[Res[V(k,\eta)] \Big|_{\eta=0} \\ &\quad + Res[V(k,\eta)] \Big|_{\eta=-\frac{1}{k\tau}} \Big] dk + u^b + u^s = \\ &\quad u^b + u^s + A + Be^{-t/\tau}, \end{aligned}$$

where u^b, u^s - displacements of body and surface waves on the free surface of the r-th component (body- and surface- wave seismograms of the displacement $\tilde{u}_r^{(0)}(r,\varphi,t)$).

It is shown that the function $u_r^{(0)}(r,\varphi,t)$ is directly depended upon the function of a source $u(t)$ and is obtained some function of time t ($A + Be^{-t/\tau}$) prior to P-wave arrival on the theoretical seismograms. This effect is shown on the seismogram that was recorded at the seismic station Chernivtsi (Ukraine) by 27.09.2004 for the earthquake in the Carpathian (the Vrancha region, at 09:16:22.47, h=160.3km, N45.749, E26.542, K=13.4, K-energetic class: lgM_0=0.6 K+15.5 for the Transcarpathian region).

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A mantle flow model for the North Atlantic and its relation to seismic anisotropy and geochemical signature

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A temperature and flow mantle model for the North Atlantic, based on a section of the tomography model by Bijwaard and Spakman (1999), was derived under the demand of a maximum fit to the observed medium wavelength gravity field. The resulting an upper mantle temperature field reveals two distinct temperature anomalies, one beneath Iceland and the westerly adjacent regions with an excess temperature of 200°C, which is connected to a deep mantle root and, and a second anomaly, starting at a depth of 300 km beneath the Kolbeinsey Ridge, for which we estimated excess temperature of 120°C. The related flow pattern is essentially radial south of Iceland with ridge parallel flow along Reykjanes Ridge and divergent flow at the Kolbeinsey Ridge north of Iceland. This flow model well explains an influence of a possible Iceland plume on the Reykjanes Ridge, which is well established both in the occurrence of rare earth elements and He-ratios of Mid-Atlantic Ridge Lavas, and predicts a deep and hot melt zone beneath Kolbeinsey creating a thick thick crust but without plume tracers which is in agreement with geochemical observations. For this flow model we also determined the longest axis of the finite strain ellipsoid (FSE) as well as the direction of the fast axis in multi-aggregate olivine (based on the formulation of Kaminski, 2002), including lattice preferred orientation (LPO) and dynamic recrystallization. The long direction of FSE and LPO are in good agreement and mainly reflect a large scale upwelling, some stronger deviations are observed in regions of a strong vertical flow component. Comparison of regional scale seismic anisotropy models based on Rayleigh waves (Levshin et al. 2001) show partly agreement to our fast directions of olivine derived from the flow model mainly south of Iceland. For the Greenland shield, however, we found a shift of 90° between the seismic anisotropy and the olivine fast direction.

A detailed model for accretion of crust in Iceland

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The Icelandic crust, though oceanic in origin, is distinctively different from normal oceanic crust. Crustal thickness is on average $\sim$ 24 km, with a maximum value of $\sim$ 50km, but the transition to the mantle is not well defined. Seismic velocities are high, and have to be explained by thermal or chemical effects. For Iceland we define four source regions of crustal accretion: surface extrusion, intrusion in fissure swarms at shallow depth connected to volcanic centers, magma chambers at shallow to midcrustal level, and a deep accretion zone, where crust is produced by widespread dyke and sill emplacement and underplating. Knowing the spreading rate, the rate of crustal production can be estimated to $\sim$ 600 m^2/y per unit length along the ridge, but the site of emplacement is not obvious. We studied the process of crustal accretion in a dynamical, numerical model, prescribing different volumetrical source functions in space and time for crustal production in the four defined regions. The process of accretion is studied by solving the Navier-Stokes-, the heat transport and the mass conservation equations including volumetric sources and identifying material from different source regions by a marker approach. After some time of spreading and accretion a characteristic temperature distribution and crustal layering evolves, which is compared to observation data, and indicates that shallow accretion and magma chamber accumulates play an important role in crustal formation in Iceland.

Ridge jumps associated with plume-ridge interaction: 1. Off-axis heating due to lithospheric magma penetration

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Surface manifestations of hotspot-ridge interaction include geochemical anomalies, elevated ridge topography, negative gravity anomalies, off-axis volcanic lineaments, and ridge reorganization events. The last of these is expressed as either captured ridge segments due to associated asymmetric spreading, such as at the Galapagos, or as discrete jumps of the ridge axis toward the hotspot, such as at the Iceland, Tristan de Cuhna, Discovery, Shona, Louisville, Kerguelen, and Reunion hotspots. Mid-ocean ridge axis reorganizations cause variations in local volcanic patterns, lead to changes in overall plate shape and ridge axis morphology, and alter local mantle flow patterns. It has been proposed that discrete ridge jumps are a product of interaction between the lithosphere and a mantle plume. An expanding mantle plume causes buoyant uplift and asthenospheric shear on the base of the lithosphere as well as enhanced volcanism above the plume center. To begin exploring the above effects, we limit the current study to the effect of thermal heating of the lithosphere due to plume-induced magma penetration. Using a two-dimensional finite element code (FLAC), the lithosphere is treated in cross section with a visco-elastic-plastic rheology. We examine the amount of heat input required to produce a ridge jump, the effect of various distributions of this heat, and the effect of crustal thickness variations.

Far interaction in the upper mantle through 3D-BEMFEM

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Slow creeping materials as mantle rocks flow through quasi-static equilibrium states, meaning that every part of the systems deforms depending on all the surrounding motions. However analytical solutions of Stokes flow indicate that two-dimensional immersed bodies interact with any far field boundary, while three-dimensional interactions decade as the inverse of the distance. This implies that slabs or plumes could have a far distance interaction but that this does not necessarily happen, depending on the regional conditions. Possible cases study are the meso-scale systems as the Mediterranean region or Tonga-Fiji trench system.

We present here the next development of a technique for Boundary Element-Finite Element coupling presented in (Morra and Regenauer-Lieb, 2005), where a two-dimensional setup has been applied to the analysis of the local effects of mantle-lithosphere coupling in subduction. The three-dimensional version of the same setup has been implemented using a combination of Python and C languages. The advantages of the technique are the possibility to model large deformation in a lagrangian framework and the efficiency of the approach, independent by the interaction distance. The next step will be the coupling of 3D BEMFEM with particles libraries.

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Generation and evolution of channels due to the melt channel instability

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We investigate melt transport in partially molten rocks under different stress fields under hydrous and anhydrous conditions. We model such aggregates with the 2D-FD code FDCON (Schmeling, 2000) by means of a porous deformable matrix with melt to clarify the following key questions: Could channeling occur in a matrix containing a random melt distribution under a given stress field? How do channels evolve during finite simple shear? Is it possible to achieve a focussing of melt towards an MOR (dykes)? How does a Plume influence the orientation of dykes?

In a deforming partially molten aggregate, weakening of the solid matrix due to the presence of melt creates an instability in which melt is localized by the following mechanism: regions of initially high melt fraction are areas of low viscosity and pressure, so that melt is drawn into these regions from higher pressure surroundings. This further enhances the melt weakening, producing a self-excited localization mechanism (Stevenson, 2000). For both, simple as well as pure shear, the growth rate α for an inclined 1D sine perturbation is highest for an orientation parallel to the direction of the maximum compressive stress (MCS). α is proportional to the applied stress, the reverse of the Melt Retention Number (Schmeling, 2000) and the wavenumber k of the 1D sine. This also confirms the theoretical growth rate α found by Stevenson, 2000.

Small-scale simulations ($\approx 1km \times 1km$ box dimensions) with inclined 1D sine, 1D single channel-like perturbations, 2D ellipses, random fields and large-scale Plume-MOR simulations are investigated. In our isothermal models we found that the influence of water reduces the growth rate, in contrast to non-isothermal models of Hall & Parmentier, 2000.

Under simple as well as pure shear (small-scale simulations), melt channels evolve from an irregular melt distribution (mean porosity $3 \pm 0.5\%$) at angles parallel to the MCS (45° and 0°, resp.). Upon further straining in the simple shear case they slightly rotate out of the orientation of maximum growth rate and partly disrupt. Even at later stages the mean channel orientation of the disintegrated melt inclusions shows an orientation parallel to the MCS. For this reason, it is sufficient to calculate the orientation of the MCS of a given model to determine the mean channel orientation. Applied to large-scale Plume-MOR simulations shows, that the majority of the ascending melt will reach the bottom of the lithosphere at distances of ≤ 80 km from the MOR. From these distances melt could percolate towards the MOR due to the form of the lithosphere ($\sqrt{t}$-law, Hall & Kincaid, 2003). On the distant side (> 80 km), melt could either be deposited on the bottom of the lithosphere or recycled back to lower regions of the plume head, from where it may try once more to reach the MOR.

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Temporal geoid variations as constraint in global geodynamics

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Density distributions derived from various seismic tomographies as well as modifications to these models with an upper-mantle slab sinking model and viscosity models of Earth's mantle are investigated in analytical flow models in order to fit the models' predicted observables to the GRACE satellite-mission's gravity and geoid measurements and to observed plate motions while reproducing estimates of dynamic topography as an additional constraint. Advecting successful models' density distributions yields temporal variations of the above observed quantities. We investigate whether identifiers of such mantle dynamic processes may be discerned from other sources' signal contributions to the GRACE-measured global temporal geoid variation in order to impose an additional constraint on global geodynamic modeling.

The ongoing 5-yr Grace satellite mission yields estimates of Earth's global gravity field of unprecedented accuracy. A globally improved resolution of the static geoid itself will not affect the constraint on global geodynamic modeling due to the large uncertainties in quantities dominating the modeling process (apparent in the large discrepancies when comparing different global seismic tomography models or geodynamic mantle models based on past slab subduction as well as in the uncertainties involved in the conversion of seismic velocity anomalies to density heterogeneities for flow model calculations) and also due to the limitations when imposing suitable upper boundary conditions in order to reproduce observed plate motions. The temporal sequence of monthly mean gravity field estimates, however, provides a time history of its global variability, which may serve as a surface observable (in addition to the commonly employed static geoid or gravity field, surface velocity or estimates of dynamic topography) constraining geodynamic flow, provided contributions from mantle flow are discernible from the main signal. Furthermore, the combined data sets of geoid and its temporal variation may be used to infer not only relative, but also absolute global viscosity distributions within the Earth. While viscosity estimates from glacial isostatic adjustment are expected to be biased by continental influences, GRACE data provides an evenly distributed coverage to this end. Also the correlation between instantaneous geoid and its rate of change possibly contains additional information about the geodynamic processes involved. It is expected to differ for retreating subduction zones, detaching slabs, and developing plumes. Global temporal geoid variations estimated by advecting density heterogeneities from our range of successful models exhibit varying spatial patterns which are, however, small (O(-6) m) in comparison to those due to ocean circulation, redistribution of water and biological masses, PGR or massive volcanic processes, which are of the order of the observed temporal variability itself (O(-3) m).

Postglacial rebound in Estonia: constraints from the measurements of Estonian geodetic networks

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Noticeable crustal movements in Estonia result mainly from the postglacial rebound (PGR) of Northern Europe. PGR has a clear impact on the establishment and the maintenance of national geodetic networks because geodetic coordinates, gravity and geoid surface vary continuously in time. In Estonia, geological and sea level data, repeated levelling and gravity measurements are available for the determination of vertical crustal movements and for the study of the glacioisostatic processes inside Earth.

In this work temporal gravity variations were estimated on the basis of precise gravimetric data measured repeatedly on the gravity network of Estonia. Those variations correlate well with the pattern of crustal movements and the time-series of sea level data. Observed variations have also been verified by the predictions of PGR models. Discrepancies between observations and predictions indicate measurement errors as well as the poor constraining of PGR models in Eastern Europe.

Thermo-mechanical modelling of a pull-apart: approaching 3D

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Pull-apart basins belong to a special type of sedimentary basins associated with continental transform faults. They are depressions that are formed as a result of crustal extension in domains where the sense of fault overstepping or bending coincides with the fault motion sense. The outstanding classic example of a pull-apart basin is the 150 km long Dead Sea basin which is located at the Dead Sea Transform and where more than 8 km of sedimentary cover has accumulated since 15-17 Ma.

To study factors controlling localization and partitioning of the strain during strike-slip lithospheric-scale, we use the internally consistent finite element thermo-mechanical modelling technique in extended 2-D (Sobolev et al., 2005).

As a next step, we develop a simplified 3-D thermo-mechanical model of a pull-apart basin formed at an overstepping of an active continental transform fault. The modelling shows that, in addition to the magnitude of strike-slip displacement, the major parameter which controls basin length, thickness of sediments and deformation pattern beneath the basin is the thickness of the brittle layer. The unusually large length and sediment thickness of the Dead Sea basin, the classical pull-apart basin associated with the Dead Sea Transform, can be explained by 100 km of the strike-slip motion and a thick (20-22 km, up to 27 km locally) brittle part of the cold lithosphere beneath the basin (Petrunin and Sobolev, 2005). The thinner sedimentary cover in the Gulf of Aqaba basin, located at the southernmost part of the Dead Sea Transform, close to the Red Sea Rift, is probably due to a thinner brittle part (less than 15 km) of the warmer lithosphere. The modelling also suggests no more than 3 km of Moho uplift beneath narrow (10-15 km) pull-apart basins formed in cold lithosphere, like the Dead Sea basin. We also infer that the values of surface heat flow of 40 mW/m^2, reported for the Dead Sea, are probably much too low, because, otherwise, either the depth of the Dead Sea pull-apart basin would be more than 16 km or no pull-apart deformation would occur in such cold lithosphere.

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The aggregation and dispersal of supercontinents in global mantle convection models

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In 1966 J. Tuzo Wilson suggested that the Atlantic Ocean basin had closed and then reopened, a process now commonly termed the Wilson Cycle. Since then, numerous paleomagnetic studies have shown that Wilson's original idea may be extended to describe a global cycle, punctuated by the periodic formation of supercontinents such as Pangea, Rodinia, and Columbia, separated by time scales of several hundred million years (Myr) (e.g. Hoffman, 1991; Rogers & Santosh, 2002). It is generally accepted that these motions are coupled to large scale mantle convection. Early two dimensional (2D) mantle convection models demonstrated the dynamic feasibility of such supercontinent cycles (e.g. Gurnis 1988; Lowman & Jarvis, 1993). Here we present the first ever high resolution, 3D spherical mantle convection models with multiple mobile continents. We study models incorporating three to six continents in a predominantly radiogenically heated mantle with radially stratified viscosity. The results of these models reinforce the plausibility of a supercontinent cycle with a period of a few hundred Myr. Underlying mantle temperatures vary by up to 100 K over $\sim$100 Myr. Continental velocities fluctuate in concert, ranging from $\sim$0–7 cm/yr. These results agree well with geologic and geophysical observations, and place dynamic constraints on global mantle flow models.

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Post-glacial rebound in North America: ice load parameters from inverse problems

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The influence of ice load evolution on glacial isostatic adjustment (GIA) has been widely recognized. In the past decades, inference of ice load parameters has often been derived from a suite of surface geophysical observables (e.g. relative sea-level, RSL, curves) associated with the post-glacial deformation of the Earth. Geophysical inversion techniques have been used to constrain ice time-history and to examine the link between data-sets and geophysical models. These models include an ice-load component, mostly based on geological and glaciological evidence, and a rheological component, specified by a viscosity profile for the Earth's mantle. Usually the ice thickness is partly undetermined and a great deal of uncertainty can also be found in the lateral extent of the large ice sheets. As a consequence, very different ice models can be generated from the same glaciological data. here, solve the problem of the determination of the ice sheets parameters from relative sealevel observations by a non-linear, globally directed, inversion technique based on the Neighborhood Algorithm (NA) method (Sambridge, 1999). To this end we introduce a new ice load model for the Laurentide sheet, characterized by 7 different parabolic ice domes covering the area of the North America, Innuitian and Greenland regions. Isochrons for ice retreat as well as the ice thickness at the center of each dome are assumed *a priori* in the model in agreement with the ICE-3G model by Tushingham and Peltier (1991). An ice-sheet scaling parameter is introduced for each dome and the Neighbourhood Algorithm inversion technique is applied to constrain these scaling factors, using 128 RSL time-series as observed data–set.

RSL synthetic predictions are computed solving the sea-level equation for a viscoelastic spherically symmetric incompressible Earth according to the formulation developed by Farrel and Clark (1976) formulation in which the eustatic, the glacio-isostatic and the hydro-isostatic terms are taken into account and the fixed-shorelines approximation is adopted. The viscosity profile is the same as Tushingham and Peltier (1991), with the shallow upper mantle, transition zone and lower mantle characterized by a viscosity of 1, 1 and 2 in Haskell units, respectively.

Our preferred North America ice sheet, when compared with ICE-3G, shows (1) a significant and sizeable reduction of the ice thickness over most of the ice-covered region and (2) a relatively slow increase of the ice thickness with distance from the ice margin in the Hudson Bay region.

3D numerical instantaneous flow models induced by subduction

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We conduct simple 3D subduction experiments using a numerical, finite element approach (Zhong et al. [2000]) to compare the predicted velocity fields with those recorded using Feature Tracking for laboratory analogue models. We prescribe slab temperature and shape based on an intermediate stage of an analogue self-consistent subduction experiment, and study the instantaneous flow field solution for a free slab. We explore the resulting flow patterns, particular the toroidal vs. poloidal component of upper mantle circulation, as a function of box size, plate width, and, importantly, viscosity contrast between slab and mantle. We show that slab rheology determines the strength of toroidal flow, an important consideration when trying to relate subduction processes with observations such as shear wave splitting.

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A new 3D finite strain elastoviscoplastic code for lithospheric scale modeling

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Modeling of coupled viscous deformation in the asthenosphere, viscoelastic deformation in the deep parts of the lithosphere and brittle failure in the upper crust requires an advanced treatment of elastic and plastic rheological mechanisms in finite deformation regime. Our approach is based on the implicit time integration of rate-type elastoviscoplastic constitutive equation in displacements variables using an objective corotational kinematic formulation. The code is called SLIM3D which stands for Semi-Lagrangian Implicit Modeler. The term Semi denotes the capability to overcome the restriction of purely Lagrangian formulations by means of particle-based remeshing procedure when the mesh becomes excessively distorted. The locking-free hexahedral finite element with hourglass control is adopted to maintain robustness and efficiency of computation. The notion of consistent linearization of stress update algorithm and derivation of tangent modulus tensor is used to achieve optimal convergence rate of global Newton-Raphson equilibrium iteration at a large time step.

Currently incorporated in SLIM3D elastoviscoplastic rheology assumes stress-independent shear modulus and shear viscosity and Von Mises plasticity with linear softening rule. To introduce more adequate description of the mechanical behavior of geological materials, we are currently working on the implementation of nonlinear creep law and non-associative two-invariant smooth-cup plasticity model. Details of finite element formulation and numerical procedures implemented in SLIM3D as well as results of numerous tests will be demonstrated.

All bent out of shape: buckling instabilities of viscous sheets and slabs

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The periodic folding of a sheet of viscous fluid falling upon a surface is a common fluid mechanical instability with applications from food processing to geophysics. Using a combination of thin-layer theory and laboratory experiments with silicone oil, we have determined how the amplitude and frequency of the folding depends on the the sheet's initial thickness, the injection speed, the height of fall, and the fluid properties. In the (geophysically most relevant) limit of negligible inertia, folding can occur in two distinct modes: "viscous" folding controlled by the injection rate, and "gravitational" folding in which the viscous forces that resist bending are balanced by gravity. Inertial effects give rise to two additional modes: "inertio-gravitational" folding characterized by frequency multiplicity and hysteresis, and "inertial" folding in which viscous forces are balanced by inertia. Our scaling laws predict a folding amplitude ≈ 500 km for the subducted Cocos plate, in good agreement with the tomographically observed apparent widening of the slab below the transition zone. To conclude, we present a new hybrid thin-layer/boundary integral representation for the dynamics of a viscous sheet embedded in a less viscous fluid, a simple model for a subducted slab interacting with the ambient mantle.

INVITED

Successes and future challenges of mantle modeling

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In this introductory talk, I will try to illustrate some of the successes and challenges of mantle modeling in relation with mineralogy, geochemistry and rheological behavior. Of course the progresses and the new questions have been closely linked to those of seismology. As geodynamicists, we hope that all these fields will be understood and related by mechanical models of mantle convection.

Our understanding of the deep mantle mineralogy mostly comes from the comparison between seismological observations and laboratory measurements. In the last 20 years, the progresses have been striking, from the 1D velocity profiles to the complex 3D tomographic v_p and v_s images now available. Similarly, the equations of states of the major mineralogical phases have been measured. The challenges are however still huge. The anomalies seen by the seismologists are usually smaller than the percent, and the measurements of elastic parameters with a similar accuracy at simultaneous high pressure and temperature is still very difficult. In particular, our data base is still very poor for rigidities, minor phases, or ultra high pressures while the high quality of seismic velocity variations cannot be accurately translated into more direct mineralogical data such as density or incompressibility variations.

The geochemical data has benefited from technological advances that have improved the precision and resolution of observations by orders of magnitudes, and largely extend the number of isotopes that can be studied. The interpretation of the geochemical observations is now much closely linked to the mechanical processes of transport, mixing, and melting. The interpretation of all these observations in terms of mantle circulation is however still debated. The end-members models are either that the differences between hotspots and oceanic ridges are related to differences in mixing/melting or in differences of source composition. The differences in sources composition can themselves be due to the preservations of primitives heterogeneities, or to the generation of new heterogeneities through recycling or melting. Even some first order problems, i.e., the Ar balance or the total quantity of radioactive elements are still debated.

The radial models of mantle rheologies, from glacio-isostatic or geoid modeling, suggest a viscosity increase with depth in the mantle by 1 to 2 orders of magnitude and an upper mantle viscosity around 10^{20} Pa s. We know however that the mantle should contain huge variations of mechanical properties related to temperature, water content, grain size or mineralogy. We do not even know whether the rheology can itself be approximated by a linear time-independent viscosity. The major problem of our poor knowledge of the mantle rheology is clearly illustrated by our inability to take into account the existence of rigid plates in our convection models. Very interesting progresses have been however made theoretically, experimentally and numerically.

Slab dehydration and fluid migration at the base of the upper mantle

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Water enters the Earth's mantle at trenches by subduction of oceanic crust. Most of this water immediately returns to the atmosphere through back 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 bottom of the upper mantle (660 km depth). Then, due to its low solubility in lower mantle minerals, water is likely to be released as an hydrated fluid, during the spinel-postspinel phase change. The dynamics of this fluid phase is investigated through a 1-D model of compaction, in which a source term has been introduced to take the fluid precipitation into account.

The competition between the advective transport by the descending slab and the buoyant rise of the fluid results in three distinct situations, depending on the properties of the solid and the fluid phases. Low matrix permeability and high fluid viscosity inhibit the compaction and favor the leakage of fluid toward the deep mantle. In this case, the entire slab water content would enter the lower mantle and would be mixed at large scale. Nevertheless, realistic values of the fluid viscosity and matrix permeability make this possibility unlikely. When effective, compaction results in an accumulation of fluid at and below the phase change. Depending on the value of the matrix viscosity, the situation evolves differently. Above 10^{20} Pas, accumulation of fluid extends below the phase change and the pressure difference between the fluid and the matrix increases continuously, exceeding the yield strength of rocks. As a results, cracks would initiate and evolve toward the formation of dykes. In case of very low mantle viscosity, possibly due to strong grain size reduction during phase change, compaction becomes very efficient and the fluid remains confined within the phase change horizon, without increasing pressure. On the long term, this last situation appears unstable and would also evolve toward the formation of dykes.

Thus, it is expected that water comes back to the upper mantle by the way of dykes propagating along the direction of the maximum compressive stress. Since slabs appears to be down-dip compressional below 300 km depth, we predict the formation of dykes extending from the 660 km phase change to 300 km depth. The possible existence of such dykes in slabs offers the necessary conditions for strong double couple component earthquake in the deepest part of the upper mantle.

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Permeability-porosity relationship in a stochastic model of partial melting

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We present a model for calculating permeability of a porous solid-melt polycrystal during melting. Unlike to previous two-phase models, a solid framework is used that does not have a regular geometry nor a typical grainsize. Instead, we use a polycrystal that is created on the basis of a stochastic nucleation and growth process for first-order phase transformations as the starting state for partial melting. It is a polycrystal with continuously distributed grainsizes and random grain locations.

Permeability is then estimated through flow simulation on the constructed 3D porous two-phase body using the Lattice-Boltzmann (LB) technique. The LB method describes fluid motion with the interaction of a massive number of particles following simple local rules, rules that recover the Navier-Stokes equation at the macroscopic scale [Rothman and Zaleski, 1997].

It is known that the LB flow simulation is able to handle successfully very complex 3D pore geometries [Keehm et al., 2004]. Here, the investigated porous framework shows a fractal-like geometry near to percolation of either melt or solid phase. The flow simulation is done with an assigned pressure gradient ∇P across opposite faces of cubes. From the local flux, the volume-averaged flux $\langle q \rangle$ is then calculated using Darcy's relationship

$$\langle q \rangle = -\frac{\kappa}{\eta} \nabla P$$

where κ is the (wanted) macroscopic permeability and η is the dynamic viscosity of the melt.

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INVITED

Seismological constraints on Earth's structure

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Seismic tomography is one of few techniques to illuminate the structure of the deep mantle. Yet, the limited sampling of the mantle by seismic waves renders tomographic images with heterogeneous resolution that are difficult to interpret (Figure 1 and 2). The resolution of seismic structure is especially variable in the transition zone (300–1000 km depth), where chemical and physical boundaries may stratify flow [*Ritsema et al.*, 2004].

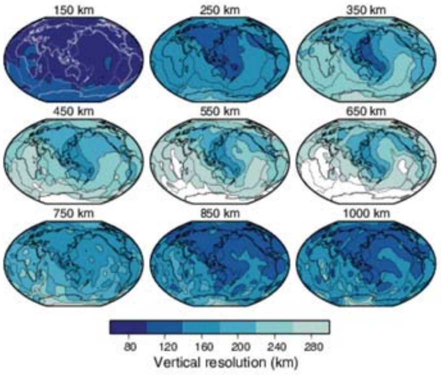

Figure 1. Maps illustrating the variable vertical resolution of shear velocity heterogeneity in tomographic model S20RTS. The vertical resolution is estimated from the vertical extent of Backus-Gilbert resolution kernels. Vertical resolution is best (worst) in the regions shaded dark blue (light blue). Note the low vertical resolution in the transition zone, where data sampling by overtone Rayleigh waves is poorest.

I will discuss the pitfalls in the interpretation of tomographic images that largely stem from heterogeneous data coverage and the simplification made in tomographic modeling. I illustrate how Backus-Gilbert resolution analysis can be helpful in estimating the distortion of real earth structure in tomographic images. In particular, I discuss my take on recent suggestions that slabs penetrate to a variable depth in the lower mantle and that plumes can be traced from Earth's surface to the core-mantle boundary.

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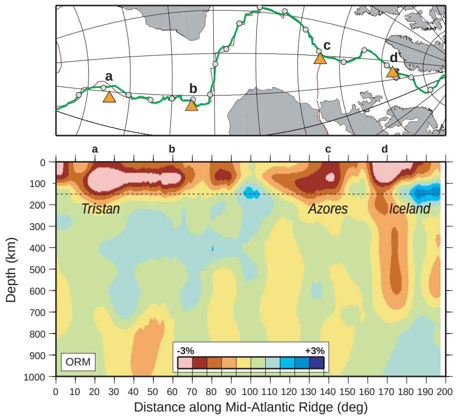

Figure 2. Cross-section through S20RTS illustrating shear velocity heterogeneity beneath the Mid-Atlantic Ridge (green line). The letters a, b, c, d indicate the location of ridge-centered hotspots. Note that reduced shear velocities (from PREM) beneath the Mid-Atlantic Ridge are confined to the upper 150 km of the mantle. Reduced shear velocities beneath Iceland extend deep into the transition zone. I will discuss the uncertain depth extent of the "Iceland Anomaly", due to the poor vertical model resolution in this region of the mantle (see Figure 1).

Analytical 2D modeling of a strike-slip fault in a viscoelastic space

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Expressions for the displacement and stress field generated by a screw dislocation embedded in a layered viscoelastic half-space have been obtained in analytical form. The equilibrium equation for the shear stress on fracture plane has been solved for a 2D fault model correspondingly to different boundary conditions, in order to obtain the slip distribution on fault plane and the displacement and stress field for the whole medium.

The evolution of these solutions is analysed in function of time for different viscoelastic configurations of the layered half-space. If the coseismic slip is 'frozen' for $t > 0$, the stress field is observed to change considerably in proximity of the boundary interface between surface layer and welded half-space. Also the stress on crack plane is found to change with the time.

Stress concentrates on the fault segment closer to the boundary interface. This may modify the expected aftershock rate, and aftershocks may cluster around the intersection between fault and interface. This process would be enhanced for a low viscosity of the viscous half-space. In fact, some indication for the predicted aftershock clustering is observed for the South Iceland Seismic Zone after the two August 2000 earthquakes.

Relation between deformation and cumulative seismicty as a possible tool for monitoring dike stability

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Volcanic edifices are characterised by intense fracturing. This arises from several processes connected to volcanic activity, as for instance degassing, chemical action of hydrothermal fluids and stress corrosion. Intense stress field produced by repeated dike injections also contributes to fracture host rocks. On the other hand, fracturing decreases rock resistance and lowers elastic stiffness, allowing magma dikes to open more and enhancing deformation.

A feedback process is then created between dike-induced deformation and dike-induced fracturing. This can be quantitatively described using the Effective Media Theory, which describes fractured media as homogeneous, with effective elastic parameters.

A linear relation is found to join the logarithm of deformation and cumulative seismicity, when injected dikes are stable and do not propagate. A deviation from this behaviour could signify dike instability, and may be used for dike real-time monitoring. Some application to recent intrusions is shown and discussed.

Visco-elastic models of greenstone belt formation by diapiric density inversion and magmatic intrusions.

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The theory of plate tectonics has shaped our current understanding of geodynamics. However, the relative importance of horizontal tectonics in terrestrial environments different from present day Earth (such as in the Archean or on the planet Venus) is not clear. Accordingly, here I present numerical models for the formation of granite-greenstone terranes (whose structure is well documented in the literature) using the numerical code Thermax2D. Thermax2D is a moving mesh visco-elastic code based on the commercially available finite element solver FEMLAB, incorporating temperature-dependent viscosities, erosion, and brittle failure (Bailey, 2005).

In the past, granite-greenstone terrains (e.g. the Superior Province of Canada and the Pilbara Province of Australia) have traditionally been viewed as the result of solid-state diapirism of granite through an insulating layer of volcanically deposited greenstones. Generally, those who prefer vertical to horizontal tectonics in the Archean invoke this model. Numerical work by Mareschal and West (1980) provided some physical constraints; however, they were limited to low activation energies (Ea), and did not include elasticity. Here we present preliminary results of a similar model including elasticity and higher Ea, which show important differences in both geometry and timescale, both of which are well-constrained by field work.

However, a growing body of geophysical and structural work indicates that in some cases GGT granites are quite shallow, and that they intruded as magma. This has led a few workers to suggest that GGT granites may have formed by i) intrusion of a tabular magmatic body, followed by compression due to regional tectonic deformation; or ii) intrusion of magma in batholithic form, with or without regional deformation (e.g. Cruden & Robin, 1998, Blenkinsop & Treloar, 2001). Thermax2D is capable of calculating the visco-elastic response of the crust to magmatic intrusion. Here we present preliminary calculations meant to test the range of usefulness of the Thermax2D for magma intrusion models.

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Trench motion, slab geometry and viscous stresses in subduction systems .

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A semi-analytic, three-dimensional model for subduction, which incorporates thin-sheet elastic slab within a Newtonian viscous upper mantle, provides a dynamically consistent means of computing viscous stress, trench motion and slab geometry. Although (negative) slab buoyancy provides the basic driving force for subduction, slabs that extend from the surface to the base of the upper mantle are over-supported by viscous stresses in the shallow (<100 km) mantle and under-supported by viscous stresses at greater depth in the upper mantle. Thus deeper parts of the subduction system act as an 'engine' for subduction while shallower parts act as a 'brake' on trench motion.

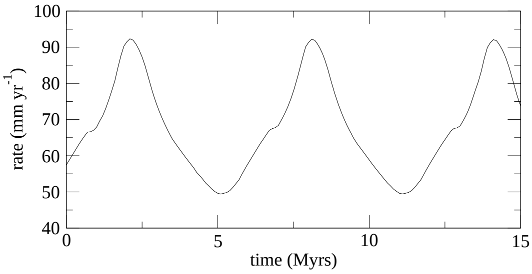

Figure 1. Rates of trench migration for subduction of alternating strips of high and low density lithosphere, with each strip being 200 km wide in a direction orthogonal to the trench. The buoyancy of each strip corresponds to oceanic lithosphere with pre-subduction water depth of 3.5 km (slight negative buoyancy) and 6.5 km (very negative buoyancy). Corresponding slab geometry in Figure 2.

Trench migration rates and slab geometry reflect a competition between these two parts of the subduction system. During steady-state subduction, trench migration rates vary approximately linearly with slab buoyancy and model rates of trench motion are in good agreement with the range of observed. Because of asthenospheric toroidal flow, slab width has a significant effect on trench migration rates, although smaller than that of slab buoyancy; the effect of an applied velocity at the base of the upper mantle is even smaller provided that the slab is not anchored within the lower mantle. Steady-state slab geometry is not affected by slab buoyancy. Rather large effects on trench migration rates and slab geometry are exerted by the structure and density of the frontal prism and overriding plate.

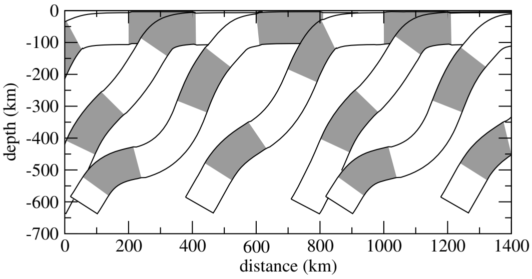

Figure 2. Geometry of subducted slab of alternating strips of high and low density lithosphere as described in Figure 1, which shows corresponding rates of trench migration. Time interval between slab positions is 4 my. Shaded areas denote lower-density lithosphere.

During non-steady-state subduction, rates of trench migration respond rapidly as variably buoyant lithosphere passes beneath the asthenospheric nose, reflecting the importance of the large magnitude viscous stresses at shallow depth. In the absence of other driving forces for convergence, trench migration rates can change by a factor of two or more in as little as 2 m.y. after anomalously dense or shallow lithosphere enters the subduction system. For example, rapid subduction of oceanic lithosphere slows dramatically within the first $\sim$ 3 m.y. after buoyant continental lithosphere enters the subduction boundary, and effective ceases within $\sim$ 10 m.y.. Slowing and cessation of trench migration rates are accompanied by steepening of the slab into a nearly vertical position. Our results indicate that the way in which subduction systems respond to the introduction of variably buoyant lithosphere into the trench is an important arena in which to test numerical subduction models against observations.

Vent modeling

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The current work presents the results of vent modeling. The Finite Element code was derived for modeling 2D vents. Equations for porous fluid flow were combined with both Mohr-Coulomb and Von Mises failure criteria for elasto-plastic rheology of the solid matrix. Results of modeling were compared with an experiment. During the experiment it was found out that there are basically three types of the crack behaviour that can occur during the injection of the Air into the sand with different sand moisture: two of them are shear bands with sufficiently different angle of cone orientation and the third one is Dome-like structure. The aim of the modeling is to understand and predict the different behaviours of the fracture in order to compare it to the nature.

Dynamic consequences of slab edges in the Calabrian subduction region

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Slab edges are a relatively common feature in plate tectonics. Near such horizontal terminations of subduction trenches, ongoing tearing of oceanic lithosphere is a geometric consequence. We refer to such kink in the plate boundary as a Subduction-Transform Edge Propagator, or STEP. We investigate the consequences of slab edges and STEP faults on the dynamics of the lithosphere and the uppermost mantle by solving for mechanical equilibrium using a 3D Lagrangian finite element model. The area of focus is the central Mediterranean, where subduction of the narrow Ionian slab is associated with roll back of the trench and the formation of the Tyrrhenian back arc basin. Data from different fields (tomography, seismology, gravity, heat flow, gps) is used to constrain the modeling geometry, forcing and material properties. The model includes STEP faults on both the northern and southern ends of the Tyrrhenian Sea. The STEP's and the subduction fault plane through the lithosphere are modelled through slippery nodes. The preliminary result we present are based on a linear visco-elastic rheology. We investigate the response to density sinking of the slab in the full-load model combined with the observed plate velocity between continental Africa and Europe.

Towards dynamic basin inversion: motivation, approaches, and some results

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Sedimentary basins, hosting Earth's hydrocarbon resources, belong to the best studied tectonic settings on Earth. The mechanisms of basin formation have been extensively explored and decades of hydrocarbon exploration have created a unique database against which geodynamic rifting models can be tested. This has led to the situation that models are now able to reconstruct a basin's formation history and present–day tectonic structure. However, practicably all basin inversion models are either kinematic in their design or use joint back–stripping/fault–matching techniques; they are tuned to be consistent with the geologic data but may not adequately describe the dynamics of rifting.

Here we show the results of a case study from the Norwegian Viking Graben in which we make the case for dynamic basin inversion models. First, we use an advanced kinematic basin model (TecMod) to reconstruct the formation history of the Northern Viking Graben. We find that the inverse model is under–constrained when only using

stratigraphy, heat flow, and palaeo water depths as inverse parameters. This becomes obvious when also incorporating vitrinite based palaeo temperature data into the reconstruction problem. Second, we review the case for accounting for mineral phase transformations during rifting. Mineral phase transformations have the potential to cause rapid syn–rift uplift if mantle material crosses the garnet/plagioclase phase boundary and rapid subsidence upon going back to the garnet stability field. In fact, basins with high stretching factors sometimes show such rapid uplift and subsidence events which 'conventional' models often fail to explain.
We take these insights as motivation to formulate a more advanced basin inversion model. This model is based an a dynamic deformation solver that accounts for viscous and elastic deformation and a temperature solver. Given the fully dynamic formulation of the model, we will be able to account for active rifting events, predict the stress state of the basin and consequently its dynamic pressure solution – which is essential for a more consistent implementation of metamorphic reactions. Furthermore, dynamic basin models have less input parameters which makes the inverse problem better constrained. This results in the situation that the dynamic basin models have the potential virtue of being more consistent, being able to account for the dynamics of coupled geodynamic and metamorphic processes and of having their inverse models better constrained. The back side of this development is that the key input parameters (e.g. rheology, chemical composition of the crust and mantle, thermodynamic parameters) are not very well known. However, here we show the first results of our work on dynamic basin inversion models. These results are promising and suggest that dynamic basin inversion is feasible.

INVITED

Nonlinear inverse problems and model space search

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Science is driven by the feedback between predictions and observations. In the Earth Sciences observations are nearly always indirect, since measurements are often made on or above the surface, and an 'inverse' problem exists in extracting information about structure and processes at depth. For more than 35 years inverse problems have been studied within the geosciences. Linear inverse problems arise when the mathematical relationship between data and unknowns is linear, and these were well understood by the mid 1970s. Unfortunately many areas of the geosciences give rise to nonlinear inverse problems, and in this case approximations must be introduced in order to use linear methods. As computational resources have increased fully nonlinear techniques have become viable in many cases. Interestingly enough the origins of fully nonlinear inversion techniques can be traced back to the very earliest days of geophysical inversion in the late 1960s.

This tutorial will provide an introduction to inverse problems and trace some of the major developments. Particular attention will be paid to fully nonlinear model space search techniques that are becoming increasingly popular today. One aspect of direct search algorithms is that they lend themselves naturally to parallel computing, which itself is becoming widely available. The lecture will conclude with a description of some recent computational tools that make model space search algorithms relative easy to use in parallel computing environments.

Oscillatory vs. stagnant plumes in the Earth's lower mantle

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Mass balance considerations based on chondrites compositions as well as the observed anticorrelation between bulk sound and shear wave velocities suggest that a significant part of the deep mantle is enriched in Si and Fe, relative to the bulk mantle composition. The presence of these compositional heterogeneities may have a first order impact on the dynamics of ascending mantle plumes through their induced chemical density contrast $\Delta\rho_\chi/\rho$ at ambient temperature and at a given pressure, with respect to the surrounding mantle. By considering an assemblage of lower mantle phases (Mg,Fe)SiO_3 perovskite and (Mg,Fe)O magnesiowüstite one can show, using mineral physics data and thermodynamic considerations, that $\Delta\rho_\chi/\rho$ may significantly vary with pressure in the lower mantle (up to 200% variation), depending on the Si and Fe enrichment considered for chemically distinct material.

We therefore present a study of the coupled effects of mineralogy and pressure on the dynamics of axisymmetric thermochemical plumes in the lower mantle, using both high resolution numerical experiments and simple analytical theory.

Our results show that depending on the composition, the effect of pressure can be considerable: (1) For relatively low Si enrichment, $\Delta\rho_\chi/\rho$ is fairly constant with pressure and an oscillatory behavior of the plume head is observed, similar to previous laboratory experiments [*Davaille, 1999*] but without the need of large volume of chemically distinct material. (2) For Si-enriched compositions with respect to a reference pyrolitic mantle, the chemical density excess increases significantly with decreasing pressure implying the presence of large volume, stagnant plume heads at a level of neutral buoyancy at various possible lower mantle depths.

These results imply that, although thermochemical plumes can fully develop and rise towards the surface, their ascent may be impeded by the chemical density excess and its increase with decreasing pressure. As a consequence, these thermochemical plumes may display broad ($\sim$ 1200 km wide) negative seismic velocity anomalies in the mid-mantle which can be associated with upwellings but also with downwellings or vertically stagnant flows. The implications on heat flow budget will also be discussed.

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INVITED

Lithospheric dynamics - can plate cooling and shrinkage explain everything?

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Plate tectonics provides an efficient means for the Earth to shed its excess radiogenic heat. Plates, created at the seafloor spreading ridges are driven across the slippery asthenosphere by a combination of gravitational sliding force and pull from the negatively-buoyant subducted slabs. Cooling and contraction of the plates with increasing seafloor age produces an array tectonic signals ranging from the well documented to the mysterious. Here we will review the effects of plate cooling beginning with the most obvious expressions and ending with predictions, uncertainties, and questions.

Obvious signatures of the cooling lithosphere

The most obvious signals of lithospheric cooling appear in measurements of heat flow, depth, geoid height, and surface wave velocity and they are best understood in terms of conductive cooling models. Heat flow is a measure of surface temperature gradient and is most sensitive to shallow thermal structure. Unfortunately, conductive heat flow versus age data do not confirm the cooling models because much of the heat is advected by hydrothermal circulation near the ridge axes (Hofmeister and Criss, 2005; Pollack et al., 1993). Seafloor depth reflects the integrated heat loss from cooling. The depth vs. age signal dominates the topography of the ocean basins and provides a firm foundation for plate tectonic theory (Parsons and Sclater, 1977). Geoid height mainly reflects the temperatures at the base of the lithosphere (Haxby and Turcotte, 1978). Unfortunately the lithospheric signal is masked by contributions from deeper in the mantle. Similarly velocities derived from surface waves reflect lithospheric cooling although there is uncertainty in mapping from velocity to temperature (Ritzwoller et al., 2004). Combined, these data sets provide a definitive picture of the bulk cooling and volumetric contraction of the lithosphere with age.

Problem 1. Use Fourier's law, energy conservation, and isostasy to derive the following expression relating the increase in seafloor depth with age $\partial d/\partial t$ to difference between the surface heat flow and the into the bottom of the lithosphere $(q_s - q_\infty)$

$$\frac{\partial d}{\partial t} = \frac{\alpha}{C_p(\rho_m - \rho_w)}(q_s - q_\infty)$$

where α is the volumetric coefficient of thermal expansion, C_p is the heat capacity and $(\rho_m - \rho_w)$ is the density difference between mantle and seawater (Doin and Fleitout, 1996; Parsons and McKenzie, 1978). We use topography and age grids to map this heat flow globally to reveal where the Earth's heat engine is most efficient.

Inferred signatures of the cooling lithosphere

The lithospheric cooling model makes a number of predictions that have been, or could be, tested experimentally including the relationship between swell-push force and geoid height and the thickening and strengthening of the plates with age.

Problem 2. Using isostasy and a long-wavelength approximation to the geoid, derive the model- independent relationship between swell-push force F_s and geoid height N

$$F_s = \frac{g^2}{2\pi G}N$$

where G is the gravitational constant and g is the acceleration of gravity (Parsons and Richter, 1980). How does geoid height, and thus swell-push force, increase with seafloor age?

Taken at face value, this equation suggests that measurements of geoid height could provide global, model-independent measurements of global lithospheric stress. However, this mapping is a miserable failure and we discuss the many assumptions needed to provide results consistent with the few existing stress data.

The thickening and strengthening of the plates with age is predicted by combining lithospheric cooling models with ductile flow laws and Byerlee's law. These models are confirmed by analyzing the gravity and topography at seamounts as well and bending of the plates at subduction (Watts, 2001).

Problem 3. (a) Using a triangular shape for the lithospheric yield strength envelope show that the saturation bending moment is related to the age of the lithosphere to the 3/2 power. (b) Show that the observed bending moment at a trench/outer rise can be simply measured using the expression

$$M(x_0) = g\int_0^\infty \rho w(x)(x - x_0)dx$$

where $\rho w(x)$ is the topographic load and $(x - x_0)$ is the moment arm (McNutt and Menard, 1982). How can these ideas be used to bound lithospheric strength at subduction zones?

Mysterious signals of lithospheric contraction

How far can this cooling/shrinking model be taken? Top-down cooling and contraction of the lithosphere will lead to a thermoelastic bending moment.

Problem 4. Calculate the thermal stress that develops in a plate that is cooled uniformly from the top down (free edges) and explain why the surface of the plate is in compression while the base is in extension (Parmentier and Haxby, 1986)? What is the magnitude of this stress? Horizontal temperature gradients in the cooling lithosphere will also produce thermoelastic stress but strain rates are low. Unanswered questions include: Are transform faults thermal contraction cracks (Turcotte, 1974)? Are gravity lineaments warps and cracks in cooling plate (Gans et al., 2003)? How do we determine if a volcanic ridge is a crack in the shrinking plate or a hole from edifice above a hot plume?

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INVITED

Numerical modeling of chemical heterogeneities in the Earth's mantle

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Convective flows govern much of the dynamics of the Earth. Examples of such flows are convection in the Earth's mantle, convection in magma chambers and much of the dynamics of the world oceans. Nowadays these time-dependent flows are often studied by means of three dimensional (3D) numerical models which solve the equations for the transport of heat and momentum alternatingly. These flows are often driven by a temperature difference. But for many flows there is also an active or passive chemical component that has to be considered. One characteristics of these flows is that the chemical diffusivity is very small. Implementing such a chemical field with a very low diffusivity into a numerical model using a field approach is difficult due to numerical diffusion introduced by the Eulerian schemes. Using Lagrangian tracers is also difficult in 3D flow since a massive amount of tracers is needed. A third class of algorithms are front-tracking methods where the the interface between two chemical distinct reservoirs calculated. Another class of algorithms are the mixed Eulerian-Lagrangian methods like the Level-Set methods. In my talk I will give an overview on the different methods highlighting their advantages and disadvantages.

What is the cause for trench roll back?

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Trench rollback is observed for various subduction zones, but quantitatively not well understood. We start with the hypothesis that subducting slabs attached to a large plate encounter a larger viscous resistance (mantle drag) compared to cases with smaller plates. Given a constant subduction velocity, this resistance may be reduced by enhanced rollback. Thus slabs attached to large plates should be associated with fast rollback. A similar hypothesis may be postulated with respect to different dip angles. To quantitatively test these hypotheses we apply the Helmholtz minimization principle: we numerically determine that rollback velocity which minimizes the dissipation rate within the mantle surrounding a subducting slab with a given geometry and subduction rate. The resulting predictions for the rollback velocity normalized by the plate velocity are in surprisingly good agreement with fully dynamical subduction models of lithospheric plates and with the retreat of the Tonga trench. This agreement suggests that mantle flow is more important for trench retreat than the deformation and bending behaviour of the subducting lithosphere.

Buckling of elastic layers: wavelength selection, strain rate dependency, and post-shortening coarsening

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Folding of layered rocks is one of the primary mechanisms that accommodate shortening. Despite the importance of elastic layer buckling in viscous media, from small scale folding to subducting slabs, the available analytical theories present us expressions that contain unknowns, namely σ_{xx}, the layer parallel driving stress. σ_{xx} is not a constant as it evolves during the shortening and buckling of elastic layers; as a thought experiment one can refer to an elastic spring that gets progressively shortened. Motivated by analogue experiments, where condoms were subjected to pure shear shortening in a PDMS matrix, we present a new analytical theory that accounts for the evolution of folds in elastic layers, from the initial to the large strain states.

We show that the dominant wavelength in elastic layer buckling is a function of the shortening rate, $\dot{\varepsilon}$, and give an explanation for the locking amplitude, where the dominant wavelength selection freezes. In addition, we present the phenomenon of post-shortening folding where the amplitudes and wavelengths increase during a stage of stress relaxation. Based on mathematical similarities we establish the relationship between the observed fold coarsening and classical coarsening mechanisms such as Ostwald ripening. Our results imply that folded elastic layers cannot be considered static but evolve with time, are more dynamic than previously anticipated, and are sensitive to the rate at which the system is driven.

Shallow low-viscous earth layers in flat 3D finite-element models of glacial isostatic adjustment

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In recent papers (van der Wal et al. 2004, Schotman & Vermeersen 2005) we have shown the effect of crustal and asthenospheric layers with low viscosity on gravity field perturbations as predicted by models of glacial isostatic adjustment, and compared these to the expected performance of the satellite gravity mission GOCE (Visser et al. 2002) and the realized performance of GRACE (GGM02S, Tapley et al. 2005). In these studies, we used a semi-analytical viscoelastic relaxation model (Vermeersen & Sabadini 1997) based on the normal-mode formalism (Peltier 1974, Wu & Peltier 1982).

The spectral model is very fast and accurate, but does not allow for lateral variations in the properties of the earth layers. Therefore we use a finite-element (FE) model based on the commercially available software package ABAQUS. As we are interested in the short-wavelength gravity field (up to harmonic degree 250 or spatial scales down to 80 km), the use of spherical 3D FE models (see e.g. Wu et al. 2005) is not yet feasible. We therefore use a flat 3D model that can be applied to loads as large as the Laurentide ice sheet (Wu 2005).

We compute gravity potential perturbations by solving Laplace's equation, as described for a spherical model by Wu (2004). For a flat model, we perform a 2D Fourier transform and solve Laplace's equation in the spectral domain, using the computed displacements as boundary conditions. In future studies this method can be used to include self-gravitation in the earth and ocean.

We benchmark the FE model with our spectral model for gravity field perturbations and 3D velocities. We show for an axisymmetric parabolic ice load that the accuracy of computed radial velocities is high, but that horizontal velocities are less accurate. Furthermore, geoid heights can be computed accurately underneath and just outside the load.

We shortly review the characteristics of flow induced by shallow low-viscous earth layers, using relaxation times and strengths and the concept of channel versus whole-mantle flow (Cathles 1975). Upon including a low-viscous layer, the accuracy of the perturbations in geoid height deteriorates underneath the load. Finally, we show the effect of lateral heterogeneities on geoid heights.

In future studies, we will use the flat 3D FE model, available recently developed ice-load histories and estimates of shallow earth viscosities from seismic data, to compute realistic gravity field perturbations and confront these with satellite gravity data.

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Rheology and the Porcupine Basin

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Rheology is the study of the relationship between stress, deformation and flow. This relationship can be described mathematically using the continuity, momentum and energy equations. Additionally an equation to relate stress to strain or stress to strain rate is required. This equation is referred to as the constitutive equation. It is usually defined empirically and is chosen to fit the particular problem under consideration. Due to the computationally difficult nature of these equations analytic solutions are currently impossible. Numerical methods are employed in conjunction with several approximations. These range from the Boussinesq approximation, setting certain parameters constant and restricting the flow under consideration to two dimensions to take advantage of stream function methods.

The Porcupine basin is located offshore to the southwest of Ireland in the North Atlantic. It is a deep water sedimentary basin. Recently acquired seismic data in this basin has highlighted some surprising results. The basin has shown a highly asymmetrical crustal thickness variation. The crust is severely stretched or completely attenuated in certain regions. These results cast doubt on the model of pure shear extension as the primary mechanism for the formation of the Porcupine basin. These seismic profiles have also highlighted evidence for substantial serpentinisation within the subcrustal mantle which may have a significant effect on the mode of extension.

Making use of current advances in computing power and methods, especially parallel and grid computing techniques, it is intended to use the aforementioned equations to investigate the influence of serpentinisation on the basin formation.

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How to make the Andes?

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The Andes, the world's second highest orogenic belt after Tibet, were generated by the Cenozoic tectonic shortening of the South America (SA) plate margin overriding the subducting Nazca plate. Using a 2D coupled thermo-mechanical numerical modeling of dynamic interaction between subducting and overriding plates we search for factors controlling the intensity of the tectonic shortening.

We employ a parallel thermo-mechanical finite element/finite difference code LAPEX (LAgrangean Particle EXplicit) which combines the explicit lagrangian algorithm FLAC with the particle-in-cell technique. Particles track material properties and full stress tensor minimizing numerical diffusion related to remeshing. The method allows employing realistic temperature- and stress-dependent visco-elastic rheology combined with Mohr- Coulomb plasticity. A number of versions of the LAPEX code are developed and extensively used in geodynamic modeling in our Group in Potsdam: 2D version (Babeyko and Sobolev, 2005; Sobolev and Babeyko, 2005), extended 2D version (Sobolev et al., 2005) and 3D version (Petrunin and Sobolev, 2005).

From the numerical modeling constrained by geological and geophysical observations we infer that the most important factor for the tectonic shortening in the Andes was fast and accelerating westward drift of the SA plate, while large changes in the subduction rate were not as important. Other important factors are crustal structure of the overriding plate and shear coupling at the plates interface. The model with thick (40-45 km at 30 Ma) SA crust and relatively high friction coefficient (0.05) at the Nazca-SA interface generates more than 300 km of tectonic shortening during 30-35 Myr and replicates well crustal structure and evolution of the high Central Andes. The model with the initially thinner (less than 40 km) continental crust and lower friction coefficient (less than 0.015) results in less than 50 km of the SA shortening, replicating situation in the Southern Andes. Our model predicts that down-dip limit of the frictional coupling domain between Nazca and South America plates should be by ca 10-20 km deeper in the Southern Andes (south of 28S) than in the high Central Andes. This prediction is consistent with the GPS and seismological observations. Another model prediction is anti-correlation of the magmatic arc activity and rate of regional tectonic shortening, which also seems to be supported by observations.

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Global P velocity models and resolution analyses: increasing grid density

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We have quantified the fictitious coupling (trade-off) existing between the voxels of global tomographic images of P-velocity in the Earth's mantle (data from ISC bulletins). We have repeated this exercise for three different voxel-sizes and have analyzed the resolution of the different models so obtained. The result is that the quality and the coverage of our data set allows us to resolve seismic structures as small as 3° at least in some portions of the mantle. By means of a comparison with some recently published P-wave and S-wave models, we have verified that our 3° voxel model (VOX3P05) is effective in imaging large scale as well as small 'plume-like' seismic anomalies. Due to the choice of a proper regularization scheme (by means of the L-curve criterion), VOX3P05 is characterized by more pronounced velocity anomalies at the base of the mantle, where other models tend to be weaker. Since, due to the differences in data sampling, the model resolution can be quite variable throughout the mantle, the associated analysis of the resolution matrix is an indispensable tool to provide estimates of the reliability of our interpretations of the imaged seismic anomalies.

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Melting and compaction in deformable two-phase media

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Melt generation and extraction are often modeled using the two-phase equations developed by McKenzie (1984) or Scott & Stevenson (1984). Usually various approximations are made to simplify the problem which may lead to some unphysical results. We present a generalized version of the set of equations introduced by Bercovici *et al.* (2001) that allows for mass transfer between the two phases and consider a self-consistent set of equations. In our description the two phases are submitted to different pressure fields whose difference is related to the surface tension at the interfaces, to the changes in porosity and to the melting rate. A kinetic relation for the melting rate arises from the second law of thermodynamics. The condition of chemical equilibrium corresponds to the usual univariant equality of the chemical potentials of each phase when the matrix and melt are motionless. In the most general form, the Gibbs-Thomson effect comes out naturally from thermodynamic equilibrium considerations. We apply these new equations to a steady state problem of pressure release of a univariant system. We treat melting and compaction simultaneously and we observe several new effects and several possible boundary layers near the onset of melting. A consequence of matrix compaction (dilation) is a pressure difference between melt and solid which favors (inhibits) melting. Melting is favored when the extraction of melt from the matrix is efficient, *i.e.* when the Darcy velocity is larger then the initial upwelling velocity of the solid matrix. For parameters corresponding to pressure release melting under mid ocean ridges melting is favored and could start at most ~ 2 km below the standard solidus. Numerical results suggest that the movement of melt and matrix should be close to the Darcy equilibrium where the buoyancy of melt is equilibrated by the mechanical interaction between the phases. The Darcy equilibrium follows an initial stage where the matrix viscous stresses balance the Darcy friction. In all situations the steady state porosity profile remains a monotonous function of depth. The existence of a compaction layer following a melting zone where the porosity is maximum as described in various earlier publications has never been found.

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Numerical simulation of mantle convection: 3D, spherical shell, temperature- and pressure-dependent viscosity

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The style of convection in planetary mantles is presumably dominated by the strong dependence of the viscosity of the mantle material on temperature and pressure. While several efforts have been undertaken in cartesian geometry to investigate convection in media with strong temperature dependent viscosity, spherical models are still in their infancy and still limited to modest parameters. Spectral approaches are usually employed for spherical convection models which do not allow to take into account lateral variations, like temperature dependent viscosity. We have developed a scheme, based on a finite volume discretization, to treat convection in a spherical shell with strong temperature dependent viscosity. Our approach has been particularly tailored to run efficiently on parallel computers. The spherical shell is topologically divided into six cubes. The equations are formulated in primitive variables, and are treated in the cartesian cubes. In order to ensure mass conservation a SIMPLER pressure correction procedure is applied and to handle strong viscosity variations up to $\Delta\eta = 10^6$ and high Rayleigh-numbers up to $Ra = 10^8$ the pressure correction algorithm is combined with a pressure weighted interpolation method to satisfy the incompressibility condition and to avoid oscillations.

We study thermal convection in a basal and mixed-mode heated shell with stress free and isothermal boundary conditions, as a function of the Rayleigh-number and viscosity contrast. Besides the temperature dependence we have further explored the effects of pressure on the viscosity. As a general result we observe the existence of three regimes (mobile, sluggish and stagnant lid), characterized by the type of surface motion. Laterally averaged depth-profiles of velocity, temperature and viscosity exhibit significant deviations from the isoviscous case. As compared to cartesian geometries, convection in a spherical shell possesses strong memory for the initial state. At strong temperature dependent viscosity ($\Delta\eta = 10^4 - 10^6$) typically a few upwelling plume structures develop. The large scale structure of the plume stays intact over a long time while the plume geometry varies on a smaller scale. The downflows are generally organized in two-dimensional sheetlike flows. Additional pressure dependence strongly influences the dynamics even if the magnitude of pressure variation is relatively small. For an appropriate combination of pressure- and temperature-dependence, we observe a well developed high-viscosity zone in the lower mantle.

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Holocene sea-level changes in the Mediterranean: the role of remote and near-field ice sheets

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The sea-level change attributed to the melting of continental glaciers is the result of global eustatic, local glacio-hydro-isostatic and geoidal contributions. The relative importance of each factor depends upon the distance between the investigated site and the ice-sheet loading centres, and from the details of the load time-history. The global solution of the sea-level equation (Clark, 1980) evidences six zones on the Earth' surface showing characteristic post-glacial relative sea-level curves. In the present work we solved the sea-level equation for a spherically symmetric visco-elastic Earth through a pseudo-spectral algorithm to investigate the effective presence of different zones of Clark in the Mediterranean Sea. At first we have implemented the complex ICE1 and ICE3G models and we have compared the relative sea-level predictions of the two models at various times. Successively the effects of their single main ice aggregates (Fennoscandia, Laurentide and Anctartica) have been studied comparing the results to the sea-levels predicted at different times considering simple ad-hoc ice loads in order to investigate the possible presence of Holocene sea-level high-stands (Zone V and Zone VI) in the Mediterranean Sea. The predicted sea-level curves have been also evaluated relatively to the sea-level observations available along the Mediterranean coasts.

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Spectral-finite element approach to present-time mantle convection

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We present a spectral-finite element approach to the forward modelling of present-time mantle convection. The differential Stokes problem for an incompressible viscous flow in a spherical shell is reformulated in weak sense by means of a variational principle. The integral equations obtained are then parametrized by vector and tensor spherical harmonics in the angular direction and by piecewise linear finite elements over the radial direction. The solution is obtained using the Galerkin method, that leads to the solution of a system of linear algebraic equations. The earth-viscosity structure is described using a two-dimensional spherical grid, that allows us to treat various kinds of lateral variation, with viscosity contrasts of several order of magnitude.

The method is first tested for the case of a one-dimensional viscosity structure. After prescribing the internal load in the form of a Dirac-delta, Green's functions for the surface topography, core topography and geoid are computed and compared with those obtained by solving the problem with the traditional matrix propagator technique.

The approach is then applied to two different axisymmetric viscosity structures consisting either of one or two highly viscous cratonic bodies embedded in the upper mantle. We compute the corresponding Green's functions, showing and discussing the non-linear coupling of various spherical-harmonic modes, and the resulting angular dependence of the flow velocity.

Numerical inversion and modeling of 1993-97 GPS data at Mount Etna, Italy

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Since 1993 geodetic data obtained by different techniques (GPS, EDM, SAR, leveling) detected a consistent inflation of the Mount Etna volcano. The inflation, culminated with the 1998-2001 strong explosive activity from summit craters and recent 2001 and 2002 flank eruptions, may be interpreted by magma ascent and re-filling of the volcanic plumbing system and reservoirs. Our purpose is to model the 1993-97 GPS data by pressurized sources simulating the magma reservoir using a 3D Finite Element modeling coupled to a Monte Carlo inversion. The power of this technique, if compared with analytical inversions, is that sources can be placed in complex media (heterogeneous, with topography, inelastic etc.) so that the inversion result is not influenced by the usual approximations of elastic, homogeneous half-space.

The FE model of Mt. Etna is characterized by a regular mesh below the volcanic edifice, and by arbitrarily distorted brick elements elsewhere. The potential point sources are contained in a volume of 64 km^3, subdivided into $10\times10\times10$ elements, and located below the summit craters, between 3 km and 7 km b.s.l.. Source parameters are obtained as a linear combination of the 6 solutions (one for each stress component) computed for each of the 1000 potential sources at the GPS observation points. The best fitting source search is performed by the Neighbourhood Algorithm inversion technique.

Synthetic test for a spherical/ellipsoidal source show a best-fit model with a χ^2 misfit as low as 0.1. The method is then applied to find the best source responsible for the 1993-97 GPS deformation. We consider four classes of models characterized by: i) homogeneous medium and flat free surface; ii) homogeneous medium with topography of Mt.Etna; iii) heterogeneous medium with flat free surface; iv) heterogeneous medium with topography. Solutions are compared also with those derived by inversions of analytical forward models in the homogeneous medium with flat free surface, showing good agreement. Differences in source parameters arising from the characteristics of the medium are also discussed.

On the viability and style of subduction in a hotter Earth

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The tectonic regime of the early Earth remains an unresolved issue. The uncertainty in the actual mantle temperature through time, and the associated increased buoyancy of the differentiated oceanic lithosphere contributes to the ongoing debate about the viability, effectiveness and presence of the modern plate tectonic mechanism in a younger Earth: today, plate tectonics are the main characteristics of geodynamics, but a hotter Precambrian mantle resulted at first sight in conditions unfavorable for plate tectonics. More compositional buoyancy and less lithospheric strength in the early period of the Earth limit the applicability of the present-day subduction process. Our numerical modeling experiments provide the first quantitative results on this subject. The overall conclusions from those calculations are that modern-style subduction remains essentially the same in a mantle which is up to 100 K hotter than today. In an even hotter mantle, crustal delamination and detachment alter the appearance of subduction, and in some cases completely blocks it.

Model parameter analysis shows that: i) a large lithospheric yield strength reduces plate velocities for mantle temperatures up to 100 K hotter than today, but can improve the effectiveness of plate tectonics in a hotter Earth, because it suppresses slab detachment. Significant mantle dehydration during more extensive melting in the hotter Earth is expected to have a similar effect. ii) Deep decoupling of converging plates is either achieved by a weak mantle wedge or weak oceanic crust. In the latter case, delamination of the thick crust in a hotter Precambrian mantle will hamper subduction significantly. iii) Heat flow analysis puts a constraint on the style of tectonics in a hotter Earth: tectonic plates had to be on average about 3 to 7 times younger than today in order to allow enough cooling. iv) A modest amount of fault friction (around 50 MPa) stabilizes the subduction process under hot mantle conditions and makes plate tectonics more viable. More friction, however, slows down the plate so much that it cannot effectively cool the Earth anymore. v) Slow eclogitization kinetics will hamper the subduction process for a thick crust in a hotter mantle. Whereas complete transformation within 1 Ma is still fast enough, 5 Ma makes plate tectonics too slow to efficiently cool the early Earth.

Composition-dependent viscosity in evolutionary models of thermo-chemical mantle convection

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Several lines of seismological and geochemical evidence hint at the existence of compositional heterogeneity in the lowermost mantle of the Earth (e.g. (Van der Hilst and Karason, 1999), (Saltzer e.a., 2004), (Hofmann, 1997)). One of the existing models that include chemical heterogeneity is a global continuous reservoir in the deep lower mantle and with a surface that develops substantial topography (Kellogg e.a., 1999). Long-term survival occurs when a compositional buoyancy force balances or exceeds the thermal buoyancy force that acts on the deep reservoir. The presence of such a reservoir affects the convection regime of the mantle and, in addition, it thermally insulates the core. Because of the anomalous composition, its physical properties may differ from those of the background mantle. Unfortunately, there are many uncertainties concerning the composition-dependence of those properties, and concerning the composition of the deep reservoir itself. In this study, the effects of composition-dependent viscosity on the evolution of the mantle and core are explored in a systematic parameter test.

We apply a thermo-chemical mantle convection model in the extended Boussinesq approximation. A finite element method was used to solve the convection equations, where the composition field is described by Lagrangian tracer particles and a Particle-in-Cell representation. The models are of 2-D cylindrical geometry and cover a time window of 4.5 Gyr. Two mineral phase transitions at 410 and 660 km depth were included and a thermal coupling model with the core allows us to study the cooling evolution of the core.

The results show that when viscosity in the deep mantle reservoir is decreased, heat transfer by means of convective motion is increased in the lowermost mantle. As a result, more heat is extracted from the core, leading to higher rates of core cooling. Also, heat inside the deep reservoir is lost relatively easily to the overlying mid-mantle so that its excess temperature is kept relatively low. In this way, the reservoir's positive thermal buoyancy is effectively reduced, leading to a more stable deep mantle reservoir.

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The transient nature of mantle plumes

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The morphology of convective features in the Earth's mantle is still heavily debated. Classical Rayleigh-Bénard convection at high Rayleigh numbers (typically $> 10^6$ as the whole mantle) in an homogeneous fluid produces "plumes", which are mushroom-shaped 3-D ephemeral structures. It has been proposed that "hotspots" (Wilson 1963) were created by mantle plumes originating from a deep thermal boundary layer (Morgan 1971). While this simple model does well explain the characteristics of a number of hotspots (Hawaii, La Réunion, Louisville…), an increasing number of observations on other hotspots cannot be explained in this framework.

My intention is to investigate and understand mantle plume dynamics consistently with fluid mechanic constraints. The aim of the experiments carried out in our laboratory is to study the characteristics of plumes: morphology, geometry, height, duration, temperature anomaly, velocity field. Our experiments focus on the temperature and velocity fields. The fluid is a Newtonian, incompressible, thermoviscous sugar syrup, which is seeded with two kinds of particles. First thermo-liquid crystals allow us the see the thermal structure of the plume. Then, microscopic hollow glass spheres brighten as tracers of the motion in the fluid. Hence we get information about the temperature and the dynamics of the convection.

The simplest case is a plume issued from a punctual heat source (source of buoyancy). We will compare the results with the analytical scaling laws. Then we will try to determine to what extent those scalings laws derived from an isolated plume can be valid for instabilities from a thermal boundary layer.

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S velocity reversal in the mantle transition zone

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Mantle transition zone in a depth range of 400 -700 km is remarkable by high P and S velocity gradients that are caused by a series of phase transitions. However, we demonstrate seismic evidence for the S velocity reversal starting at a depth around 500 km, found by applying S receiver function techniques in several regions. S velocity reduction is in a range of 0.15 - 0.2 km/s. The lower boundary of the anomalous layer is not detected, perhaps owing to a reduced sensitivity of the method at larger depths. As documented by seismic tomography, S velocity in the transition zone close to the regions with the detected S velocity reversal is anomalously low compared to the world average, and some regions correspond to prominent hotspots. We argue that the low velocity is, most likely, caused by transformational plasticity corresponding to the phase transition from β to γ spinel at a depth around 520 km.

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