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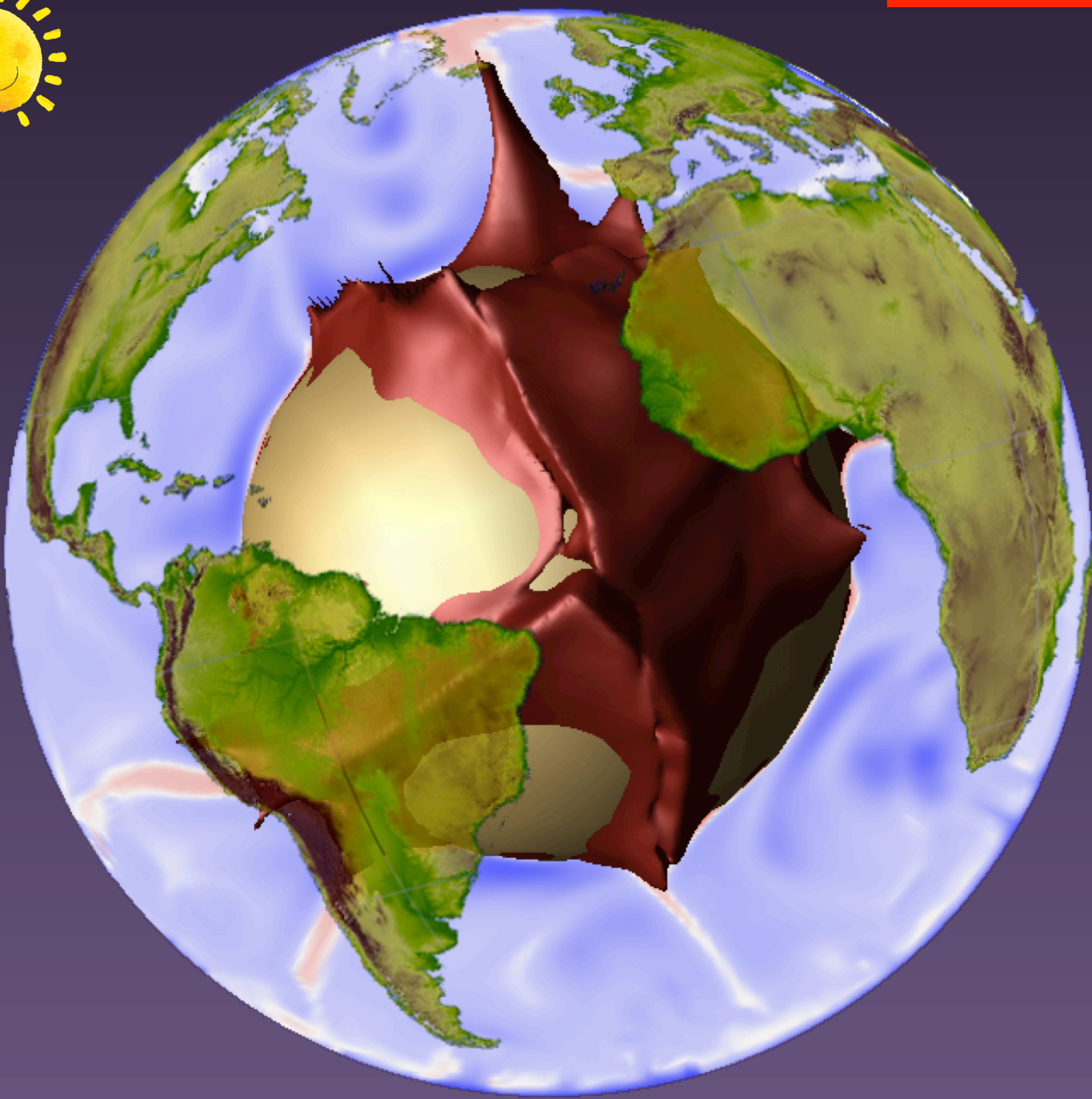

XIII International Workshop on Modelling of Mantle and Lithosphere Dynamics

August 31 – September 5, 2013, Hønefoss, Norway

Scientific Program and Abstracts

European Geosciences Union

Research Council of Norway

European Research Council

Centre for Earth Evolution and Dynamics

University of Oslo

International Association of Seismology and Physics of the Earth's Interior

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XIII International Workshop on Modelling Mantle and Lithosphere Dynamics
Hønefoss, Norway, August 31 – September 5, 2013

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For more information, please contact:

Organizing Committee
XIII International Workshop on Modelling of Mantle and Lithosphere Dynamics
c/o Dr. Stephanie C. Werner
Centre for Earth Evolution and Dynamics (CEED)
University of Oslo
PO Box 1047, Blindern
0316 Oslo, Norway
Phone: +47 2285 6472
E-mail: stephanie.werner@fys.uio.no

Editors: Trond H. Torsvik, Pavel V. Doubrovine, Abigail L. Bull-Aller, Stephanie C. Werner, and Susanne Buiter

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Contents

Dear Participant,

We would like to welcome you to the XIII International Workshop on Modelling of Mantle and Lithosphere Dynamics, this time held in Hønefoss, Norway!

The advent of the theory of plate tectonics in the mid-late 1960s established that most near-surface geological phenomena such as earthquakes, volcanoes, and mountain belts can be understood in the context of a model of interacting surface plates. The theory was extremely successful in providing a framework for understanding deformation and volcanism at plate boundaries, and allowed us to recognize that continent motions through time are a natural result of heat escaping from Earth's deep interior. However, our understanding of the Earth as a dynamic system has largely been limited to detailed kinematics of plate motions, leaving the nature of the driving forces in the interior as a puzzle. In the last two decades, three-dimensional (3D) seismic imaging of the Earth's interior has achieved breakthrough advances, revealing fundamental geodynamic processes of convective motion throughout the Earth's mantle and core. Because these deep dynamic processes take place over time-scales and at depths that are beyond direct observations, numerical modelling became a prime tool for studying Earth evolution and dynamics.

Numerical models are currently used to study processes at a range of spatial scales related to extension, continental break-up, and the formation of mid-ocean ridges, subduction processes, orogenesis, mantle circulation, plume dynamics, and core dynamo processes. A major computational challenge arises because the models that we need are intrinsically 3D, exhibit a complex structure, involve non-linear materials, and operate on a wide range of spatial and temporal scales. Models that focus on dynamics of the crust and lithosphere face additional numerical challenges related to accurately resolving large contrasts in viscosity that may occur across shear zones and between lithosphere and asthenosphere, the requirement of a stress-free top surface, and the ability to achieve large deformations including offsets on shear zones. In addition, new avenues are opening up as the field of numerical Earth Sciences increasingly incorporates new knowledge from neighbouring disciplines such as mineral physics, geomorphology, and seismology. These add further complexity to the already complex non-linear numerical simulations.

To discuss numerical techniques, investigate exciting new avenues, foster collaboration, and introduce students to the interesting challenges of mantle and lithosphere modelling, the numerical Earth Sciences community meets every two years at the International Workshops on Modelling of Mantle and Lithosphere Dynamics held in various European countries. The workshop series started in 1987 in Neustadt an der Weinstrasse, Germany. Previous meetings have taken place in Germany, France, the Netherlands, Czech Republic, Italy and Switzerland. Now it is time for Norway.

In 2011, the series became a part of the European Geosciences Union (EGU) Thematic Meetings Series. The thirteenth workshop is also co-sponsored by the European Research Council (ERC), the Norwegian Research Council (NFR), the Centre for the Earth Evolution and Dynamics (CEED, University of Oslo), and the International Association of Seismology and Physics of the Earth's Interior (IASPEI).

I hope you will have an inspirational and fruitful meeting!

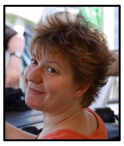
On behalf of the organizing committee,

Trond Helge Torsvik

Organizing Committee

Local Organizing Committee

Trond H. Torsvik
University of Oslo, Norway



Stephanie C. Werner
University of Oslo, Norway

Susanne Buiter
Geological Survey of Norway and University of Oslo, Norway

Pavel V. Doubrovine,
University of Oslo, Norway

Abigail L. Bull-Aller
University of Oslo, Norway

Marcin Dabrowski
University of Oslo, Norway

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Doris Breuer
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Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway, *www.mn.uio.no/ceed*

International Association of Seismology and Physics of the Earth's Interior (IASPEI), *www.iaspei.org*

Program

Saturday, August 31. Arrival and Check-in

16:00 Arrival and check-in

19:00 Ice breaker reception followed by the conference dinner

Sunday, September 1. Subduction and Plume Dynamics, Numerical Techniques I

09:00 Welcome: **Trond Torsvik**

Subduction and Plume Dynamics 1 (SPD-1), *Chair:* ***Trond Torsvik***

09:05 Plume Generation and Migration: **Eh Tan**

10:05 Seismic Observations of Subduction Zones and Implications for Modelling, Hydration, and Volcanism: **Ellen Syracuse**

11:05 *Coffee break*

Numerical Techniques 1 (NT-1), *Chair:* ***Stephanie Werner***

11:30 Adding Complexity – Magnetohydrodynamics: **Mats Carlsson**

12:30 *Lunch*

14:00 Short presentation of posters (PS-1), *Chair:* ***Marcin Dabrowski***

14:45 Meeting of students with day's lecturers

15:30 *Coffee Break*

16:00 Poster Session 1 (PS-1): Numerical Techniques; Subduction and Plume Dynamics

18:00 Geology of Oslo area: **Bjørn-Tore Larsen**

18:30 General discussions, *moderated by* ***Boris Kaus*** *and* ***Paul Tackley***

20:00 *Dinner*

Monday, September 2. Numerical Techniques II

Numerical Techniques 2 (NT-2), *Chair: **Abigail Bull-Aller***

09:00 Building Simulation Software for the Next Decade – Trends and Tools: **Hans Petter Langtangen**

10:00 ASPECT - Challenges and Solutions: **Thomas Geenen**

11:00 *Coffee break*

11:30 Meeting of students with day's lecturers

12:30 *Lunch*

13:30 Geological Excursion (bus): **Bjørn-Tore Larsen**

20:00 *Dinner*

Tuesday, September 3. Linking Surface and Deep Processes

Linking Surface and Deep Processes 1 (LSD-1), *Chair: **Craig Bina***

09:00 Mineral Physics of the Dynamic Planets: **Razvan Caracas**

10:00 Mantle Structure - Temperature or Other Bulk Properties: **Karin Sigloch**

11:00 *Coffee break*

Linking Surface and Deep Processes 2 (LSD-2), *Chair: **Pavel Doubrovine***

11:30 Assimilating Lithosphere and Slab History in 4-D Dynamic Earth Models: **Dan Bower**

12:30 *Lunch*

14:00 Short presentation of posters (PS-2), *Chair: **Nicolas Flament***

14:45 Meeting of students with day's lecturers

15:30 *Coffee break*

16:00 Poster Session 2 (PS-2): Linking Surface and Deep Processes

18:00 A New Generation of Satellite Data to Study the Lithosphere: **Joerg Ebbing**

18:30 General discussions, *moderated by **Dave Stegman** and **Takashi Nakagawa***

20:00 *Dinner*

Wednesday, September 4. Dynamics of Planetary Interiors

Dynamics of Planetary Interiors 1 (DPI-1), *Chair: **Huw Davies***

09:00 Diversity of Mantle Dynamics and Evolutions: **Slava Solomatov**

10:00 Thermal Boundary Control in Models of Rotating Convection and the Geodynamo: **Christopher Davies**

11:00 *Coffee break*

Dynamics of Planetary Interiors 2 (DPI-2), *Chair: **Hana Cizkova***

11:30 Modeling Dynamic Topographies of Planetary Bodies: **Bernhard Steinberger**

12:30 *Lunch*

14:00 Short presentation of posters (PS-3), *Chair: **Wim Spakman***

14:45 Meeting of students with day's lecturers

15:30 *Coffee break*

16:00 Poster Session 3 (PS-3): Dynamics of Planetary Interiors; Multi-Scale Physics of the Crust and Lithosphere

18:30 General discussions, *moderated by **Harro Schmeling** and **Mike Gurnis***

20:00 *Dinner*

Thursday, September 5. Multi-Scale Physics of the Crust and Lithosphere

Multi-Scale Physics of the Crust and Lithosphere 1 (PCL-1), *Chair: **Susanne Buiter***

09:00 Computational Porous Media Modelling: **Hans Muhlhaus**

10:00 Plasticity and Strain Localisation in the Crust and Lithosphere Models – Numerical Aspects: **Laetitia Le Pourhiet**

11:00 *Coffee Break*

11:30 Meeting of students with day's lecturers

12:30 *Lunch*

14:00 Check-out and departure (buses to Gardermoen)

Activities

Saturday, August 31: Ice Breaker, 19:00

Monday, September 2: Geological excursion in the Oslo area, bus leaving at 13:30

List of Posters by Session

PS-1: Numerical Techniques; Subduction and Plume Dynamics

Sunday, September 1, 16:00

Agrusta et al.	Effects of Partial Melting on the Dynamic of Small-scale Convection Developing in a Plume-fed Layer Beneath a Moving Plate
Austmann and Govers	The Role of Elastic Compressibility in Dynamic Subduction Models
Bina	Comparative Buoyancy Anomalies from Metastable Minerals During Subduction
Bottrill et al.	Slab Tearing and Lateral Variation in the Exhumation of Ultra-High Pressure Terranes with Application to the Norwegian Caledonides
Čížková et al.	Effects of Realistic Material Properties on Slab Deformation in the Mantle
Cox et al.	Simulation of Mantle Convection via Novel Adaptive Finite Element Methods
Crameri and Tackley	Spontaneous Trench Migration and Mantle Flow in Self-consistent Mantle Dynamics
Dannberg and Sobolev	Modelling Type Diversity of Thermo-chemical Plumes: Asymmetry, Ponding, Finger-like Structures and Wide Tails
Fischer and Gerya	History and Evolution of Subduction in the Precambrian
Garel et al.	Quantifying the Role of Downgoing and Overriding Plates on the Deformation of Subducting Slabs within the Mantle Transition Zone: A Thermo-mechanical Modelling Approach
Gassmöller and Steinberger	Spatial Characteristics and Clustering of Hotspot Positions and Mantle Plumes: A Comparison Between Observations and Convection Models
Glerum et al.	Subduction Modelling with ASPECT
Gurnis et al.	Trench Rollback: From the Birth of Subduction to Global Plate Motions
Hassan et al.	Three Dimensional Regional Models of Mantle Plumes
Huettig et al.	A Novel and “Cheap” Pre-conditioner for Stokes-flow with Varying Viscosities
Huettig et al.	Can We Approximate Non-Newtonian Rheology?

Kaus et al.	Evolution of Earth's Early Crust: Lessons Learned from Coupled Petrological and Geodynamic Modelling
Khaleque et al.	Strongly Temperature and Pressure-dependent Viscous Convection
Lawton and Davies	Modelling Subduction Zone Magmatism due to Hydraulic Fracture
Lehmann et al.	A Discontinuous Galerkin Method for Variable-viscosity Stokes Flow
Magni et al.	Slab Dehydration in the Early Earth: Insights from Numerical Models Integrated with Thermodynamic Data
Naliboff et al.	Constraints on the Dynamics of Outer Rise Deformation: 2D Numerical Modeling of the Tonga Subduction System
Petersen et al.	Controls on Two-sided Subduction on Dry Planets
Plesa et al.	Sheet-like and Plume-like Thermal Flow in a Spherical Convection Experiment Performed under Microgravity
Stegman et al.	Sinking of Spherical Slablets Through a Non-Newtonian Mantle
Thieulot et al.	Multiphase Geodynamical Modelling Using Aspect
van Heck and Davies	Modeling Melting With Particles in Whole Mantle Convection

PS-2: Linking Surface and Deep Processes

Tuesday, September 3, 16:00

Barry et al.	Can Variations in Radial Viscosity Explain the Persistence of Indian MORB Mantle in the Shallow-most Asthenosphere over 100's Millions of Years?
Bull et al.	The Effect of Plate Motions on the Longevity of Deep Mantle Heterogeneities
Davies	Global Heat Flow Map
Flament et al.	Global Models of Mantle Flow and Lithospheric Stretching Since the Jurassic
Kaislaniemi et al.	Sub-lithospheric Small Scale Convection - A Mechanism for Continental Collision Magmatism
Li et al.	Effects of a Low Viscosity Post-perovskite on the Stability and Structures of the Primordial Dense Reservoirs in the Lower Mantle

Mulyukova el al.	Numerical Modeling of Deep Mantle Flow: Thermochemical Convection and Entrainment
Nakagawa and Tackley	A Coupled Thermo-chemical Evolution of Earth's Mantle and Core: Effects of a Three-component Mantle Dynamics
Shahraki and Schmeling	Effects of Post-perovskite Phase Change on the Observed Geoid
Steinberger et al.	Possible Links Between Subduction History, Generation of Mantle Plumes, True Polar Wander, Core-mantle Boundary Heat Flux and Core Processes
Tackley	Evolution of Mantle Convection and Plate Tectonics from a Hot/Molten Initial State on Earth and Super-Earths
Fuchs et al.	Numerical Models on Thermal and Rheological Sensitivity of Deformation Pattern at the Lithosphere-asthenosphere Boundary
Golabek et al.	Towards Coupled Giant Impact and Long Term Interior Evolution Models
Plesa et al.	How Can We Constrain the Amount of Heat Producing Elements in the Interior of Mars?
Rolf et al.	The Timescales of Continental Drift Controlled by the Strength of the Lithosphere?
Rozel and Tackley	Internal Temperature and Heat Flux in a Super-Earth
Torsvik et al.	Linking Mantle Dynamics to Plate Tectonics
Trønnes et al.	Chemical Geodynamics of the NE Atlantic and Arctic Mantle
Werner	The Earliest Evolution of Moon, Mars And Mercury - How Old Are Their Oldest Surfaces?

PS-3: Dynamics of Planetary Interiors; Multi-Scale Physics of the Crust and Lithosphere

Wednesday, September 4, 16:00

Alisic et al.	Shear Banding in a Partially Molten Mantle
Baumann et al.	Constraining the Rheology of the Lithosphere Through Joint Geodynamic and Gravity Inversion
Buiter	Numerical Models of the Response of Passive Margins to Syn-rift Surface Processes

Caron et al.	Effect of Burgers Rheology on Glacial Isostatic Adjustment Models
Dabrowski et al.	MILAMIN 2 – Fast MATLAB FEM Solver: Algorithms, Implementation and Applications
Delannoy et al.	Virtual Patterson Experiment - A Way to Access the Rheology of Aggregates and Mélanges.
Fry et al.	Depth Variable Crustal Anisotropy, Patterns of Crustal Weakness, and Destructive Earthquakes in Low-Strain Rate Areas
Gac	Control of Lithosphere Structure on Surface Deformation in the Central Barents Sea: Insights from Dynamical Modeling
Huerta and Crane	Strain Evolution and the Relative Role of Heat and Strain Rate During Continental Rupture
Kohut et al.	Formation Conditions Recorded by OH-point Defects in Quartz – Experimental and Analytical Approach
Liao and Gerya	Inheritance of Continental Rifting on Incipient Seafloor Spreading Pattern: Insights from 3D Numerical Modeling
Lourenço and Tackley	The Effect of Melting and Crustal Production on Plate Tectonics on Terrestrial Planets
Lu et al.	Strong Intracontinental Lithospheric Deformation in South China: Implications from Seismic Observations and Geodynamic Modeling
Maas et al.	Crystal Settling and Crystal Growth Caused by Ostwald Ripening in a Terrestrial Magma Ocean Under Rotation
Medvedev	Estimating Lithospheric Stresses: Parameters Check with Applications to the African Plate
Mezri et al.	Impact of Fluid-rock Interactions and Metamorphic Reactions on Rheological Evolution and Style of Rifting During Extension
Noack et al.	Relevance of Continents for Habitability and Self-consistent Formation of Continents on Early Earth
Püsök et al.	Modeling the India-Asia Collision Zone: 3D Simulations and Numerical Insights
Roy et al.	Landscape Response to Lithospheric Strain Localization
Ruh et al.	3D Deformation Patterns In Accretionary Wedges: Effects of Strain and Velocity Weakening
Schmeling et al.	Symmetric Versus Asymmetric Spreading, Rifting, and Ridge Migration: the Role of Visco-plasticity
Schroeder and Gloaguen	Modelling the Influence of Faults on a Developing River System

Tan	DynEarthSol3D: An Efficient and Flexible Unstructured Finite Element Method to Study Long-term Tectonic Deformation
Tétreault and Buiter	A Discussion of Mantle Temperatures in Numerical Studies of Rift-to-drift Extension
Trubienko et al.	Interseismic and Postseismic Deformations Associated with 2011 Magnitude 9.0 Tohoku-Oki Earthquake: 2D and 3D Finite Element Models with a Viscoelastic Rheology
Wallner and Schmeling	Numerical Model Exploration of a Movable Emplacement Zone for Melt Extraction in a Continental Lithospheric Extension Scenario

Abstracts

Invited Talks

Assimilating Lithosphere And Slab History In 4-D Dynamic Earth Models

D. J. Bower[1], N. Flament[2] and M. Gurnis[1]

[1]*Seismological Laboratory, California Institute of Technology, USA*

[2]*Earthbyte Group, School of Geosciences, The University of Sydney, Australia*

We develop a new method called "progressive data assimilation" to incorporate paleogeographical constraints into numerical simulations of convection in the Earth's mantle. This enables convection models to honor geophysical and geological data near the surface while offering predictive power at greater depths by the solution of Stokes flow. The method consists of four independent constraints determined a priori from a plate history model: (1) plate velocities, (2) thermal structure of the lithosphere, (3) thermal structure of slabs in the upper mantle, and (4) velocity of slabs in the upper mantle. These constraints are implemented as temporally- and spatially-dependent boundary conditions that are blended with the Stokes flow solution at each time step in the convection code. We construct Earth-like regional models with oceanic and continental lithosphere, trench migration, oblique subduction, and asymmetric subduction to demonstrate the application of the method to a variety of geological settings. Furthermore, we test the robustness of the method by computing the temperature, velocity, and buoyancy flux in the lithosphere and slab. Finally, convection simulations in the full sphere are used to make a variety of predictions that range from the present day structure of the mantle to the evolution of surface deformation and topography.

Mineral Physics of the Dynamic Planets

R. Caracas[1]

[1]*Centre National de la Recherche Scientifique, Laboratorie de Géologie de Lyon, Université de Lyon, Université Claude-Bernard Lyon 1, France*

The planetary interiors are characterized by a succession of geological bodies, usually concentric regions, with distinct properties, which are in a continuous interaction. The boundaries between these bodies are some of the most interesting places inside a planet; here they interact, can melt partially or completely, and exchange matter and chemistry via fluids. These boundaries are also detected remotely, seismically. Their origin may be geological, chemical, but also related to phase transitions of major constituent minerals. Here we focus on some of the most recent exciting applications of first-principles calculations based on density-functional theory and density-functional perturbation theory to the study of the mineral transformations taking place at these boundaries. We exemplify with some of the representative transitions in minerals of the subduction zones and the shallow mantle. We discuss the stability of hollandite – a major host of large cations, and the elastic softening of serpentine-type minerals. We analyze the structural stability of $CaSiO_3$ perovskite based on results from lattice dynamics and group theory and show that the octahedral tilt system that lowers the symmetry from cubic to tetragonal has the lowest energy. Then we investigate the perovskite to post-perovskite phase transition in $MgSiO_3$ and discuss its influence on the layering of the lowermost mantle. We show that Fe partitions preferentially in the high-pressure form and it decreases the transition pressure while Al slightly increases it. Both Fe and Al decrease the seismic wave velocities. We compute the Raman spectra of the two structures and show that it can be used as an identification tool for the phase transition. Then we discuss the newly discovered magnetic transitions in Fe-bearing minerals: under pressure the magnetic spin of the iron atoms decreases. This phenomenon is gradual and takes places in the middle of the mantle. It influences the seismic anisotropy and may change the thermodynamical properties of the minerals involved. We discuss the physical basis of this magnetic transition in perovskite, as well as how this transition can be identified in situ in experiments. We finish with a few suggestions for future work relevant to the study of the Earth's mantle.

Adding Complexity – Magnetohydrodynamics

M. Carlsson[1]

[1]*Institute of Theoretical Astrophysics, University of Oslo, Norway*

The plasma in normal stars can be reasonably well described by the equations of compressible hydrodynamics. In addition the collisional frequencies are high enough that particles couple and the their velocity distribution can be well described by a Maxwellian distribution. In the outer, thinner, parts of stellar atmospheres magnetic fields can start to play an essential role and we need to switch the description to Magnetohydrodynamics. In the thinner parts, collisional frequencies are not high enough to maintain equilibrium and we will even have to abandon the concept of a unique temperature. In this talk we will review the modelling of the solar outer atmosphere and concentrate on non-hydrodynamics aspects: magnetic fields, radiative transfer and non-equilibrium processes. We will also describe some numerical methods used to solve the resulting systems of equations on modern supercomputers.

Thermal Boundary Control in Models of Rotating Convection and the Geodynamo

C. Davies[1], L. Silva[2] and J. Mound[1]

[1]*School of Earth and Environment, University of Leeds, UK*

[2]*School of Mathematics, University of Glasgow, UK*

Convection in Earth's fluid outer core is responsible for the continual generation of the geomagnetic field through the geodynamo process. Secular variation of the geomagnetic field provides information on flows at the top of the core, which may be linked to the dynamics of the core's interior. The spatio-temporal evolution of core convection and the geomagnetic field are likely to be significantly influenced by thermal (and perhaps composition) anomalies that are externally imposed. At the core-mantle boundary (CMB), mantle convection generates lateral variations in heat-flux that are dominated by a component of spherical harmonic degree and order 2. The outer core may also be subjected to lateral heat-flux variations at the inner-core boundary (ICB). The hemispheric seismic structure of Earth's inner core has been attributed to a self-sustained rigid-body translation of the inner core material, which results in a hemispheric pattern of heat-flux imposed at the base of the outer core. We use numerical models of both non-magnetic convection and the geodynamo to investigate the relative influence of thermal anomalies imposed at the CMB and ICB on the flow in the outer core.

ASPECT – Challenges and Solutions

T. Geenen[1]

[1]*SURFsara, The Netherlands*

We present ASPECT (the advanced solver for problems in earth's convection) as a tool to solve large and complex geodynamic models efficiently on supercomputers. We will focus on general design considerations for ASPECT and show its extensible and modular framework, as well as go into more detail with respect to the specific methods used to achieve high accuracy and computational efficiency. From several examples of model results generated with ASPECT, we illustrate some of its key features and capability of the application to solve current scientific questions in geodynamics. Maintaining a community code can be a challenge and requires a dedicated team of developers as well as a support infrastructure that allows for long term support and embedding in the scientific community. We will look at the development model needed to maintain such a code and how that could be integrated in the European supercomputer program following the successful model of CIG. Finally we also want to look at future developments in supercomputer hardware and discuss some of the challenges that this poses to traditional solution methods which use grid based discretization strategies, such as the finite element method in ASPECT.

Building Simulation Software for the Next Decade: Trends and Tools

H. P. Langtangen[1]

[1]*Simula Research Laboratory AS, Lysaker, Norway*

A large portion of research budgets is often spent on software development and maintenance, but a critical view on the quality of this work usually receives much less attention than the physics and mathematics that make the foundation for the software. This talk is therefore centered around software development habits and techniques. For decades, Fortran was the dominating programming language, and the large cost of software development and maintenance of enormous Fortran codes was often compensated by a long lifetime of the codes, frequently 2-3 decades. Today's rapid changes in science require faster turnaround times of simulation codes. For more than a decade now, C++ and more sophisticated programming techniques have been popular in the science community to create more flexible and adaptive software. Even more popular now is high-level languages and MATLAB in particular. A fundamental problem, however, is the computational efficiency of high-level languages, which is normally much inferior to Fortran and C++. In this presentation we try to answer the following question: If a research group plans to develop new mechanistic models and associated software for the next decade and beyond, what type of programming languages, tools and techniques should be adopted? The talk will highlight recent trends in using high-level programming languages combined with compiled languages for efficiency (Fortran, C, C++). We will in particular describe the Python ecosystem for development of scientific software and point to upcoming trends. A key issue is how to deal with computational efficiency in the future heterogeneous and unknown landscape of hardware architectures. High-level programs that generate Fortran, C or C++ programs represent a promising approach. The FEniCS project (fenicsproject.org) is based on such code generation and aims at making it very easy to solve partial differential equations by finite element methods. Some cutting edge simulation tools built on FEniCS will be highlighted. Another key element of the talk is how to ensure reproducible science. For example, how can my current results, made in a hurry for a paper, be rerun, checked and extended by anyone in 10 years? An associated topic is modern collaboration principles to ensure that future students and researchers have full access to and can utilize the research software developed today. Project hosting sites, version control systems, and scripts automating all numerical experiments in papers are key tools in this respect.

Plasticity and Strain Localisation In the Crust and Lithosphere Models: Numerical Aspects

L. Le Pourhiet[1]

[1]*UPMC-Paris, France*

In order to model the formation of faults and or plate boundary in the long term numerical models of the crust, the lithosphere and the whole upper mantle, the earth science community has been implementing plastic rheologies in numerical codes that solves for pseudo-static approximation of force balance. These rheologies have been shown to be necessary to generate plates at the surface of the convecting earth, or to reproduced the main patterns observed at rifted margins or in the fold and thrust belts. However, numerically speaking these rheologies are nasty. They not only introduce very strong non-linearities in the problem but they also introduce mesh dependence issues. As a result, all the codes used in geodynamic produce different picture one from each other for a similar given problem. In this presentation, I'll first introduce what is plasticity, from a mechanical and energy balance point of view. I will then review how plasticity has been implemented in various numerical code in earth science and beyond our community before focusing in more details on the specific problems related to the most commonly implemented flow rule, i.e. visco-plasticity in the rigid limit. I will show with simple examples why simple problems such as weak viscous notch embedded in homogeneous visco-plastic media can cause headache when it comes to reproducibility of results, i.e., discretisation (DFM, FEM, ALE), convergence of non-linear solver, convergence of the solution with grid size and time integration. Finally, I will present some other visco-plastic rheologies issued from engineering community. These pressure-dependent plastic rheologies present the advantage of getting to a unique solution for which we can solve for efficiently and accurately. By this last sentence I mean on the one hand that non-linear residuals can be reduced using a combination of Picard and Newton with efficient line-searching algorithm and on the other hand that the non linear solution of the problem converges with increasing mesh resolution.

Computational Porous Media Modelling

H. Muhlhaus[1], L. Gross[1] and A. Scheuermann[2]

[1]*School of Earth Sciences, ESSCC, The University of Queensland, Australia*

[2]*School of Civil Engineering, The University of Queensland, Australia*

Porous media are ubiquitous in Geology and geomechanics. On a plate thickness scale the mathematical theory of porous media flow is used to describe the localised intrusion of lava into the upper lithosphere e.g. around spreading centres and subduction zones. In geological and geotechnical engineering the interaction of a flowing fluid with granular matter leading to a suspension consisting of fluidized particles is of great importance in geology but also in engineering disciplines such as chemical engineering and minerals processing. On the one hand, the forces of liquid- particles-or liquid matrix interactions can be used very efficiently for example in industrial processes – in particular in minerals processing – involving size and weight segregation, mixing and transport. On the other hand, the interaction of soil and water can be the trigger of destruction, destabilizing the integrity of engineering structures leading to the collapse and failure of slopes, dams and foundations. Likewise the propagation and penetration of the localised lava channels to the surface is a necessary accompaniment of volcanic eruptions.

I will begin with an introduction into the theory of porous media flow (notations, balance equations Darcy's law, propagation modelling: Stefan condition), examples. In the main part of my talk I will concentrate on a representative example of porous media modelling, namely sand erosion. In general, sand erosion involves a combination of hydraulic and solid deformation –soil plasticity type-mechanisms. In our contribution we shall show, that under certain conditions, sand erosion can be formulated as an internal boundary value problem, a so-called Stefan problem. We assume that the number of eroded particles-determining the local porosity change caused by erosion-is determined by the magnitude of the local pore fluid velocity. We focus on purely hydraulic erosion mechanisms, neglect solid deformations, and assume that the concentration c of the eroded particles per volume pore space, which means the particles in suspension is very low, i.e., $c << 1$. As a consequence, for the situation of a fluidized bed, an initially homogeneous porosity distribution, upon change of pressure gradient, is modified from a constant value in front- to a different value behind a propagating discontinuity line (2D) or surface (3D). In the following section we give an outline of the governing conservation laws, Darcy's law and the erosion model (Scheuermann et al., 1999; Vardoulakis, 2004). Subsequently a simplified model for the erosion process leading to an internal boundary value problem with discontinuous porosity alteration (Muhlhaus and Gross, 2013) is presented. In section 3 we derive a closed form expression for the propagation speed of a 1D porosity discontinuity. We then linearise the governing equations and conduct a linear instability analysis. Analogies to the chemical infiltration model by Orteleva et al. (1986) are pointed out. In the remainder of the paper we employ a finite element model (Gross et al., 2006, 2007) to investigate nonlinear regime of the governing equations. In our numerical model the discontinuity surface is modeled by means of the level set method (Tornberg and Engquist, 2000).

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Mantle Structure - Temperature or Other Bulk Properties

K. Sigloch[1]

[1]*Ludwig-Maximilians-Universität, Sektion Geophysik, Germany*

Seismological imaging delivers only present-day snapshots of the convecting mantle, and yet it is among our prime tools for inferring mantle dynamics. Sharper images result primarily from the rapidly growing numbers of high-quality, broadband, digital seismic stations, but also from improvements in imaging techniques – these two factors are in fact symbiotically linked. "Modern" seismology is characterized by the ongoing transition from computationally inexpensive approximations to the seismic wave equation, to its fully numerical simulation. As wave phenomena have been considered in increasing realism, both conceptually and in the computer, seismologists have produced significantly refined images of the mantle over the past decade. I will discuss some newer observations and developments that should offer rewarding starting points for geodynamic modeling: (1) How waveform tomography is starting to "properly" image certain complex mantle regions for the first time; (2) The observability of seismic anisotropy, the most important proxy for mantle flow; (3) Possible reasons for why subducted plates have been so relatively easy to observe, whereas plumes have remained surprisingly elusive.

Diversity of Mantle Dynamics and Evolutions

V. S. Solomatov[1]

[1]*Department of Earth and Planetary Sciences, Washington University, USA*

In the past two decades the models of the dynamics and evolution of the interiors of terrestrial planets have been shifting from relatively simple and Earth-centric towards more complex and planet-specific ones. This shift has been driven by observations as well as theoretical and numerical advances. The discoveries made by space missions to Venus, Mars and Mercury showed that each of these planets has its own character, whether it is Venus' volcanism, Mars' global dichotomy, Mercury's contraction or Earth's plate tectonics. The theoretical models attempting to explain these observations are becoming increasingly complex, and not, or at least not only, because of the imagination of the modellers but because the models incorporate more realistic physical processes than they did before. This produces more diversity in models of planetary evolutions than was previously possible. At the same time the expanding repertoire of dynamic phenomena inevitably generates a higher degree of non- uniqueness in constructing the narrative of a planet's history. I will discuss a few factors that contributed to this diversity, including the stochastic aspects of planetary accretion and magma oceans, post-accretion catastrophic events such as superplumes and widespread melting, and localized convection. I will also discuss one of the most important changes in comparative planetology – the reversal of the plate tectonics question from ``why do not other planets have plate tectonics'' to ``why does the Earth have plate tectonics''. The latter is especially intriguing because of the rapidly growing list of extra-solar planets and because of the suspected relationship between plate tectonics and planetary habitability.

Modeling Dynamic Topographies of Planetary Bodies

B. Steinberger[1,2]

[1]*GFZ German Research Centre for Geosciences, Potsdam, Germany*

[2]*Centre for Earth Evolution and Dynamics, University of Oslo, Norway*

Dynamic topography is the part of topography that is caused by density anomalies and flow in the convecting mantle. On Earth, its amplitude is probably ~ a few hundred meters, and since continental elevations are close to sea level, it should have a strong influence on which regions are flooded, and hence on the geologic evolution of continents. Dynamic topography of the ocean floor influences the volume of the ocean basins and hence sea level. Here I discuss how dynamic topography on Earth is inferred from geodynamic models of flow and convection in the mantle, and how modelling results can be compared to observations, both for present-day spatially and spectrally, and for rates of uplift and subsidence in the geologic past. For other planets and the Moon, there exist little or no direct evidence for mantle density anomalies and flow. I will discuss how, by assuming certain analogies to the Earth, one can nevertheless attempt to extract which parts of topography and equipotential surface ("geoid") undulations are caused in their mantles, and how this information in turn can be used to infer mantle density anomalies.

Seismic Observations of Subduction Zones And Implications for Modelling, Hydration, and Volcanism

E. Syracuse[1]

[1]University of Wisconsin-Madison, USA

Subduction zones are a major expression of tectonism and mantle convection on Earth, with a linear extent of approximately 40,000 km at the surface. They present the seeming contradiction of a cold oceanic slab descending into the mantle, while creating melting within the overlying mantle. They are also the sites of the largest and deepest earthquakes, as well as the majority of subaerial volcanism, making them of both scientific and human interest. While there is no "typical" subduction zone, there are many features common to all or most that should be taken into consideration in geodynamical modelling. In seismic velocity tomography studies, subducting slabs typically have high velocities due to their relatively cool temperatures, while the mantle wedge that is entrained in corner flow has lower velocities due to a combination of elevated temperature, hydration, and melting. Velocity tomography also illuminates a range of slab morphologies. On the global scale, some slabs continue to descend below the mantle transition zone, while others appear to accumulate at it and travel laterally as opposed to vertically, indicating a range in the style of interactions between subduction zones and the deep mantle. On regional scales, tomography and seismicity within subducting slabs highlight features such as slab tears or bends, which are often associated with structures on the subducting seafloor. Seismicity distributions also reflect the hydration state, the thermal state, and faulting within slabs. Seismic attenuation is often used to identify differences in temperature and hydration in the mantle wedge. In the majority of studies of mantle wedges in subduction zones, a low-attenuation corner is observed above where the top of the subducting slab is at ≤80 km depth; this is attributed to the presence of cold serpentine that is created by the incorporation of water released by the slab as it warms during subduction. This "cold nose" is cut off from the larger-scale corner flow in the hotter mantle wedge, which appears as a highly attenuating region. The intensities of these low- and high-attenuation regions provide information on the differences in wedge temperature among different subduction zones, which affect the viscosity and degree of melting within the wedge. Seismic anisotropy, which, at subduction zones, is attributed to the alignment of olivine crystals under strain, provides constraints on the three-dimensional patterns of mantle flow. While its interpretation is complicated by the stress and water dependence of the fast directions of olivine, laboratory studies provide robust constraints on the different types of fabric that develop. Although many subduction zones show a predominance of two-dimensional trench-perpendicular flow, some studies show more complex flow around the edges of slabs or at changes in slab curvature. I will present an overview of the information that seismology provides on both the uniformity and diversity of Earth's subduction zones, focusing on the constraints that it provides for geodynamical modelling.

Plume Generation and Migration

E. Tan[1]

[1]*Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan*

Plumes must originate from a thermal boundary layer (TBL). The most likely source of plumes is the core-mantle boundary (CMB), but other TBLs are also possible. An endothermic phase discontinuity (e.g. the 660-km discontinuity) can hinder the vertical flow and develops a TBL on top of the phase discontinuity. A stable chemical layer would also establish a TBL along the chemical boundary. The temperature contrast across the TBL controls the magnitude of the excess temperature of plumes. Plumes originate from TBL of large temperature contrast would have higher excess temperature upon initiation. However, the excess temperatures of plumes are also affected by the surrounding environments, the travelling distance, and the amount of entrainment. A classical mantle plume is consisted of a large plume head and a thin conduit. The size of plume heads could vary significantly due to the viscosity of the overlaying mantle when the plume initiated. Sometimes, the buoyant material rises as a linear sheet initially, but the sheet will eventually break up to several cylindrical plumes spontaneously. The plumes move passively with regard to the large scale mantle flow. Strong subducted slabs can push plumes away. On the other hand, plumes could be captured to the edges of steeply inclined thermo-chemical boundary. As a result, plumes tend to cluster around steep-edged chemical piles, which might explain the observations of hotspots clustering along the edge of the Large Low Shear Velocity Provinces.

Poster Presentations

Effects of Partial Melting on the Dynamics of SSC Developing in a Plume-Fed Layer Beneath a Moving Plate

R. Agrusta[1], D. Arcay[2] and A. Tommasi[2]

[1]*Department of Earth Sciences, Science Laboratories, Durham University, UK*

[2] *Geosciences Montpellier, CNRS, Université de Montpellier 2, France*

Mantle plume are traditionally proposed to play an important role in the lithosphere erosion. Seismic images beneath Hawaii show a lithosphere-asthenosphere-boundary (LAB) up to 50 km shallower than the surroundings. Numerical models show that the development of SSC in the plume pancake may erode the lithosphere, even for a fast-moving plate like the Pacific. However, the thermo-mechanical erosion of the lithosphere does not exceed 30 km. Partial melting has multiple possible consequences on the dynamics of SSC convection. The absorption/release of latent heat during melting/crystallization may affect the thermal structure, and, consequently, the thermal buoyancy. The effective buoyancy may, on the other hand, increase both by melt retention and by removal of dense mineral phases from the solid residue. Convection may also be enhanced due to a viscosity reduction, as the presence of even low volume fractions of melt has been shown to decrease the peridotites strength. A 2D petrological-thermo-mechanical numerical model is used to study the role of partial melting on the plume-lithosphere interaction. A homogeneous peridotite composition with a Newtonian temperature- and pressure-dependent viscosity is used to simulate both the plate and the convective mantle. A constant velocity, ranging from 7.5 to 12.5 cm/yr, is imposed at the top of the plate. Plumes are generated by imposing a thermal anomaly of 250 to 375 K on a 50 km wide domain at the base of the model, to simulate a plume ascending from the transition zone. The plate right above the thermal anomaly is 40 Myr old. Partial melting is estimated using batch-melting curves for anhydrous melting as a function of pressure, and depletion of the solid residue. The progressive depletion of peridotite and its effect on partial melting is modeled by assuming that the melting degree only strictly increases through time. Melt is accumulated until a porosity threshold is reached and the excess melt is extracted. The rheology of the partially molten peridotite is determined using viscous constitutive relationship based on a contiguity model, which enables to take into account the effects of grain-scale melt distribution. Above a threshold of 1%, melt is instantaneously extracted. The density varies as a function of partial melting and depletion degree. We analyze the dynamics of time-dependent small-scale convection (SSC) instabilities, and the resulting thermal rejuvenation of the lithosphere. The models show an accelerated development of the gravitational instabilities at the base of the lithosphere. The reduction of the onset time may be explained by an increase in the local Rayleigh number of the unstable layer, resulting from both a viscosity reduction and an increase of the buoyancy force, due to depletion in solid dense phases. The major contribution to the development of the instabilities is the increase in buoyancy due to chemical depletion, in particular in case of cold plumes, in which the effect of melt retention only locally reduces viscosity. The low viscosity and increased density contrast between the two layers (molten vs. un-molten layers) also produce a more vigorous SSC, favouring the thermo-mechanical erosion of the lithosphere.

Shear Banding in a Partially Molten Mantle

L. Alisic[1], J. Rudge[1], G. Wells[1], R. Katz[2] and S. Rhebergen[2]
[1] *University of Cambridge, UK*
[2] *University of Oxford, UK*

We investigate the nonlinear behaviour of partially molten mantle material under shear. Numerical models of compaction and advection-diffusion of a porous matrix with a spherical inclusion are built using the automated code generation package FEniCS. The time evolution of melt distribution with increasing shear in these models is compared to laboratory experiments that show high-porosity shear banding in the medium and pressure shadows around the inclusion. We focus on understanding the interaction between these shear bands and pressure shadows as a function of rheological parameters.

The Role of Elastic Compressibility in Dynamic Subduction Models

W. Austmann[1] and R. Govers[1]
[1] *Department of Earth Sciences, Utrecht University, The Netherlands.*

Recent advances in geodynamic numerical models show a trend towards more realistic rheologies. The Earth is no longer modeled as a purely viscous fluid, but the effects of, for example, elasticity and plasticity are also included. However, by making such improvements, it is essential to include these more complex rheologies in a consistent way. Specifically, compressibility needs also to be included, an effect that is commonly neglected in numerical models. Recently, we showed that the effect of elastic compressibility is significant. This was done for a gravity driven cylinder in a homogeneous Maxwell fluid bounded by closed boundaries. For a fluid with a realistic compressibility (Poisson ratio equals 0.3), the settling velocity showed a discrepancy with the semi-analytical steady state incompressible solution of approximately 40%. The motion of the fluid was no longer restricted by a small region around the cylinder, but the motion of the cylinder compressed also the fluid near the bottom boundary. This compression decreased the resistance on the cylinder and resulted in a larger settling velocity. Here, we examine the influence of elastic compressibility in an oceanic subduction setting. The slab is driven by slab pull and a far field prescribed plate motion. Preliminary results indicate that elastic compressibility has a significant effect on the fluid motion. Differences with respect to nearly incompressible solution are most significant near material boundaries. In line with our earlier findings,

the flow is increased in regions of confined flow, such as the mantle wedge or the subduction channel. As a consequence, an increasing compressibility results in a larger slab velocity. We seek to identify surface observables, such as topography and plate motion, that allow us to distinguish the compressible and incompressible behaviour.

Can Variations in Radial Viscosity Explain the Persistence of Indian MORB Mantle in the Shallow-most Asthenosphere over 100's Millions of Years?

T. L. Barry[1], J. H. Davies[2] and M. Wolstencroft[3]

[1]*Deptartment of Geology, University of Leicester, UK*

[2]*School of Earth and Ocean Sciences, Cardiff University, UK*

[3]*Deptartment of Geography, Durham University, UK*

In terms of isotope geochemistry, Indian mid-ocean ridge basalts (MORB) stand out as distinct from adjacent Pacific and Atlantic MORB (e.g., Kempton et al., 2002; Janney et al., 2005). Since the work of Mahoney et al. (1998) on old west Indian Ocean and east Tethyan MORBs, we have known that Indian MORB mantle resided beneath at least parts of Neo-Tethys. Furthermore, work on a ~350 Ma ophiolite from China demonstrates that Indian MORB mantle must have contributed, in some places, to MORB genesis during the formation of Paleo-Tethys (Xu and Castillo, 2004). Together, this evidence suggests that Indian-MORB mantle has at least to some extent remained within the shallow-most asthenosphere during multiple Wilson cycles, over 100's millions of years. Here we set out to examine how a distinct upper mantle chemistry might be preserved or maintained within the shallow-most upper mantle during successive ocean closure and opening, as suggested by the Palaeo- to Neo-Tethys and Indian Ocean MORBs. Using mantle circulation models for the past 120 Ma with 3D mantle convection code TERRA, we set out to assess what effect radial viscosity has on preserving this isotopically distinct Indian MORB mantle composition in the upper mantle.

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Constraining the Rheology of the Lithosphere Through Joint Geodynamic and Gravity Inversion

T. Baumann[1], B. Kaus[1] and A. Popov[1]

[1]*Johannes Gutenberg University Mainz, Germany*

Understanding the physics of lithospheric deformation and continental collision requires having good constraints on lithospheric rheology and in particular on the effective viscosity of various parts of the lithosphere. Typically, rheology is determined from laboratory experiments on small rock samples, which are extrapolated to geological conditions – an extrapolation over 10 orders of magnitude in deformation rates. These laboratory experiments generally show that small changes in the composition of the rocks, such as adding a bit of water, can dramatically change its viscosity. Moreover, it is unclear which rock type gives the best mechanical description of, for example, the upper crust and whether a small sample is even appropriate to describe the large scale mechanical behaviour of the crust (or whether this is rather controlled by heterogeneities such as fault zones and batholiths). So the viscosity of the lithosphere is probably the least constrained parameter in geodynamics and might vary over maybe 10 orders of magnitude. The concept of the effective elastic thickness (EET) is often used to make statements about the mechanical strength of the lithosphere. Whereas there is general agreement that the concept of EET works well in oceanic lithospheres, there are huge discrepancies in the EET for active collision belts in continental lithospheres, partly because the (mechanical) lithosphere at those locations is unlikely to be a thin elastic plate floating on a viscous mantle, but is rather multi-layered. Ideally, we thus need a new independent method that allows constraining the effective rheology of the lithosphere directly from geophysical data, which is the aim of this work. Our method uses the fact that the geodynamically controlling parameters of lithospheric deformation are its effective viscosity and density structure (which can both be depth-dependent). By appropriately parameterizing the rheological structure of the lithosphere we perform instantaneous forward simulations of present-day lithospheric deformation scenarios with a finite element method to compute the gravity field as well as surface velocities. The synthetic forward modelling results can be compared with observations such as Bouguer anomalies and GPS-derived surface velocities. More precisely, we automatize the forward modelling procedure with a Monte Carlo method, and in fact solve a joint geodynamic and gravity inverse problem. The resulting misfit can be illustrated as a function of rheological model parameters and a more detailed analysis allows us to constrain probabilistic parameter ranges. For a simple setup we can demonstrate mathematically that this joint geodynamic-gravity inversion approach results in a unique solution (as opposed to inverting for gravity alone which is a well-known non-unique problem). Moreover, we will show an application of our method to a 2D cross-section of the India-Asia collision system.

Comparative Buoyancy Anomalies from Metastable Minerals during Subduction

C. R. Bina[1]

[1]Northwestern University, USA

Subducting lithospheric slabs encounter two significant families of high-pressure phase transformations as they enter the mantle transition zone: polymorphism of olivine (i.e., the olivine-wadsleyite-ringwoodite transitions) and dissolution of pyroxene into garnet-majorite solid solution (i.e., the eclogite-garnetite transitions). Sluggish reaction kinetics under cold subduction conditions may lead to metastable persistence of lower-pressure phases within the equilibrium stability fields of higher-pressure phases. Metastable low-pressure phases are less dense than corresponding equilibrium high-pressure phases, contributing to diminution of the negative buoyancy driving subduction or to the acquisition of positive buoyancy impeding descent. Consequences may include: lower seismic wave speeds in the slab, development of down-dip compressive stress fields, slowing of slab descent rates (potentially accompanied by changes in trench retreat), and wholesale flexure of the slab into a subhorizontal "stagnant" posture in the transition zone. Such kinetic inhibition of equilibrium transformation (e.g., to wadsleyite) has been observed experimentally in olivines. Moreover, transformations in pyroxenes (both disproportionation to a wadsleyite-plus-stishovite assemblage and dissolution into garnet-majorite) have been found to exhibit even greater kinetic inhibition than in olivines. While metastable persistence of olivine appears to be feasible at temperatures of at most 1000 K, the most recent (2013) reports on low diffusion rates in garnet indicate that pyroxene may persist metastably at temperatures up to 1800 K. While metastable pyroxene may potentially persist in subduction zones over greater volumes and to greater depths than metastable olivine, the relative potential contributions to buoyancy anomalies of the two mineral families are complicated by such factors as: intrinsic density contrasts of the respective transitions, relative volumetric proportions of the minerals, differential thermal expansivities of the phases, and possible transition to other metastable phases. Here we attempt to quantify the relative potential contributions of olivine and pyroxene metastability to subduction buoyancy anomalies.

Slab Tearing and Lateral Variation in the Exhumation of Ultra-High Pressure Terranes with Application to the Norwegian Caledonides

A. Bottrill[1], J. van Hunen[1], S. Cuthbert[2] and M. Allen[1]

[1]Department of Earth Sciences, Durham University, UK

[2]School of Science, University of the West of Scotland, UK

The lateral tearing of subducted oceanic slabs has been proposed (Wortel and Spakman, 2000) and modelled (van Huen and Allen, 2011) as a method for the removal of subducted lithosphere. Here we investigate whether this laterally propagating tear can explain exhumation patterns in collision zones. A number of mechanisms have been proposed for the return of high and ultra-high pressure metamorphic rocks to the surface. A possible return mechanism after slab break-off is eduction (Brueckner and Cuthbert, 2013), which has been carefully and elaborately studied by Duretz et al. (2012). Eduction is the return of material to the surface by reversing the shear sense of the subduction system, this can happen when slab break-off removes the slab pull force. Focussing on along strike features, we present both 2D and 3D dynamic numerical slab break-off models, to assess along-strike variation in the ultra-high pressure metamorphic terranes of the Norwegian Caledonides. The Caledonian collision between the continents Laurentia and Baltica occurred in the Early Devonian (Dewey and Strachan, 2003). A section of this collision and proposed subsequent slab loss formed the Western Gneiss complex in southwest Norway. This region is of special interest as it contains coesite and micro-diamonds, implying it has experienced pressures of 1.5–5 GPa and temperatures 550–900 °C (Chopin, 2003). The Western Gneiss Complex also has prograding metamorphism from high or ultra-high pressures recorded in the west to virtually unmetamorphosed in the east (Hacker et al., 2010). Asynchronous and asymmetric collision (Dewey and Strachan, 2003) and subsequent plate rotation and eduction have been hypothesized to explain this along-strike variation (Brueckner and Cuthbert, 2013), and we address this hypothesis with dynamical models.

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Numerical Models of the Response of Passive Margins to Syn-rift Surface Processes

S. Buiter[1, 2]

[1] *Geological Survey of Norway, Norway*

[2]*Centre for Earth Evolution and Dynamics, University of Oslo, Norway*

Seismic observations of passive continental margins show different amounts of surface transport of sediments from onshore to offshore. The Goban Spur, Galicia Bank, and the Red Sea are examples of sediment-starved margins, whereas thick packages of syn-rift basin sediments occur on the Grand Banks and Norwegian margin. What is the role of offshore sedimentation and onshore surface erosion in margin development? Here I use numerical models to explore the lithospheric response to surface processes from initial rifting to continental break-up. Erosion is a weakening process: it reduces the overburden, which induces an isostatic surface uplift, and lowers vertical stress, which reduces pressure-dependent brittle strength. However, sedimentation is both strengthening and weakening. Sedimentation increases brittle strength because of the increase in vertical stress under the extra load. But sediments may have a lower density and cohesion, and therefore a lower brittle strength than the adjacent crust. Sediments with a low thermal conductivity may also act as a 'thermal blanket' preserving heat in the crust below, thereby reducing crustal ductile strength. The feedback effects between surface processes and tectonic deformation during passive margin formation are more than a simple isostatic response and require careful quantification of the contributing processes in relation to crustal strength evolution. To explore the dynamic feedback relationships between surface processes and the lithospheric strength of passive margins, I perform a series of numerical experiments using SULEC-2D. SULEC is an arbitrary Lagrangian-Eulerian (ALE) finite-element code for solving incompressible, thermo-mechanical, geodynamic problems. Characteristics of the code include a structured mesh of quadrilateral elements, material advection on tracers, Uzawa pressure iterations, and a true free surface. The models are on the scale of the upper mantle with highest resolution in the lithosphere. The rocks deform either following pressure-dependent brittle yielding or a temperature-, pressure- and strain-rate-dependent viscous rheology. The numerical results highlight the importance of crustal strength evolution at passive margins in relation to surface processes. For a wide range of surface processes, a strong lower crust leads to relatively fast lithospheric break-up accompanied by rift flank uplift and focussed mantle upwelling. A weak lower crust delays break-up. But increasing the amount of sediments for intermediate strength lower crust can switch break-up style from fast break-up to prolonged rifting and delayed break-up. In that case, the strengthening effect of sedimentation dominates over its weakening properties.

The Effect of Plate Motions of the Longevity of Deep Mantle Heterogeneities

A. L. Bull[1], M. Domeier[1] and T. H. Torsvik[1-3]

[1]*Centre for Earth Evolution and Dynamics, University of Oslo, Norway*

[2]*Geodynamics, Geological Survey of Norway, Norway*

[3]*School of Geosciences, Witwatersrand University, South Africa*

Understanding the first-order dynamical structure and temporal evolution of Earth's mantle is a fundamental goal in solid-earth geophysics. Tomographic observations reveal a lower mantle characterised by higher-than-average shear- wave speeds beneath Asia and encircling the Pacific, consistent with cold slabs of descending lithosphere beneath regions of ancient subduction, and lower-than-average shear-wave speeds in broad regional areas beneath Africa and the Central Pacific (termed LLSVPs). The LLSVPs, although not as easily understood from a dynamical perspective, are inferred to be broad upwelling centres between Mesozoic and Cenozoic subduction zones. Heterogeneous mantle models place these anomalies into the context of thermochemical piles, characterised by an anomalously dense component, with their location and geometry being controlled by the movement of subducting slabs. The origin and temporal evolution of the LLSVPs remain enigmatic. Recent numerical studies propose that the LLSVP beneath Africa is post-Pangean in origin and formed as a result of return flow in the mantle due to circum-Pangean subduction. In contrast, palaeomagnetic reconstructions, which show that 80% of Kimberlites from the last 540 million years erupted at locations on the present day margins of the LLSVPs, require the LLSVPs to have remained in their present positions for at least such a time period. Here we investigate the temporal evolution and possible long-term persistence of LLSVPs by integrating plate tectonics into numerical models of mantle dynamics. In the numerical models of McNamara and Zhong (2005) and Bull et al. (2009), a dense component in the lower mantle was focused into LLSVP-like structures beneath Africa and the Pacific due to the imposed subduction history. In both cases the calculations employed surface velocity boundary conditions consistent with 119 million years of plate history. In this work, we improve upon these studies by employing a new palaeomagnetically-derived global plate motion data set to impose surface velocity boundary conditions for a time period that encompasses the creation and subsequent break-up of Pangea. We aim to understand the role that Earth's plate motion history plays on the development of LLSVPs within Earth's mantle. Specifically, we investigate the effect of plate history on the present day observed degree-2 structure of the mantle and explore the possibility that both LLSVPs existed prior to the Pangea.

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Effect of Burgers Rheology on Glacial Isostatic Adjustment Models

L. Caron[1], M. Greff-Lefftz[1], L. Fleitout[2] and L. Métiviter[3]

[1]*Géomagnétisme, IPGP, France*

[2]*Laboratoire de Géologie de L'ENS, France*

[3]*LAREG, IGN, France*

The phenomenon by which Earth deforms after a change in ice surface loading, called Glacial Isostatic Adjustment (GIA), depends on ice loading history, as well as Earth rheology. Considering it occurs on time scales ranging from a hundred years to a thousand hundred years, a viscoelastic behavior is usually assumed and modeled by a Maxwell material. However, if the Earth elastic properties are relatively well known from the seismology field, the viscosity parameter still remains a rough estimation. In addition, the time-dependent continental ice distribution for the last glacial cycle is assessed by sea level data and geological markers contouring the ice caps, however the resulting constrains are too weak to validate a single model. These considerations lead us to test non-classical assumptions on the Earth rheology to improve current GIA models. If a Maxwell behavior seems appropriate for most homogeneous rock materials, the Earth's internal material, at a fixed depth, is essentially a mix of homogeneous materials, therefore heterogeneous. Rather than a Maxwell behavior, a Burgers model describes such material. With the ultimate goal of performing an inversion of both the viscosity profile and the ice loading distribution using GPS, space gravimetry and paleo sea-level data, we will first focus on comparing the Earth's response to surface loading for Maxwell and Burgers rheologies.

Effects of Realistic Material Properties on Slab Deformation in the Mantle

H. Čížková[1], A. van den Berg[2] and M. Jacobs[3]

[1]*Department of Geophysics, Charles University in Prague, Czech Republic*

[2]*Institute of Earth Sciences, Utrecht University, The Netherlands*

[3]*Institute of Metallurgy, TU-Clausthal, Clausthal-Zellerfeld, Germany*

Deformation of subducted lithospheric slabs in the mantle has been widely discussed in recent years. Material properties were usually considered either constant or depth dependent with only few exceptions. It is however known that for example thermal expansivity varies significantly with temperature (and related mineral phase). In a strongly nonlinear rheological model the deformation of subducted slab may be quite sensitive to the buoyancy variations due to the realistic, pressure and temperature dependent material properties. Therefore, we present here the results of convection experiments in a model with material properties (density, thermal expansivity and specific heat) derived from a thermodynamic formalism based on lattice dynamics (Jacobs and de Jong, 2007). Our 2D Cartesian model setup includes subducting and overriding plates separated by a thin crustal layer prescribed at the top of the subducting plate. We assume strongly nonlinear rheology combining diffusion creep, dislocation creep and a power-law stress limiter. Some of our models have fixed trench position while others allow for a rollback. We demonstrate that basic characteristics of slab dynamics in models with complex material properties are usually similar to simplified models with depth-dependent properties. Slabs reach transition zone, buckle at the 660 km interface and as a large blobs penetrate to the lower mantle. Slab velocities are however considerably higher especially at the early stages of slab descent (by 2-4 cm/yr with respect to depth dependent model). Slabs are now more negatively buoyant and our previous estimate of lower mantle viscosity from slab sinking speed (Čížková et al., 2012) thus has to be modified. We show here that preferred lower mantle viscosity should be somewhat higher than previously estimated – by about a factor of 2-3. Thermal anomaly of the slabs when they arrive to the deep lower mantle is also affected – slabs are by up to 100 K colder than in depth dependent model. Further, in some models these differences in thermal state and subduction velocity may result in a completely different slab morphology due to the strongly nonlinear rheology. Thus in some model cases we observe flat-lying stagnant slabs where periodic buckling and penetration was reported in simplified depth-dependent models.

Simulation of Mantle Convection via Novel Adaptive Finite Element Methods

S. P. Cox[1], T. L. Barry[1], A. Cangiani[1] and E. H. Georgoulis[1]

[1]*University of Leicester, UK*

While finite element method simulations of whole-earth mantle convection using adaptive meshes is currently a very popular area of research (e.g. Burstedde et al., 2008; Davies et al., 2001; Kronbichler et al., 2012), little has been done to investigate the mathematical errors generated in the numerical solutions as compared to an exact solution of the partial differential equations. In particular, there has been little quantification of error propagation with regards to the adaptivity strategy. We propose to analyse these errors using a posteriori error indicators based on rigorous mathematical techniques, and to formulate a finite element simulation of mantle convection that takes advantage of this analysis. The simulator will be built on the finite element library deal.II (Bangerth et al., 2007). This work will lead to a fast and cost-effective simulation capable of handling timespans of the order of 100Ma, while being able to quantify the error bounds within simulations and, hence, optimise the distribution of available degrees of freedom for reliable computations.

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Spontaneous Trench Migration and Mantle Flow in Self-consistent Mantle Dynamics

F. Crameri[1] and P. J. Tackley[1]

[1]*Department of Earth Sciences, ETH Zurich, Switzerland*

The work presented in this poster aims at a better understanding of plate tectonics, a crucial dynamical feature within the global framework of mantle convection. Special focus is given to the interaction of subduction-related mantle flow and surface topography. Thereby, the application of a numerical model with two key functional requirements is essential: an evolution over a long time period to naturally model mantle flow and a physically correct topography calculation. The global mantle convection model presented in Crameri et al. (2012a) satisfies both of these requirements. First, it is efficiently calculated by the finite-volume code Stag-YY (e.g., Tackley 2008) using a multi-grid method on a fully staggered grid. Second, it applies the sticky-air method (Matsumoto and Tomoda 1983; Schmeling et al, 2008) and thus approximates a free surface when the sticky-air parameters are chosen carefully (Crameri et al., 2012b). This leads to dynamically self-consistent mantle convection with realistic, single-sided subduction. New insights are thus gained into the interplay of obliquely sinking plates, toroidal mantle flow and the arcuate shape of slabs and trenches. Numerous two-dimensional experiments provide optimal parameter setups that are applied to three-dimensional models in Cartesian and fully spherical geometries. Features observed and characterised in these experiments include (i) the spontaneous development of arcuate trench geometry due to toroidal mantle flow, (ii) a strongly varying behaviour of subduction mode along the trench strike including subduction polarity reversals and slab tearing, (iii) spreading ridges that are laterally offset by normally striking transform „faults“, and (iv) an interesting, newly discovered feature called ‘slab tunnelling’. Overall, this poster demonstrates the strong interaction between surface topography and mantle currents.

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MILAMIN 2 – Fast MATLAB FEM Solver: Algorithms, Implementation and Applications

M. Dabrowski[1,2], M. Krotkiewski[2] and D. W. Schmid[2]
[1] *Polish Geological Institute - National Research Institute, Computational Geology Laboratory, Wrocław, Poland*
[2]*Physics of Geological Processes, University of Oslo, Norway*

MILAMIN is an efficient MATLAB-based two-dimensional FEM solver utilizing unstructured meshes (Dabrowski et al., 2008). The freely downloadable code consists of steady-state thermal diffusion and incompressible Stokes flow solvers implemented in approximately 200 lines of native MATLAB code. The brevity makes the code easily customizable. Another important quality of MILAMIN is its speed – it can handle millions of nodes within minutes on one CPU core of a standard desktop computer. The new package MILAMIN 2 allows modeling of three-dimensional scalar, e.g. thermal diffusion, and vector-valued problems such as the Stokes flow problem. Here, we discuss a multi-level iterative strategy of solving the incompressible Stokes problem in 3D. A performance analysis of crucial code components such as mesh generation, computation and assembly of the stiffness matrix, and linear system solution is given. We provide applications showing how the power and flexibility of the unstructured mesh approach can be used in 3d modeling. In addition, MILAMIN 2 provides a set of utilities called MUTILS that can be used as building blocks for efficient FEM simulations using MATLAB. The utilities are implemented either as native MATLAB functions or compiled MEX functions optimized for shared memory multi-core computers.

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Modelling Type Diversity of Thermo-chemical Plumes: Asymmetry, Ponding, Finger-like Structures and Wide Tails

J. Dannberg[1] and S. V. Sobolev[1]
[1]GFZ Potsdam, Section 2.5 Geodynamic Modelling, Potsdam, Germany

According to widely accepted models, plumes ascend from the core-mantle boundary and cause massive melting when they reach the base of the lithosphere. Most of these models consider plumes as purely thermal and predict flattening of the plume head to a disk-like structure, thin plume tails with a radius on the scale of 100 km and kilometer-scale topographic uplift before and during the eruption of flood basalts (e.g., Farnetani and Richards, 1994). However, several paleogeographic and paleotectonic field studies indicate significantly smaller surface uplift during the development of many LIPs, and seismic imaging reveals thicker plume tails (Montelli et al., 2006) as well as a more complex plume structure in the upper mantle, including broad low-velocity anomalies up to 400 km depth (Wolfe et al., 2009) and elongated low-velocity fingers. Moreover, geochemical data indicate a plume composition that differs from that of the average mantle and recent geodynamic models of plumes in the upper mantle (Sobolev and Sobolev, 2011; Ballmer et al., 2013) show that plumes containing a large fraction of eclogite and therefore having very low buoyancy can explain the observations much better. Nevertheless, the question remains how such a low-buoyancy plume can rise through the whole mantle and how this ascent affects its dynamics. To study the dynamics of the plume ascent as well as the interaction between plate- and plume-driven flow we perform numerical experiments in both 2D axisymmetric and 2D geometry with prescribed velocity at the upper boundary. For that purpose, we use modified versions of the finite-element codes Citcom (Leng and Zhong, 2010; Moresi et al., 1996) and Aspect (Kronbichler et al., 2012). Our models employ complex material properties incorporating phase transitions with the accompanying density changes, Clapeyron slopes and latent heat effects for the peridotite and eclogite phase, mantle compressibility and a highly temperature- and depth-dependent viscosity. We study under which conditions (excess temperature, plume volume and eclogite content) thermo-chemical plumes can ascend through the whole mantle and what structures they form in the upper mantle. Modelling shows that high plume temperature and/or volume together with low content of eclogite result in plumes directly advancing to the base of the lithosphere. Due to the high eclogite density in a region between 300 and 400 km depth, plumes with slightly lower buoyancy (due to higher content of eclogite or lower temperature) pond there and form pools or a second layer of hot material. These structures become asymmetric when the plume interacts with the quickly moving overlying plate. Further reduction of buoyancy leads to plumes accumulating at 300–400 km depth range and never approaching the base of the lithosphere, but instead heating the adjacent mantle material above to form smaller secondary plumes. Our models also suggest that thermo-chemical plumes ascend in the mantle much slower compared to thermal plumes and therefore have thicker plume tails. The conversion of plume excess temperatures to anomalies in seismic velocity shows that thermo-chemical low-buoyancy plumes can explain a variety of features observed by seismic tomography much better than purely thermal plumes.

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Global Heat Flow Map

J. H. Davies[1]
[1]*School of Earth and Ocean Sciences, Cardiff University, UK*

Heat flow is a very useful observable. It can be used directly in such tasks as judging geothermal resources, and indirectly in constraining temperatures. Since temperature underpins much of rheology and buoyancy in geodynamics, heat flow is a very powerful geodynamic constraint. Making good heat flow measurements is very expensive, as a result they are unfortunately limited and very heterogeneous in distribution. There is a global compilation of ~38000 measurements which has been used to make a global estimate of the total heat flow out of Earth, 47 ± 3 TW (Davies and Davies, 2010). Here I use the same data-set but now rather than extracting one number I develop a global map. To produce the map I will use data in regions where measurements exist, I will use a half-space model for young oceanic crust (since raw measurements are frequently affected by hydrothermal circulation in these regions) and assume a correlation with geology for other regions. The results are produced on a 2 degree equal area grid. Methods from Geographical Information Systems are used to allow precise answers to be produced. For example we use area-weighting for multiple geologies and this can be done exactly. Also we use spatial processes such as Union, Summarise and Intersect. We also test the validity of the correlation between geology and heat flow in regions where heat flow measurements exist. We show that it is better than taken the straight average, but reduces the spread by just 10%. The global heat flow map will be provided on a 2 degree equal area grid.

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Virtual Patterson Experiment - A Way to Access the Rheology of Aggregates and Mélanges

T. Delannoy[1-2], E. Burov[1-2] and S. Wolf[1-2]

[1]*UPMC University of Paris 6, ISTeP, France*

[2]*CNRS, ISTeP, France*

The data of the experimental rock mechanics are limited by the conditions of human-scale laboratory experiments, which are often bound to operate with simple mono-phase minerals, short time scales, exaggerated temperatures and strain rates, so the resulting constitutive laws are still to be validated for real rock compositions, geological spatial and temporal scales. The main goal of this numerical thermo-mechanical modeling study is hence to bridge the gap between the experiments and the geological reality, by improving our understanding of both, the effective rheology of poly-mineral aggregates that constitute real rocks, and the mechanisms of strain localization at different spatial scales and temporal scales. At the first stage, we have adapted our thermo-mechanical code Flamar (based on the FLAC algorithm) to allow it to operate at all spatial and temporal scales, from sub-grain to geodynamic scale, and from seismic time scales to millions of years. The code enables coupled resolution of Newton's equations of motion, heat transfer equations and visco-elasto-plastic constitutive equations in large strain mode. We here focused our primary efforts on direct reproduction of real rock mechanics experiments on deformation of simple tri-component aggregates in Patterson's load machine (15 by 15 mm sample deformed at 750 °C and 300 MPa). This mixture includes a molten phase and a solid phase composed of quartz and mica, in which shear bands develop as a result of interaction between ductile and brittle deformation and stress concentration at the boundaries between weak and strong phases. The numerical experiment uses as initial configuration digitized x-ray scans of real samples and the physical properties of the components are varied until the model-predicted strain distributions and overall stress-strain behavior match those observed in the laboratory experiment. Analysis of the model material parameters providing the best match with the Patterson's press experiments leads to a better understanding of the mechanisms governing the localization of the deformation across the aggregate. The strain-rate and stress patterns as well as the stress-strain curves generated by the numerical experiments allow us to study in detail the evolution of the rheological behavior of each phase as well as that of mixtures of different phases, in order to formulate constitutive relations for mélanges and poly-mineral aggregates. One of the important observations refers to the finding that brittle strain localization may temporarily develop at some stages within ductile shear bands because local intra-band strain rates temporarily exceed the background strain rates by several orders of magnitude. Consequently, the bulk constitutive law may significantly deviate from the expected power-law dependence between stress and bulk strain rate as well as from the expected exponential dependence on temperature and pressure. The next objective would be to link the constitutive laws obtained on a small scale to large-scale behavior of the lithosphere (laws that govern the rheology of a polymineralic aggregate, the effect of the presence of a molten phase, etc.) on the localization of the deformation.

A New Generation of Satellite Data to Study the Lithosphere

J. Ebbing[1], J. Bouman[2], R. Floberghagen[3], R. Haagmans[3] and S. Gradmann[1]

[1]*Geological Survey of Norway, Norway*

[2]*DGFI, Germany*

[3]*ESA/ESTEC, The Netherlands*

To understand the interplay between mantle and lithosphere dynamics requires an integrated approach to estimate the physical properties. For example, in recent years, it has become evident that the thermal structure and composition of the upper mantle have a large influence on topography. Lithospheric structures are affected by large-scale tectonic processes and are, in turn, expected to influence the amount, localization and style of surface deformation. Prominent changes in the upper mantle are expected at the lithosphere-asthenosphere boundary (e.g., partial melting) and at cratonic edges (changes in composition and thermal structure). These changes can be recorded by a number of different geophysical data sets, sensitive to seismic wave velocity, electrical resistivity and density. Although all properties are controlled by temperature and water content to some extent, seismic velocities in the lithosphere are determined mainly from the temperature and bulk composition distributions, whereas electrical conductivities are largely controlled by variations in minor conductive constituents like water or melt. Despite the increasing amount of geophysical observables, the heterogeneous data distribution is still a challenge for large scale study areas. Globally available data sets with homogenous coverage are satellite data, as for example the on-going GOCE gravity gradient mission or the soon to be launched SWARM magnetic field mission. These satellites are part of the Earth Explorers missions by the European Space Agency and add a scale of observation that cannot be achieved at the Earth's surface. For example, the gravity gradients from the GOCE mission data have a depth sensitivity that makes them a useful tool to study the density distribution in the uppermost mantle. The characteristic of the gradients is that they are not sensitive to the sub-lithospheric regional trend (unlike terrestrial gravity and the geoid), but especially sensitive to the uppermost 150 km of the lithosphere. Sensitivity tests show that if reasonable crustal models exist, with the use of satellite gravity gradients, it enables us to distinguish between density domains influenced by the thermal structure or composition of the upper mantle, and herby to link crust and upper mantle in great detail, which makes them an ideal data set to be used in combination with seismic tomography.

History and Evolution of Subduction in the Precambrian

R. Fischer[1] and T. Gerya[1]

[1]*Geophysical Fluid Dynamics Group, Institute of Geophysics, Department of Earth Sciences, Switzerland*

[2]*Federal Institute of Technology, ETH-Zurich, Switzerland*

Plate tectonics is a global self-organising process driven by negative buoyancy at thermal boundary layers. Phanerozoic plate tectonics with its typical subduction and orogeny is relatively well understood and can be traced back in the geological records of the continents. Interpretations of geological, petrological and geochemical observations from Proterozoic and Archean orogenic belts however (e.g., Brown, 2006), suggest a different tectonic regime in the Precambrian. Due to higher radioactive heat production the Precambrian lithosphere shows lower internal strength and is strongly weakened by percolating melts. The fundamental difference between Precambrian and Phanerozoic subduction is therefore the upper-mantle temperature, which determines the strength of the upper mantle (Brun, 2002) and the further subduction history. 3D petrological-thermomechanical numerical modelling experiments of oceanic subduction at an active plate at different upper-mantle temperatures show these different subduction regimes (Fig. A1). For upper-mantle temperatures <175 K above the present day value a subduction style appears which is close to present day subduction but with more frequent slab break-off. At upper-mantle temperatures 175–250 K above present day values steep subduction changes to shallow underplating and buckling. For upper-mantle temperatures >250 K above the present day value no subduction occurs any more. The whole lithosphere starts to delaminate and drip-off. But the subduction style is not only a function of upper-mantle temperature but also strongly depends on the thickness of the subducting plate. If thinner present day oceanic plates are used in the Precambrian models, no shallow underplating is observed but steep subduction can be found up to an upper-mantle temperature of 200 K above present day values. Increasing oceanic plate thickness introduces a transition from steep to flat subduction at lower temperatures of around 150 K. Thicker oceanic plates in the Precambrian also agree with results from earlier studies (e.g., Abbott, 1994).

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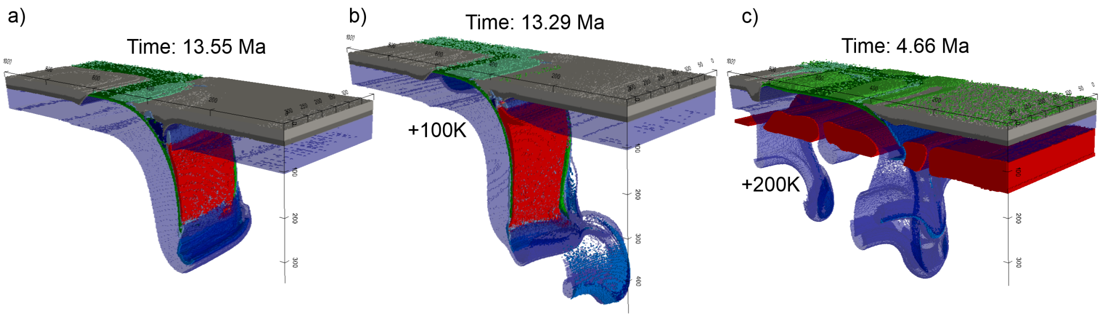

Figure A1. Subduction depends strongly on upper-mantle temperature. (a) Modern subduction with present day temperature gradients in upper-mantle and lithosphere. (b) Increase of temperature by 100 K at the lithosphere-asthenosphere boundary (LAB) leads to melting and drip-off of the of the slab-tip. (c) A temperature increase of 200 K leads to buckling of the subducting slab and Rayleigh-Taylor instabilities not only at the slab-tip but the whole LAB. At this stage subduction is no longer possible as the slab melts or breaks before it can be subducted into the mantle.

Global Models of Mantle Flow and Lithospheric Stretching Since the Jurassic

N. Flament[1], M. Gurnis[2], S. Williams[1], M. Seton[1], R. D. Müller[1] and J. Skogseid[3]

[1] *Earthbyte Group, School of Geosciences, The University of Sydney, Australia*

[2] *Seismological Laboratory, California Institute of Technology, USA*

[3] *Statoil ASA, Norway*

Over the last ten years, it has become evident that mantle flow affects the evolution of "passive" continental margins, in addition to better-known isostatic and elastic processes. The continental lithosphere and the underlying mantle must therefore both be considered to estimate the evolution of the topography and accommodation space at a given continental margin. This constitutes a numerical challenge since mantle flow should be modelled globally to avoid edge effects and to capture plate motions while maintaining sufficient resolution to capture the isostatic and thermal evolution of the lithosphere. Here we present global mantle flow models with lithospheric deformation that extend back to the early Jurassic (200 Ma). The models, computed using CitcomS, consist of $\sim 12.8 \times 10^6$ elements for an average surface resolution of 50 x 50 km and an average radial resolution of 45 km, refined to 15 km in the lithosphere. The kinematics of global tectonic reconstructions with continuously closing and deforming plates are imposed as time-dependent boundary conditions. Compositionally distinct continental crust and lithosphere are tracked using tracers embedded within the thermal lithosphere. We use the ratio method to compute the composition field, modified to give ambient composition for empty elements, which limits the total number of tracers required to track the composition of the lithosphere. The thermal structure of the non-deforming lithosphere, analytically derived in million year increment from age grids consistent with the reconstruction in the ocean and based on simplified tectonothermal ages (i.e., Archean, Proterozoic, or Phanerozoic) in the continents, is assimilated in the geodynamic model, allowing us to control the surface heat flow and the topography of rigid plates. Finally, the shallow thermal structure of subducting slabs is assimilated into the dynamic model, allowing us to obtain asymmetric subduction and slab rollback. Focusing on the South Atlantic, we compare model predictions (mantle temperature, continental crustal thickness, dynamic topography, "total" model topography that includes isostasy and thermal diffusion) to independent present-day (tomography, crustal thickness, residual topography, topography) and historical (tectonic subsidence, thermochronology) constraints. We show that our model reproduces the first-order topographic asymmetry of the South Atlantic region that we attribute to whole-mantle rather than asthenospheric processes. Investigating the effect of mantle viscosity structure, we find that model fits are best with a lower mantle that is at least 40 times more viscous than the upper mantle. We show that simultaneously coupling lithospheric stretching with mantle flow improves the fit between the tectonic subsidence predicted by our model and that constrained from borehole data. This suggests that mantle flow should not be overlooked when estimating crustal stretching factors and the evolution of accommodation space at rifted margins.

Depth Variable Crustal Anisotropy, Patterns of Crustal Weakness, and Destructive Earthquakes in Low-Strain Rate Areas

B. Fry[1], P. Eberhart[2], F. Davey[1] and S. Lebedev[3]

[1]*GNS Science, New Zealand*

[2]*University of California Davis, USA*

[3]*Dublin Institute for Advanced Studies, Ireland*

Low strain rate areas of the earth are often host to long-recurrence but damaging earthquake cycles. In many cases, these events occur on reactivated and previously un-recognized faults. Noise-based imaging of seismic anisotropy is capable of revealing the seismic fabric of inherited structures that have the potential to fail causing catastrophic earthquakes. By understanding the orientation of seismic weaknesses, seismic hazard in areas of low-strain rate can be better understood. The geometric relation of crustal anisotropy and plate convergence (or the 3-D crustal stress tensor) has the potential to qualitatively inform the likelihood of large crustal earthquakes in regions with little previously recorded seismicity. In this study, noise cross correlation techniques were used to image surface-wave velocities. These measurements were inverted to solve for azimuthal anisotropy of fundamental mode Rayleigh waves in the Canterbury region of the South Island of New Zealand. The results of passive imaging show a distinct difference in magnitude and azimuth of surface-wave anisotropy for the crust. We suggest that the approximately east-west fast direction at shallow crustal levels reflects the Cretaceous faulting of the impacting Chatham Rise and the approximately northwest-southeast fast direction at upper mantle depths reflects the present plate boundary strain direction. Fast axes also show a significant apparent rotation (15–40° anticlockwise) in azimuth and amplitude across the study area.

Furthermore, the measured upper crust fast axis parallels the surface-rupturing Greendale Fault, which gave rise to the on-going destructive Canterbury earthquake sequence. We further suggest that our approach is capable of revealing dominant patterns of crustal weaknesses in regions like Canterbury that could be prone to low-recurrence, highly damaging earthquakes.

Numerical Models on Thermal and Rheological Sensitivity of Deformation Pattern at the Lithosphere-asthenosphere Boundary

L. Fuchs[1], H. Schmeling[2] and H. Koyi[1]

[1]*The Hans Ramberg Tectonic Laboratory, Department of Earth Sciences, Uppsala University, Sweden*

[2]*Goethe-University, Institute of Geosciences, Frankfurt am Main, Germany*

Understanding the interaction between the oceanic lithospheric plate and the upper mantle is a crucial part in understanding plate tectonics, especially along the lithosphere-asthenosphere boundary (LAB). In this study, we analysed shear strain integrated over time, within the upper 400 km of the mantle. The deformation is calculated using 1D self-consistent velocity profiles for certain plate ages. Thereby, the velocity depends on plate temperature, composite viscosity and a constant plate velocity. We used variable and constant thermal parameters to calculate the temperature field for a half space cooling model (HSCM) as well as plate model like temperature fields. The depth of the LAB is assumed to be mechanical and corresponds to the depth of the maximum shear strain, separating the high-viscous lithosphere from the low-viscous asthenosphere. Compared to a HSCM with constant thermal parameters, a model with variable thermal parameters results in a temperature difference of up to 110 °C within the upper 100 km of the oceanic lithosphere. The higher temperature leads to a shallower low viscosity region. Thus we obtain an upward shift of 35 km for the depth of the maximum shear strain. However, with a maximum depth of 120 km for an old (120 Ma) oceanic lithosphere it is still fairly deep. Therefore, a temperature field described by variable thermal parameters cannot be the only explanation for a shallow LAB. In the case of a plate-like temperature distribution, the depth of the maximum shear strain correlates with the thickness of the plate. However, calculating the rheologically consistent velocity across a “plate bottom” with a fixed temperature may be questionable. Including a horizontal pressure gradient resulting in a model with a faster flowing asthenosphere might be more consistent. Hence, the applied pressure gradient will change the deformation pattern significantly and we will further on focus on this. We also used a recent formulation of single-phase grain size evolution models, including damage theory, to calculate variable grain sizes. However, due to model stress and strain rate conditions, the resulting grain sizes are relatively large when intermediate parameters corresponding to laboratory data are applied. In these models, a 100% dislocation creep deformation occurs in the upper 400 km (i.e., the entire depth of the model). The grain sizes produced within the model are relatively large and might be compensated through the presence of a secondary phase (e.g. pyroxene).

Control of Lithosphere Structure on Surface Deformation in the Central Barents Sea: Insights From Dynamical Modeling

S. Gac[1]

[1] *Centre for Earth Evolution and Dynamics, University of Oslo, Norway*

The Barents Sea is located in the Northern European Arctic. The Eastern part of the Barents Sea features one of the deepest sedimentary basins in the world whereas the Western part is covered by a shallow sedimentary platform. Seismic tomography data (Levshin et al., 2007; Ritzmann and Faleide, 2009) show slower S wave velocity in the upper mantle beneath the East Barents Sea compared to the West Barents Sea indicating a steep deepening of the Lithosphere-Asthenosphere Boundary (LAB) in the Central Barents Sea from West to East. The Central Barents Sea is also marked by a South-North succession of regularly-spaced inverted structures (uplifted domes) such as the Fedinsky high and the Sentralbanken high. The origin of those inverted structures is under debate. The interpretation of recent seismic data in the Central Barents Sea suggests that the inversion is contemporaneous with the Late-Triassic-Early Jurassic westwards thrusting of Novaya Zemlya. This suggests that the origin of domes might be linked to compressional events on the east side of the Barents Sea. A 2D thermo-mechanical model of lithosphere shortening is used to explore the effect of LAB geometry on the surface deformation in the Central Barents Sea. The model is based on a Lagrangian finite element method (Gac et al., 2013). The model consists of a crust - mantle lithosphere characterized by non-linear temperature and pressure dependent visco-elastic-plastic rheologies. The mechanical model is coupled with a thermal model taking into account heat advection and diffusion. Sedimentation and gravity are taken into account. Contractional boundary conditions are applied on vertical sides of the model resulting in buckling of the crust. Several models are run for different geometry of the LAB. Preliminary results are shown. 3D conceptual models are then proposed to explain the 3D distribution of inverted structures in the Central Barents Sea. We further propose that this modeling can bring constraints on the kinematics of plates (mostly direction) involved at the time of formation of the domes.

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Quantifying the Role of Downgoing and Overriding Plates on the Deformation of Subducting Slabs within the Mantle Transition Zone: A Thermo-mechanical Modelling Approach

F. Garel[1,2], R. Davies[1,3], S. Goes[1], H. Davies[2], S. Kramer[1] and C. Wilson[4]

[1]*Department of Earth Science and Engineering, Imperial College London, UK*

[2]*School of Earth and Ocean Sciences, Cardiff University, UK*

[3]*Research School of Earth Sciences, The Australian National University, Canberra, Australia*

[4]*Lamont Doherty Earth Observatory, New York, USA.*

Seismic tomography images a wide range of slab morphologies within Earth's mantle, with some steep slabs extending deeper than 1500 km (e.g. Central America), whereas others seem to stagnate above the 660-km mineral transition from ringwoodite to perovskite (e.g. Japan). The forcing that resulted in these different morphologies is also likely to have affected plate velocities, overriding plate deformation and plate coupling. Previous studies have proposed a range of factors that may affect the interaction between slabs and the mantle transition zone. However, it is not yet clear which factors actually control the observed variability. The most systematic work, thus far, has been done in compositionally-defined subduction models with finite-length plates. We develop here a first-order thermo-mechanical model of a free subduction in 2D, to investigate the role of overriding plate geometry and downgoing plate strength (age/thickness and yield strength) on the deformation of a subducting plate that encounters a viscosity jump between upper and lower mantle. The rheology of the simulated material (representing both slab and mantle) is a composite law comprising diffusion creep, dislocation creep and a stress limiting rheology. The higher slab density arises purely due its temperature difference with surrounding mantle. A weak decoupling interface is present between subducting and overriding plate to allow for asymmetric subduction. The upper boundary can be modelled either as free slip or as a free surface. The adaptive dynamic meshing of the code Fluidity allows for high resolution (<<1 km) inside and around the plates, and lower resolution (>>100 km) near the boundaries of a large simulation domain, which are dynamically less significant. In our reference simulation, we observe an initial fast sinking of the slab, later slowed down by the viscosity jump. The strain-weakening rheologies lubricate the mantle around the slab and weaken the slab in high-stress regions. The specifics of the surface bending and plate deformation, as well as the characteristics of the weak layer, control the amount of trench retreat, and are a first-order control on deep slab morphology. The second control arises from the competition between slab strength and the mechanical deformation induced by the viscosity jump. By varying plate properties, we obtain a wide range of slab morphologies: old, thick slabs have a tendency to retreat, hence to flatten, more due to their high buoyancy. However, trench motion is reduced for slabs with a high yield strength, which may be associated with colder slabs. We also find that the role of the overriding plate on subduction dynamics is just as important as the role of the lower subducting plate. We see in our simulations that the dip of the slab in the middle of the upper mantle (resulting from trench retreat) has a strong influence on slab penetration through 660 km. However, it is not fully deterministic, since the deformation of sinking slabs by the viscosity jump is also dependent upon plate strength.

Spatial Characteristics and Clustering of Hotspot Positions and Mantle Plumes: A Comparison Between Observations and Convection Models

R. Gassmöller[1] and B. Steinberger[1,2]

[1] *GFZ Potsdam, Germany*

[2] *Centre for Earth Evolution and Dynamics, University of Oslo, Norway*

The positions of hot spots and eruption locations of large igneous provinces at the Earth's surface correlate well with the two Large Low Shear-wave Velocity Provinces (LLSVPs) at the core-mantle boundary (Torsvik et al., 2006). Moreover the fit between the hot spots and the edges of the LLSVPs was interpreted in the concept of the plume generation zones (PGZs) at these edges – zones of hot, possibly partially molten regions that may be associated with the seismically observed ultra-low-velocity regions near the core-mantle boundary (Burke et al., 2008). Mantle convection modelling and seismic observations have revealed a number of possible features and dynamic processes occurring near these PGZs including the arrival of slabs and the distinction between purely thermal or thermo-chemical boundary layers (Bower et al., 2012). In particular the incorporation of global plate reconstructions as surface velocity boundary conditions increased the fit and comparability between model results and real Earth observations (e.g., Bower et al., 2012; McNamara and Zhong, 2005). Nevertheless, the positions of plume generation and surface impingement have so far been far from realistic in these global models (Bower et al., 2012; McNamara and Zhong, 2005). In our work we compare positions and clustering of observed hot spots and model plumes to investigate the connection between prescribed subduction zones and the regions of plume generation. We show that a strong link exists between plate tectonics at the surface and plume generation at the core-mantle boundary. Moreover, we can show that with reasonable material properties the model plumes form two clusters that are similarly arranged as observed hot spots, overlying the centre of the LLSVPs. This connection and clustering is not observed in models without prescribed plate velocities and less pronounced in a purely thermal convection. The characteristics of these clusters are much closer to the observed hotspot distribution than to a convection model without prescribed plate velocities, further showing the large influence of plate tectonics on the mode and position of plume generation.

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Subduction Modelling with ASPECT

A. C. Glerum[1, 2], C. Thieulot[1, 3] and W. Spakman[1-3]

[1]*Department of Earth Sciences, Utrecht University, The Netherlands*

[2]*The Netherlands Research Centre for Integrated Solid Earth Science, The Netherlands*

[3]*Centre for Earth Evolution and Dynamics, University of Oslo, Norway*

ASPECT (Advanced Solver for Problems in Earth's ConvecTion) is a promising new code designed for modelling thermal convection in the mantle (Kronbichler et al., 2012). The code uses state-of-the-art numerical methods, such as high performance solvers and Adaptive Mesh Refinement (AMR). It builds on tried-and-well-tested libraries and works with plug-ins allowing easy extension to fine-tune it to the user's specific needs. We make use of the promising features of ASPECT, especially AMR and the advection of fields, for modelling lithosphere subduction in Cartesian and spherical geometries. As subduction modelling is not standard to ASPECT, we explore the necessary adaptive grid refinement and test ASPECT with well-known benchmarks and other models. We showcase examples of mechanical and thermo-mechanical oceanic subduction in which we vary the number of materials making up the overriding and subducting plates as well as the rheology (from linear viscous to more complicated rheologies). Both 2D and 3D geometries are used, as ASPECT easily extends to three dimensions (Kronbichler et al., 2012). We drive subduction self-consistently through negative buoyancy, material inflow or through prescribed surface velocities derived from tectonic reconstructions. Based on the above models, we discuss the importance of weak zones and AMR as well as the advection of compositional fields coupled to material properties.

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Towards Coupled Giant Impact and Long Term Interior Evolution Models

G. J. Golabek[1], M. Jutzi[2], T. V. Gerya[1] and E. I. Asphaug[3]

[1]*Institut für Geophysik, ETH Zürich, Switzerland*

[2]*Physikalisches Institut, University of Bern, Switzerland*

[3]*School of Earth and Space Exploration, Arizona State University, USA*

The crustal dichotomy (McCauley et al., 1972) is the dominant geological feature on planet Mars. The exogenic approach to the origin of the crustal dichotomy (Wilhelms and Squyres, 1984; Frey and Schultz, 1988; Andrews-Hanna et al., 2008; Marinova et al., 2008; Nimmo et al., 2008) assumes that the northern lowlands correspond to a giant impact basin formed after primordial crust formation. However these simulations only consider the impact phase without studying the long-term repercussions of such a collision. The endogenic approach (e.g., Weinstein, 1995), suggesting a degree-1 mantle upwelling underneath the southern highlands (Zhong and Zuber, 2001; Roberts and Zhong, 2006; Zhong, 2009; Keller and Tackley, 2009), relies on a high Rayleigh number and a particular viscosity profile to form a low degree convective pattern within the geological constraints for the dichotomy formation. Such vigorous convection, however, results in continuous magmatic resurfacing, destroying the initially dichotomous crustal structure in the long-term. A further option is a hybrid exogenic–endogenic approach (Reese and Solomatov, 2006, 2010; Reese et al., 2010; Golabek et al., 2011), which proposes an impact-induced magma ocean and subsequent superplume in the southern hemisphere. However these models rely on simple scaling laws to impose the thermal effects of the collision. Here we present the first results of impact simulations performed with a SPH code (Benz and Asphaug 1995, Jutzi et al., 2013) serially coupled with geodynamical computations performed using the code I3VIS (Gerya and Yuen, 2007) to improve the latter approach and test it against observations. We are exploring collisions varying the impactor velocities, impact angles and target body properties, and are gauging the sensitivity to the handoff from SPH to I3VIS. As expected, our first results indicate the formation of a transient hemispherical magma ocean in the impacted hemisphere, and the merging of the cores. We also find that impact angle and velocity have a strong effect on the post-impact temperature field (e.g., Marinova et al., 2008) and on the timescale and nature of core merger.

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Trench Rollback: From the Birth of Subduction to Global Plate Motions

M. Gurnis[1], L. Alisic[2], W. Leng[3], V. Ratnaswamy[1] and G. Stadler[4]

[1]*California Institute of Technology, USA*

[2]*Unviersity of Cambridge, UK*

[3]*USTC, China*

[4]*University of Texas, USA*

Plates are driven by buoyancy forces distributed in the mantle, within cooling oceanic plates (ridge push) and within subducted slabs. Although the case is often made that subducted slabs provide the principle driving force on plate motion, consensus has not been achieved. This is at least partially due to the great difficulty in realistically capturing the role of slabs in observationally-constrained models as slabs act to drive and resist plate motions through their high effective viscosity. Slab buoyancy acts directly on the edge of the plate (slab pull), while inducing mantle flow that tends to drag both subducting and overriding plates toward the trench. While plates bend during subduction they undergo a form of 'plastic failure' (as evident through faulting, seismicity and reduction of flexural parameters at the outer trench wall). The birth of a new subduction zone, subduction initiation, provides important insight into plate motions and subduction dynamics. About half of all subduction zones initiated over the Cenozoic and the geophysical and geological observations of them provide first order constraints on the mechanics of how these margins evolved from their preexisting tectonic state to self-sustaining subduction. We have examples of subduction initiation at different phases of the initiation process (e.g. early versus late) as well as how margins have responded to different tectonic forcings. The consequences of subduction initiation are variable: intense trench roll back and extensive boninitic volcanism followed initiation of the Izu-Bonin-Mariana arc while both were absent during Aleutian arc initiation. Such differences may be related to the character of the preexisting plates, the size of and forces on the plates, and how the lithosphere was initially bending during initiation. I will address issues associated with the forces driving plate tectonics and initiating new subduction zones from two perspectives. A common thread is the origin and evolution of intense back arc spreading and rapid roll back associated with some ocean-ocean subduction zones. I will look at the dynamics driving global plate motions and the time-dependence of trench rollback regionally. Capitalizing on advances in adaptive mesh refinement algorithms on parallel computers with individual plate margins resolved down to a scale of 1 kilometer, observationally constrained, high-resolution models of global mantle flow now capture the role of slabs and show how plate tectonics is regulated by the rheology of slabs. Back-arc extension and slab rollback are emergent consequences of slab descent in the upper mantle. I will then describe regional, time-dependent models, address the causes and consequences of subduction initiation, and show that most back arc extension follows subduction initiation. Returning to the global models, inverse models using the full adjoint of the variable viscosity, Stokes equation are now possible and allow an even greater link between present-day geophysical observations and the dynamics from local to global scales.

Three Dimensional Regional Models of Mantle Plumes

R. Hassan[1], N. Flament[1], R. D. Müller[1] and M. Gurnis[2]

[1]*School of Geosciences, The University of Sydney, Australia*

[2]*Seismological Laboratory, California Institute of Technology, USA*

Mantle plumes are proposed to explain a broad range of geological and geodynamical phenomena, such as volcanic island chains showing an age progression. Numerical studies suggest that mantle plumes could originate deep within the Earth, possibly at the core-mantle boundary, as a result of thermal instabilities. Thermal buoyancy causes such plumes to rise through the mantle and reach the base of the lithosphere. Numerical models of mantle plumes are routinely used to study their inception and subsequent ascent through the mantle. Numerous 2D studies have been performed - however, the combined effects of temperature dependent viscosity, thermal and chemical boundary layers on plume generation and their subsequent ascent velocities are still relatively poorly understood. Significant advances in computational capacity now allow for systematic 3D studies to be undertaken at resolutions fine enough to resolve highly convective plume features. We first design simple 3D isoviscous regional plume models under the Boussinesq approximation in CitcomS as a starting point, comparing results against analytical solutions. We impose a hot sphere of radius 200 km with an excess temperature of ~200 K – at the base of the lower mantle – to initiate our plume models. We study the effects of mesh resolution on resolving fine structures of ascending plumes, along with associated return flow as they reach the base of the lithosphere, and on that of the rate of convergence to analytical solutions. Building onto these results we then investigate the effects of thermal and chemical boundary layers, heat content and heat distribution of the initial temperature anomaly and temperature-dependent viscosity on the ascent velocity of plumes. In addition, we investigate the predicted evolution of dynamic topography and surface heat flux. We will use the results of our regional tests to devise appropriate parameterizations to implement active upwellings in forward global mantle flow models with compositionally distinct thermal boundary layers.

Strain Evolution and the Relative Role of Heat and Strain Rate During Continental Rupture

A. Huerta[1] and J. Crane[1]

[1]*Department of Geological Sciences, Central Washington University, USA*

The evolution of strain during continental rupture can be quite complex, with complexities due to changes in far-field stresses, or due to the naturally evolving strength profile of the lithosphere. Here we use a 2D finite element model to examine the evolution of rift systems and the relative impact of strain rate versus the initial thermal structure of the lithosphere. Model results indicate that the initial thermal structure of the lithosphere has first-order control on the rifting evolution and subsequent rupture, while stretching rate places a second-order control on the rifting evolution. Three styles of rift-to-rupture

evolution are recognized as distinguished by the location of rupture and the amount of strain accommodated prior to rupture. Style 1 is distinguished by limited strain prior to rupture that is located in the center of the rifted region; style 2 is distinguished by moderate amount of strain prior to rupture that is located near the edge of the rifted region, and style 3 is distinguished by extensive rifting without transition to rupture. In general, cool upper mantle temperatures are associated with style 1, moderate upper mantle temperatures and slower strain rates are associated with style 2, while hot upper mantle temperatures are associated with style 3. Detailed tracking of the modeled rifts provides key insights to the importance of the interaction between the evolving thermal structure, strength profile, and rift geometry. For example, the West Antarctic Rift System displayed an early stage of wide rifting, followed by a transition to rifting across a narrow region. Numerical simulations of the region suggest that this transition in rifting style was the natural result of the evolving thermal/strength structure of the lithosphere, and no change in plate motions nor impingement of a thermal plume is necessary to explain the strain evolution.

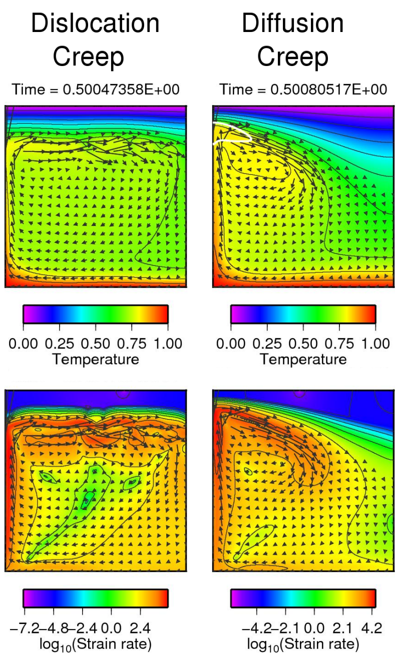
Can We Approximate Non-Newtonian Rheology?

C. Huettig[1], A-C. Plesa[1] and N. Tosi[2]

[1]*German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany*

[2]*Department of Planetary Geodesy, Technical University Berlin, Germany*

Over the past decades, with the increase of computational power, fully dynamical models of mantle convection have become one the most powerful tools to investigate the thermal evolution of planetary bodies and their interior processes. One of the most important parameters in mantle convection studies is the rheology since it is directly responsible for the convection vigor, the structural complexity and the shape of the up- and downwellings. In terrestrial mantles there are two main deformation mechanisms: diffusion and dislocation creep. The latter is thought to play an important role at lower pressure ranges, as inferred by seismic anisotropy in the Earth's upper mantle (van Hunen et al., 2005). Dislocation creep is more challenging to model than diffusion creep as the viscosity becomes strain rate dependent (Karato and Wu, 1993) introducing a strong non-linearity that requires much more computational time. To avoid this additional non-linearity, a Newtonian rheology (diffusion creep) with reduced activation parameters is used to mimic non-Newtonian behaviour as described in Christensen (1984). Although the steady-state simulations presented in Christensen (1984) show



that the reduction of the activation parameters should be used with care because they depend on the problem, subsequent studies often use these simplifications to a broad extend (i.e. Huang, 2013). We investigate the implications of this simplification for various scenarios to approximate an error and show comparisons. We show that, although some global properties as mean temperature, root mean square velocity and Nusselt number are pretty similar, the structure of the plumes and the stress distribution is quite different. Furthermore, systematic errors evolve for thermal evolutions around 3%. We conclude that approximating dislocation creep with diffusion creep may strongly affect the results if introducing local effects like partial melt production and plastic yielding.

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A Novel and "Cheap" Pre-conditioner for Stokes-flow with Varying Viscosities

C. Huettig[1], A-C. Plesa[1] and N. Tosi[2]

[1]*German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany*

[2]*Department of Planetary Geodesy, Technical University Berlin, Germany*

Over the past decades, with the increase of computational power, fully dynamical models of mantle convection have become one the most powerful tools to investigate the thermal evolution of planetary bodies and their interior processes. The so-called Stokes-flow is a simplification of the Navier-Stokes equations to conserve momentum and mass. Solving these equations is far from trivial as it involves a saddle-point problem. Many efficient approaches exist for similar iso-viscous problems as they share a wide range of applications, but with the increased complexity of introducing varying viscosities necessary almost only in the domain of mantle convection, many of these simplifications vanish or become extremely complicated to implement (Langtangen et al., 2002). We present a novel method to tackle this problem in an easy to understand and yet very efficient manner. Our method focuses on solving a single matrix involving all four unknown elements, the velocity components and pressure. Usually this is tackled by splitting methods such as SIMPLE(R/C) (Caretto et al., 1972), but we found a more efficient way using a single matrix solve using only the iterative solver BiCGS (Saad, 1996) with a novel selective Jacobi pre-conditioner. The pre-conditioner is not a matrix and very easy to set up. Usually methods like BiCGS perform poorly on saddle-point problems, but with viscosity-based matrix conditioning and our new selective pre-conditioner these problems can be mitigated. We show how the new method performs against splitting methods and different pre-conditioners and solvers. Parallel speed-up is shown on multiple 2D and 3D grids, including spherical.

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Sub-lithospheric Small Scale Convection - A Mechanism for Continental Collision Magmatism

L. Kaislaniemi[1], J. van Hunen[1], M. B. Allen[1] and I. Neill[1]

[1]*Department of Earth Sciences, Durham University, UK*

We present a combined geodynamic-petrological model to explain the widespread but relatively small volume mantle-derived volcanism that develops during continent-continent collision. The model is applied to the Turkish-Iranian plateau, and is also applicable to many other areas of collisional magmatism, e.g. the circum-Mediterranean region and across Tibet. Volcanism has occurred within the Arabia-Eurasia collision zone since the initial collision at ~25–35 Ma, mainly on the Eurasian side of the suture within Iran, Armenia and eastern Anatolia (Turkey). It is irregularly distributed in space and in time, and has intensified during the Pliocene and Quaternary. The magmatism is geochemically heterogeneous, ranging from basalts to rhyolites, and from alkaline to calc-alkaline. Both enriched, subduction modified, lithospheric mantle and OIB-like asthenospheric sources are proposed as source regions by geochemical studies. Seismic studies show thickened crust (45–60 km) but highly variable lithospheric thicknesses (60 to >200 km). Slab break-off and mantle delamination have been previously proposed as mechanisms for the volcanism, but these mechanisms cannot fully explain the scattered patterns of the volcanism across the whole Turkish-Iranian plateau. Using a numerical mantle convection model, linked with melting, water dependent viscosity and depletion dependent buoyancy parameterizations, we show that the volcanism can be caused by a decreased viscosity of the asthenosphere and lower lithosphere, due to elevated water contents. This viscosity decrease enhances the spontaneous Rayleigh-Taylor instabilities of the base of the lithosphere and allows a small scale convection pattern to form. These convection cells are able to erode locally the bottom of the lithosphere, and, together with lowered solidus of the mantle, small-degree (< 1%) asthenospheric melts form. If extracted directly to the surface, these melting pockets cause an irregularly spaced pattern of volcanic centres, that have a dominant wavelength of 200–300 km and typical thicknesses from tens of meters to a few hundreds of meters. The volcanic centres can be productive for less than 500 ka up to 5 Ma and have a binomial periodicity of ~20–30 Ma and of a few million years. The amount of water in the mantle, contributing to the viscosity and solidus lowering, needs to be about 200 ppm (causing a viscosity decrease of about one order of magnitude). This is not enough to cause deep mantle wedge melting during the pre-collision subduction, so it will not be removed by the wedge flux melting, but could be transferred down within the stable hydrous phases of the mantle peridotite by the wedge flow.

Two hundred ppm is, however, enough to cause melting at shallower level, garnet-spinel transition depths, after erosion of the base of the lithosphere. The source of the increased asthenospheric water amounts can then be attributed to the "leftovers" of the mantle wedge melting, dragged down with the wedge corner flow. The water is released by the breakdown of the hydrous phases once the subduction has stopped, the flow pattern has normalized, and the hydrous phases are convected to shallower levels. Our model does not require oceanic slab break-off, but such additional dynamics could enhance the melting process. The model shows asthenospheric decompressional melting, but also lithospheric melting. The latter occurs as parts of the lithosphere are eroded during the convection, then circulated in the hot asthenosphere, heated up, and then returned to shallower levels where they melt. Conductive heating of the lithosphere does not seem to play an important role in melting of the lithospheric mantle. This asthenosphere-lithosphere interaction can be understood as the reason for the bimodal source region distribution within the volcanics: prolonged hydration of the lithosphere during the subduction, and subsequent post-collisional melting of the asthenosphere and lithosphere, the latter being further enriched by the asthenospheric melts.

Evolution of Earth's Early Crust: Lessons Learned from Coupled Petrological and Geodynamic Modelling

B. Kaus[1], T. Johnson[1], M. Brown[2] and J. van Tongeren[3]

[1]*Johannes Gutenberg University Mainz, Germany*

[2]*University of Maryland, USA*

[3]*Yale University, USA*

Understanding how crust was created and evolved during early Earth history is important. Petrological and thermal models suggest that ambient mantle potential temperatures in the Archaean were > or >> 1500 °C, leading to a higher degree of partial melting and the generation of a thick (up to 45 km) MgO-rich primary crust that was underlain by highly residual mantle. However, the preserved volume of this crust is low, which suggests most of was recycled or sequestered at depth in the mantle. Here we couple calculated phase equilibria for hydrated and anhydrous crust compositions and their residues with parameterized 2-D geodynamic models to investigate the stability and evolution of early Archaean lithosphere. Petrological modelling shows that, with increasing ambient mantle potential temperature, the density of primary crust increases more dramatically than the density of residual mantle decreases. Depending on the degree of hydration, MgO-rich primary crust was ultramafic (i.e. it lacked plagioclase) and would have become gravitationally unstable at thicknesses of around 35 km (anhydrous) to 45 km (fully hydrated). Geodynamic modelling of this process requires developing an adequate melting and melt extraction algorithm that allows the creation of new crust and the depletion of the remaining mantle in a simple, yet efficient manner. We have developed this for a tracer-based geodynamic code. Modelling results show that a gravitationally unstable crust does not necessarily

mean that it will rapidly form Rayleigh-Taylor instabilities, contrary to a widely-held belief in the petrological community. Only if the viscosity around the Moho is sufficiently low is the mechanism geodynamically plausible. Models indicate that this is the case for potential temperatures that are larger than 1550–1600 °C, depending on whether a “wet” or a “dry” diffusion and dislocation creep mechanism is employed for the mantle rheology. In cases where Rayleigh-Taylor instabilities develop, upwellings in the mantle and decompression melting cause the crust to locally thicken, such that it’s base becomes both gravitationally unstable and hot. Relatively small-scale Rayleigh-Taylor instabilities drip off at the base of the crust, driving mantle flow and further upwellings. The delaminated crust would have refertilized residual mantle or melted and, with adiabatic melting, forms new plateau-like units of new crust by magmatic thickening, further driving delamination at the base of the crust. Ultimately this new crust could have melted to produce the tonalitic to trondhjemite rocks that characterise the Archaean continental crust. Scaling laws are developed to explain the key observations in the numerical models and explain why drips at the base of the crust are rather small-scale features that are likely to have existed in the Archean crust, but unlikely to occur on the present-day Earth.

Strongly Temperature and Pressure-dependent Viscous Convection

T. S. Khaleque[1], A. C. Fowler[1] and P. D. Howell[1]

[1]*Oxford Centre of Industrial and Applied Mathematics (OCIAM), Mathematical Institute, University of Oxford, UK*

The unusual behaviour of the convection of the Earth's mantle comes from the complicated nature of the convecting mantle materials. Our focus is on the influence of variable viscosity on the mantle convection. We propose a mathematical model for a basally heated mantle that incorporates temperature and pressure-dependent viscosity defined in an Arrhenius form. The mathematical model is solved numerically for large viscosity variations (of order 10^{30}) across the mantle in a unit aspect-ratio cell and steady solutions for temperature, isotherms and streamlines are obtained. In order to improve the efficiency of numerical computation, we use a modified form of viscosity with a low temperature cut-off. The results are in good agreement with the previous results. There is a suggestion that narrow cells are preferred at extreme viscosity contrasts.

Formation Conditions Recorded by OH-point Defects in Quartz – Experimental and Analytical Approach

M. A. Kohut[1], R. Stalder[1] and J. Konzett[1]

[1]*Institute of Mineralogy and Petrography, University of Innsbruck, Austria*

Quartz is a common nominally anhydrous mineral of the Earth's crust. It occurs in many different geodynamical environments both as a primary or secondary phase. Traces of hydrogen found in quartz as molecular water in fluid inclusions, or as a structurally incorporated hydroxyl ions can dramatically change physical properties of minerals that are a key to understand dynamical processes within the crustal conditions. Moreover, the structurally bound hydrogen commonly acts as a charge compensator, associated with point defects, such as substitution of Si^{4+} by Al^{3+} with charge balance maintained be monovalent cations (H^+, Li^+ and Na^+), trivalent (Fe^{3+}, B^{3+}) or pentavalent cations (P^{5+}). The occurrence of hydrogen affects thermodynamic properties of minerals and even small amounts of OH defects influence their kinetic behavior during diffusion and phase transformations. In this work the incorporation of OH-defects in quartz in the systems granite-tourmaline-water and granite-spodumene-water was studied at different pressures and temperatures. Piston-cylinder experiments were carried at pressures between 5 and 25 kbar and temperatures between 800 and 1050°C. Oriented and polished single quartz crystals from each run were characterized with FT-IR spectroscopy and water contents were calculated using mineral-specific (Aines et al. 1984; Thomas et al., 2009), and general wavelength-specific calibrations (Libowitzky and Rossman, 1997) calibrations. The observed OH absorption features were assigned to Al^{3+} substitution (Al-H defect, band-triplet at 3320, 3383 and 3434 cm^{-1}), B^{3+} substitution (sharp absorption band at 3597 cm^{-1}), Li^+ incorporation (weak absorption band at 3475 cm^{-1}) and hydrogarnet $(4H)_{Si}$ defect (absorption at 3585 cm^{-1}). The contents of OH-point defect in quartz are highly variable, depending on pressure, temperature and the chemical environment. Specifically, synthesized crystals show a negative correlation of water content vs. pressure. Under lower pressures quartz incorporates more OH (5 kbar: 450–750 ppm H_2O) than at higher pressures (25 kbar: 72–106 ppm H_2O). Therefore, our results imply that IR spectra of quartzes have a potential to be used as a geobaromether to indicate petrological formation conditions. Moreover, the B- and Li-specific OH absorption bands may be used to quantify the charge balancing B^{3+} and Li^+ content that could be used as a novel and indirect analytical tool to detect traces of B and Li in quartz crystals.

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Modelling Subduction Zone Magmatism due to Hydraulic Fracture

R. Lawton[1] and J. H. Davies[1]

[1]*School of Earth and Ocean Sciences, Cardiff University, UK*

The aim of the project is to investigate the effect of the addition of water, from hydraulic fracture, to the mantle in a subduction zone. We assume the water interconnects in the subducting slab causing a build up of pressure until hydrofracture occurs. The hydrofracture will expand in the direction of the least compressive stress and propagate perpendicularly to this. For angles greater than the critical angle the fracture will propagate away from the wedge corner and for an angle less than the critical angle the fracture will propagate towards the wedge corner. We calculated the fracture paths for a range of fracture start points from the subducting slab. A temperature field for a subduction zone was calculated to establish the degree of melting due to the addition of water; this used a finite difference Matlab code to solve the heat equation for a subduction zone region. To calculate the degree of melting for points along the fracture paths we assume two things: a) a flash melting regime where all the water has been added at once and b) this causes saturation of water. Using the temperature taken from the thermal model the melt fraction is calculated. Only the melt fractions for angles greater than the critical angle are calculated; angles lower than the critical angle we assume to be caused by magma fracture as opposed to a hydrofracture. For points along the line where the angle equals the critical angle as distance from the wedge corner (r) increases so does the temperature, until r ~300 km at which point the temperature becomes constant. In conclusion as r increases from the wedge corner the melt fraction increases until r ~300 km where the melt fraction then starts to decrease. This is due to the melt fraction being dependent on temperature and pressure thus as the temperature becomes constant the melt fraction decreases. Future work will involve modelling the melt due to hydrous fluxing and adiabatic decompression; this will use markers in the thermal model to track the water and subsequent melt.

A Discontinuous Galerkin Method for Variable-viscosity Stokes Flow

R. Lehmann[1, 2], B. Kaus[1, 2] and M. Lukacova[1, 3]

[1]*Center for Computational Sciences, JGU Mainz, Germany*

[2]*Institute of Geosciences, JGU Mainz, Germany*

[3]*Institute of Mathematics, JGU Mainz, Germany*

We present results of a study comparing two different numerical approaches for solving the Stokes equations with variable viscosity: the continuous Galerkin (i.e., FEM) and the discontinuous Galerkin (DG) method. Nonlinearities in the viscosity or other material parameters can lead to discontinuities in the velocity-pressure solution that may not be approximated well with continuous elements. The DG method allows for discontinuities across interior edges of the underlying mesh. Furthermore, it provides the capability to locally adapt the polynomial degree and needs communication only between directly

adjacent mesh cells making it highly flexible and easy to parallelize. The methods are compared for several benchmarking setups and discussed with respect to speed, accuracy, computational efficiency. Elements of different order are used for both methods on a quadrilateral grid (rectangular and non-rectangular).

Effects of a Low Viscosity Post-perovskite on the Stability and Structures of the Primordial Dense Reservoirs in the Lower Mantle

Y. Li[1], F. Deschamps[2] and P. J. Tackley[1]
[1]*Institute of geophysics, ETH Zurich, Switzerland*
[2]*Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan*

A major discovery of the past decade in mineral physics is the post-perovskite phase transition, which may occur in the lower-most mantle of the Earth (e.g., Oganov, 2004). More recent studies (e.g., Ammann et al., 2010) show that the post-perovskite may be less viscous than perovskite in an order of 10^3 or 10^4. Such a low viscosity post-perovskite as well as its large Clapeyron slope may play an important role to the dynamics of the lower mantle. Here we performed numerical simulations of thermo-chemical convection in 2D-annulus geometry to investigate the effects of a low viscosity post-perovskite on the stability and structures of primordial dense reservoirs in the lower mantle. Preliminary results show that a low viscosity post-perovskite (10^{-3}) weakens the primordial dense reservoirs located at the bottom of the annulus, but amplifies the spreading of these reservoirs around the CMB. A large Clapeyron slope of the post-perovskite phase change (13 MPa/K) slightly increases the temperature of the mantle, the size of heterogeneities decreases, and the reservoirs of dense material are less stable.

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Inheritance of Continental Rifting on Incipient Seafloor Spreading Pattern: Insights from 3D Numerical Modeling

J. Liao[1] and T. Gerya[1]
[1]*Institute of Geophysics, ETH Zurich, Switzerland*

Seafloor spreading is a consequence of successive continental rifting, starting when continental breakup occurs. Spreading ridges have diverse geometries on a map view, for instance, short straight ridge segments connected by transform faults versus long curved ridge without any transform faults such as the Knipovitch ridge in the Arctic ridge system (Dick et al., 2003), orthogonal spreading versus oblique spreading (Gerya, 2013; Hieronymus, 2004), and two end member interactions between ridge segments: overlapping versus transform faults (Tentler and Acocella, 2010; Acocella, 2008; Choi et al., 2008; Allken et al., 2011; Allken and Huismans, 2012). Oceanic ridge pattern is organized greatly by the ridge itself once when the seafloor spreading commences (Hieronymus, 2004), and different oceanic ridge patterns can be generated from an incipient straight oceanic ridge based on different physical parameters (Gerya, 2010, 2013). The physical parameters controlling oceanic ridge geometries remain hotly debated in geodynamic literatures (Gerya, 2010, 2013; Choi et al., 2008; Hieronymus, 2004). Inheritance of the previous extension history and pre-existing structures play a significant role in controlling continental rifts development. Continental rifts do not occur randomly, but like to follow the pre-existing weakness (such as fault zones, suture zones, failed rifts, and other tectonic boundaries) in the lithosphere (Dunbar, 1988, and the references therein), although the origin of the earliest weakness formed in the proto-lithosphere is debated. The early stage formed rift can be a template for the future rift development and continental breakup (Keranen and Klemperer, 2008). Dynamic models suggest that oceanic ridge patterns are formed in the early spreading stage without substantial influence from mantle flow (Hieronymus, 2004; Choi et al., 2008). Here, a fundament question is related to the inheritance from the rifting history. Besides the intrinsic physical parameters affecting ridge patterns, is there any inheritance transmitted from rifting to spreading through the continental breakup influence ridge patterns? If yes, how the inheritance influences the incipient oceanic ridge pattern? We use 3D numerical modeling to study the inheritance of continental rifting on the incipient seafloor spreading patterns. An initial weak zone is imposed in either crust or mantle lithosphere, and the whole extension process from continental rifting to seafloor spreading is simulated. In our study, we find that: 1. 3D continental breakup and seafloor spreading patterns are controlled by (a) crust-mantle rheological coupling and (b) geometry and position of the pre-existing weak zones. 2. Three spreading patterns are obtained: (a) straight ridges, (b) curved ridges and (c) overlapping ridges. 3. When crust and mantle are decoupled, abandoned rift structures often form.

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The Effect of Melting and Crustal Production on Plate Tectonics on Terrestrial Planets

D. L. Lourenço[1] and P. J. Tackley[1]

[1] *Institute of Geophysics, Department of Earth Sciences, ETH Zürich, Switzerland*

In the Solar System, Earth is the only planet to be in a mobile-lid regime, whilst it is generally accepted that all the other terrestrial planets are currently in a stagnant-lid regime, showing little or no surface motion. A transitional regime between these two, showing episodic overturns of an unstable stagnant lid, is also possible and has been proposed for Venus (e.g., Armann and Tackley, 2012). Using plastic yielding to self-consistently generate plate tectonics on an Earth-like planet with strongly temperature-dependent viscosity is now well-established, but such models typically focus on purely thermal convection, whereas compositional variations in the lithosphere can alter the stress state and greatly influence the likelihood of plate tectonics. For example, Rolf and Tackley (2011) showed that the addition of a continent can reduce the critical yield stress for mobile-lid behaviour by a factor of around 2. Complicating matters is the finding that the final state of the system (stagnant- or mobile-lid) can depend on initial condition. Weller and Lenardic (2012) found that the parameter range in which two solutions are obtained increases with viscosity contrast, leading to Lenardic and Crowley (2012) proposing a bistability of the system, introducing bifurcation theory to predict the tectonic state of a planet. We can also say that melting has a major role in the long-term evolution of rocky planets: (1) Partial melting causes differentiation in both major elements (like Fe and Si) and trace elements, because trace elements are generally incompatible. Some of these trace elements contain heat-producing isotopes, which contribute around 50% of the present-day heat loss from the interior; (2) Production of partial melt and its eruption to the ocean floor, where it solidifies and cools, is the transportation of heat from the interior. At earlier times when the Earth was hotter and heat-producing elements were more energetic, this transported heat could have contributed greatly more than today; (3) Melting and volcanism are an important heat loss mechanism at early times that act as a strong thermostat, buffering mantle temperature and preventing it from getting too hot; (4) Mantle melting dehydrates and hardens the shallow part of the mantle and introduces viscosity and compositional stratifications in the shallow mantle due to viscosity variations with the loss of hydrogen upon melting. In this work we present a set of 2D spherical annulus simulations using StagYY (Tackley, 2008), which uses a finite-volume scheme for advection of temperature, a multigrid solver to obtain a velocity-pressure solution at each time step, tracers to track composition, and a treatment of partial melting and crustal formation. We focus on the question whether melting-induced crustal production changes the critical yield stress needed to obtain mobile-lid behaviour as a function of governing parameters, particularly the reference viscosity and thus the Rayleigh number. Our results show that melting and crustal production strongly influences plate tectonics on terrestrial planets, both making plate tectonics easier and harder, i.e., for the same yield stress and reference viscosity the use or not of a treatment for melting and crustal production may result in a change from a stagnant-lid regime into an episodic-lid regime or a change from mobile-lid regime to an episodic-lid regime. Several factors can play a role on these, namely laterally-heterogeneities and differences in the thickness of the lid induced by melting and crustal production, the maximum depth of melting, etc.

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Strong Intracontinental Lithospheric Deformation in South China: Implications from Seismic Observations and Geodynamic Modeling

G. Lu[1], L. Zhao[2], T. Zheng[2] and B. Kaus[3]

[1]*Key Laboratory of the Earth's Deep Interior, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China*

[2]*State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China*

[3]*Johannes Gutenberg University Mainz, Institute of Geosciences, Germany*

Classical plate tectonics theory expects concentrated deformation at plate boundaries and weak deformation within the plates. Yet, the existence of intracontinental orogens shows that highly deformed regions can occur within continental plates, which is geodynamically incompletely understood. Shear wave splitting measurements in South China show belt-parallel fast directions beneath the Wulingshan-Xuefengshan Belts, while no dominant fast direction is found in the Sichuan Basin, which is consistent with it being a cratonic core. Tomographic studies in the same area showed that the shear velocity beneath the intracontinental orogen is higher than that beneath the cratonic core. In order to better understand the seismic observations, we performed numerical experiments of collision of a continental lithosphere with a craton. By comparing model results with topography data and constraints on the accumulated amount of shortening in the study region, we find that the best-fitting results are obtained for models with a weak mantle lithosphere beneath the orogen belt with an effective viscosity that is 1–2 orders of magnitude smaller than that of the craton. Our numerical model successfully explains the belt-parallel anisotropy and high velocity anomaly beneath intracontinental orogen and suggests that significant intracontinental lithospheric deformation occurred in South China.

Crystal Settling and Crystal Growth Caused by Ostwald Ripening in a Terrestrial Magma Ocean Under Rotation

C. Maas[1], A. Möller[1] and U. Hansen[1]

[1]*Institute for Geophysics, University of Münster, Germany*

About 4.5 billion years ago the earth was covered by a global magma ocean approximately 1000 km deep caused by an impact of a mars-sized impactor in a later stage of the earth's accretion. This early magma ocean was heavily convecting and rotating. Some time after the separation of metal and silicate and the formation of the earth's core the magma ocean began to crystallize. At a certain depth and pressure the temperature of the magma ocean reaches the Liquidus and small silicate crystals emerge. When the fluid is supersaturated with crystals they begin to grow by Ostwald Ripening. This process can be observed in solutions and emulsions and results in shrinking of small crystals and growing of large crystals on behalf of the smaller ones. So with increasing time the silicate crystal radius changes which also affects the settling time of the crystals. One question which is still under great debate is whether fractional or equilibrium crystallization occurred in the magma ocean. Fractional crystallization means that different mineral fractions settle one after the other which would lead to a strongly differentiated mantle after solidification of the magma ocean. In contrast to that equilibrium crystallization would result in an undifferentiated and well-mixed mantle. These two scenarios can be distinguished by comparing the settling time of the crystals with the crystallization time of the magma ocean. Whether fractional or equilibrium crystallization occurred is for example important for the starting model of plate tectonics or the understanding of the mantle development until today. To study the settling, shrinking and growing of crystals in the vigorously convecting and rotating magma ocean we employed a 3D Cartesian numerical model with finite Prandtl number. Due to the low viscosity of the early magma ocean and strong rotation the influence of rotation on the fluid flow cannot be neglected. Our numerical model is divided in two parts, the fluid model and the particle model. The fluid code is based on a Finite Volume discretization, while the silicate crystals are modelled with a discrete element model. The crystals influence the fluid flow and are able to grow, shrink, vanish and form. In addition to that they interact with each other through a collision algorithm and gravitational, Coriolis and drag forces due to the fluid acts on them. In our present work we study the crystal settling depending on different rotation rates and rotation axes with two configurations. For the first setting the rotation axis is parallel to the gravitational acceleration, which corresponds to the situation at the earth pole, the other case is located at the equator where the rotation axis is perpendicular to gravity. At the pole with low rotation a large fraction of crystals is kept in suspension. With increasing rotation the crystals settle and form a thick crystal layer at the bottom of the magma ocean. At the equator we find three regimes depending on the rotation strength. At low rotation a high fraction of silicate crystals settle at the bottom. At higher rotation the silicates form a thick crystal layer in the bottom 1/3 of box. At high rotation all crystals are suspended and we observe a ribbon structure in the middle of the box. With a second model we investigate growing and shrinking of crystals by Ostwald Ripening and also include formation and melting of crystals. In general we observe the same behaviour and regimes as described above. However due to Ostwald Ripening the evolution of crystal radius with time depends on the strength of rotation and on the orientation of the rotation axis. Very first results show that at the pole the growth of the silicate crystals is limited. The resulting small radius leads to a slow crystal settling. At the equator the crystals are able to grow larger than at the pole and therefore settle faster. This could lead to an asymmetrical crystallization of the magma ocean. Due to the different settling times in an extreme case this could lead to a well mixed mantle at the pole after the solidification of the magma ocean whereas at the equator the mantle could be strongly differentiated.

Slab Dehydration in the Early Earth: Insights from Numerical Models Integrated with Thermodynamic Data

V. Magni[1], P. Bouilhol[1], J. van Hunen J[1] and L. Kaislaniemi[1]

[1]*Department of Earth Sciences, Durham University, UK*

The andesitic nature of the bulk continental crust, as well as its characteristic trace element ratios, have a close resemblance to the differentiated crust of volcanic arcs, thus leading to models for formation of continental crust in subduction zone settings. Even if the modern processes leading to continental crust formation at convergent margins are well constrained, the extrapolation to early Earth conditions is hazardous, because the composition of Earth's early crust is affected by a number of poorly constrained processes. However, a large part of the Archean continental crust is made of a composite rock assemblage dominated by granitoids belonging to the TTG series (tonalite-trondhejmeite-granodiorite) that show a subduction signature. We present the results of a study where numerical models of subduction are integrated with a thermodynamic database. We particularly focus our attention on the fate of water, since it is a component that is essential to the formation of TTG series. The amount and composition of water bearing fluids in a subduction zone is controlled by slab devolatilization, and influence both the melting regime and the melt composition. Our goal is to investigate under which conditions (i.e., pressure, temperature and paragenesis) dehydration occurs, since this has a main influence on the composition of the fluids released during subduction and, on the trace elements composition of the continental crust that would ultimately form in the arc. We compare results from two main different scenarios representing the present-day and the Early Earth subduction system. Our preliminary results show that in an early Earth regime slab dehydration occurs at much shallower depths and higher temperatures compared with the present-day situation. Moreover, different mineral phases are involved in the dehydration process leading to different trace elements patterns of the released fluids.

Estimating Lithospheric Stresses: Parameters Check with Applications to the African Plate

S. Medvedev[1]

[1]*Centre for earth Evolution and Dynamics, University of Oslo, Norway*

Several mechanisms control the state of stress within plates on Earth. The list may be long, but first-order mechanisms are well known and include ridge push, mantle drag, stresses invoked by lateral variations of lithospheric density structure and subduction processes. We attempt to quantify the influence of these mechanisms and to construct a reliable model to understand modern and, in perspective, palaeo-stresses within the lithosphere using the African plate (TAP) as an example. The finite-element based suite ProShell was developed to combine several data sets and calculate stresses on the real (non-planar) geometry of TAP. We introduced several quantitative parameters to measure proximity of results and observations and iterated the model parameters to match the observed stresses as good as possible. The starting model is based on the CRUST2 data set and half-space-cooling model to approximate the lithospheric mantle. The results, however, are not satisfactory, which might be related to oversimplifications of the starting model. Consecutive increase of the model complexity was performed by considering additional features, such as exact match between model depth structure and observed topography, a basal drag from the mantle, lateral variations of physical parameters of lithosphere within TAP and along its boundaries. These complexities not only bring the model closer to reality, but also bring results of calculations closer to observations and therefore show improvement of model predictability and reliability. Our models show that stress regime within TAP is mainly set up by global balance of masses and mass moments within the lithosphere. The orientation of stresses, in contrast, influenced more by the local features. In addition to the traditional mechanisms controlling stress orientations (e.g., lateral variations of crustal density structure, basal drag from convecting mantle, and rheological variations of TAP), we demonstrate that density variations in the lithospheric mantle are important for stress directions.

Impact of Fluid-rock Interactions and Metamorphic Reactions on Rheological Evolution and Style of Rifting during Extension

L. Mezri[1]**, L. Le Pourhiet**[1]**, S. Wolf**[1] **and E. Burov**[1]

[1]*UMPC, ISTEP, Paris, France*

Over the last decade, the scientific community pushed forward models with heterogeneous initial conditions to simulate the impact of structural inheritance on the geometry and on the amount of pre-break up extension accommodated by passive margins. In this study, we develop a new model of inheritance where the latter is introduced by considering rocks out of thermodynamical equilibrium. However, the metamorphic reactions imply important mass transfers and occurrence of non-hydrostatic fluid pressure gradients during deformation and exhumation rocks. These phenomena are associated to fluid circulation which is affected by porosity and permeability that in-turn are the functions of strain and of degree of metamorphism. They are known to have a considerable influence on the effective mechanical properties of the rocks within the shear zone. The observed P-T-t paths indicate that during extension, the rocks experience initial decompression, followed by a phase of reheating and ended, almost systematically, by retrograde phase, in winch temperature and pressure diminish with increasing deformation. The occurrence of retrograde reactions implies that at some stages the water re-enters the dehydrated parts of the system, resulting in rheological (re)-softening. Otherwise, without water, metamorphic reactions would not occur and the rocks would have preserved their dry (i.e., strong) rheologies. These last factors, i.e., meta-stable states and retrograde reactions in presence of water, are not accounted in current thermo-dynamically coupled thermo-mechanical models. Using a new numerical approach that couples fluid flow and out-of-equilibrium thermodynamics, we undertake a parametric study of porosity and permeability. We study the impact of metamorphic inheritance on rifting for a composition of homogeneous granite rock calibrated at thermodynamical equilibrium. We demonstrate that these factors influence the rheology of the lithosphere and deformation styles at large scale during extensional regime.

Numerical Modeling of Deep Mantle Flow: Thermochemical Convection and Entrainment

E. Mulyukova[1], B. Steinberger[1], M. Dabrowski[2], S. Sobolev[1] and D. Bercovici[3]

[1]*GFZ Potsdam, Physics of the Earth, Germany*

[2]*Computational Geology Laboratory, Polish Geological Institute - National Research Institute, Wroclaw, Poland*

[3]*Yale University, Department of Geology and Geophysics, USA*

One of the most robust results from tomographic studies is the existence of two antipodally located Large Low Shear-wave Velocity Provinces (LLSVPs) at the base of the mantle, which appear to be chemically denser than the ambient mantle. Results from reconstruction studies (Torsvik et al., 2006) infer that the LLSVPs are stable, long-lived, and are sampled by deep mantle plumes that rise predominantly from their margins. The amount of the anomalous LLSVP-material that gets entrained into the rising plumes poses a constraint on the survival time of the LLSVPs, as well as on the plume buoyancy, on the lithospheric uplift associated with plume interaction and geochemical signature of the erupted lavas observed at the Earth's surface. Recent estimates for the plume responsible for the formation of the Siberian Flood Basalts give about 15% of entrained dense recycled oceanic crust, which made the hot mantle plume almost neutrally buoyant (Sobolev et al., 2011). If it wasn't for the destabilizing flow, or entrainment, by the hot rising plumes, the anomalously dense material in the Earth's deep mantle may have never made its way to the surface. In order for the entrainment to take place, the destabilizing viscous stresses acting on a volume of anomalously dense material must exceed the gravitationally stabilizing stresses associated with buoyancy. Just how capable is a mantle plume at uplifting an otherwise gravitationally stable material? To investigate this question, we perform numerical simulations of thermal convection with presence of a chemically dense basal layer in a 2D Cartesian box. In agreement with other studies, we find that the governing parameters are the buoyancy ratio between the thermal and the chemical density anomalies, as well as the viscosity variations. This observation elucidates the link between the geometry of the dense material and its stability: the effective buoyancy forces acting on the dense material depend on its volume, while the effective viscous drag due to ambient flow depends on its surface area. Additional complexity arises due to the thermal and mechanical feedback between the two materials. The amount of basal heat that flows into the ambient material, and provides the excess buoyancy to drive the destabilising flow, depends on the topography (thickness) of the dense basal layer. This is because the latter acts as a thermally insulating layer between the isothermal hot lower boundary and the overlying ambient material. The topography of the layer, in turn, depends on the flow of the ambient material: the dense layer is thickened beneath the upwelling flow, and thinned, or absent, beneath the downwelling flow. The amount of thickening or thinning of the dense layer is proportional to the strength of the ambient flow. We present the results of the numerical simulations, demonstrating the mechanical and thermal interplay between the anomalously dense and the ambient materials, and its effect on the entrainment of the dense material by the ambient flow. We also present the preliminary results of a semianalytical model, which we use to analyse this physical system, as well as to help interpret the numerical results.

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A Coupled Thermo-chemical Evolution of Earth's Mantle and Core: Effects of a Three-component Mantle Dynamics

T. Nakagawa[1] and P. J. Tackley[2],

[1]*Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan*

[2]*Institute of Geophysics, Department of Earth Sciences, ETH Zurich, Switzerland*

We investigate thermo-chemical evolution of mantle and core with a coupled model of 2D and 3D spherical geometry of thermo-chemical mantle convection and core heat balance. The bulk composition of mantle is expressed as a three-component (depleted harzburgite, enriched and recycled basalt and enriched primordial material) because mantle composition is expressed as only depleted harzburgite and enriched mid-oceanic-ridge-basalt (MORB) in our previous studies (e.g., Nakagawa and Tackley, 2013). Regarding several hypotheses of deep early Earth's interior, the primordial origin (generated in the core formation process) material could be found in the lowermost mantle, which might be initially-layered structure (Labrosse et al., 2007; Lee et al., 2010; Tackley, 2012). The main aim of this study is

to reproduce the possible thermo-chemical structure in the present mantle inferred from early Earth hypothesis, which is called as 'BAM' (Basal Mellange) (Tackley, 2012) and its influence to the heat flow across the core-mantle boundary (CMB) as well as core evolution (to explain the size of the inner core, magnetic field generation and onset time of geodynamo). The major results of this study is to find that the structure of BAM could be 'sandwich'-like structure, which means the primordial material could be found below the segregated MORB material, to explain the size of the inner core and magnetic field generation caused by dynamo actions. Regarding the onset time of geodynamo, it might affect the thermal conductivity of the Earth's core, which seems to influence the adiabatic heat flow along the adiabatic temperature and ranges from 5 to 15 TW with typical range of thermal conductivity of Earth's core (de Koker et al., 2012; Pozzo et al. 2012).

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Constraints on the Dynamics of Outer Rise Deformation: 2D Numerical Modeling of the Tonga Subduction System

J. Naliboff[1], M. Billen[1], T. Gerya[2] and M. Faccenda[3]

[1]*Dept. of Geology, University of California, Davis, USA*

[2]*Institute of Geophysics, ETH Zürich, Switzerland*

[3]*Department of Geoscience, University of Padua, Italy*

During subduction, bending and flexure of oceanic lithosphere combines with slab pull forces to generate extensional stresses located both seaward and down-dip of the trench. The resulting extensional deformation in the upper half of the down-going plate is observed through seismicity and well-preserved normal fault scarps, which often penetrate deep into the mantle lithosphere. While such seismicity and faults offsets are certainly second order in comparison to motion along the subducting plate interface, extensional deformation patterns are still closely linked to coupling along the plate boundary. Consequently, patterns of extensional deformation in subducting oceanic plates may provide a key constraint on the nature of plate boundary interfaces, as well as constraints on the rheology of the oceanic lithosphere and forces acting on down-going plates. To date, numerical studies have examined the relationship between outer rise deformation, fluid transport, rheology, slab pull, plate age, convergence velocity and downgoing-overriding plate coupling. While these studies provide key insights into the dynamics of outer rise deformation, comparisons to specific regions are difficult due to the time-dependent nature of the calculations and strong dependence of outer rise deformation on multiple parameters. Here, we present a new series of numerical experiments to elucidate the factors controlling outer rise deformation using constraints on the upper mantle slab shape and plate-boundary structure in the Tonga region. In contrast to previous studies of outer rise deformation where subduction is initiated through a velocity boundary condition, we prescribe an initial condition that contains the present-day slab structure through the upper mantle and lithosphere. The slab structure is defined by combing transects of the upper mantle slab surface from Slab 1.0 and observed bathymetry, while the plate boundary structure is derived from a high-resolution 2D tomographic transect across the Tonga trench. The resulting model provides a "semi-instantaneous" snapshot of outer rise deformation, which is self-consistently determined from the prescribed upper mantle buoyancy structure (slab-pull), variations in slab shape (bending stresses), convergence velocity and coupling across the downgoing-overriding plate interface. In order to examine the relationship between outer rise deformation and plate-boundary coupling, we will present initial models that examine the role of a prescribed weak shear zone separating the down-going slab and overriding plate.

Relevance of Continents for Habitability and Self-consistent Formation of Continents on Early Earth

L. Noack[1], T. Van Hoolst[1], D. Breuer[2] and V. Dehant[1]

[1]*Royal Observatory of Belgium, Brussels, Belgium*

[2]*German Aerospace Center (DLR), Institute for Planetary Research, Berlin, Germany*

The purpose of this study is to understand how Earth's surface might have evolved with time and to examine in a more general way the initiation of plate tectonics and the possible formation of continents on an Earth-like planet. Plate tectonics and continents seem to influence the likelihood of a planet to harbour life, and both are strongly influenced by the planetary interior (e.g. mantle temperature and rheology) and surface conditions (e.g. stabilizing effect of continents, atmospheric temperature), but may also depend on the biosphere. Earth is the only terrestrial planet (i.e. with a rocky mantle and iron core) in the solar system where long-term plate tectonics evolved. Knowing the factors that have a strong influence on the occurrence of plate tectonics allows for prognoses about plate tectonics on terrestrial exoplanets and helps to understand why Mars, Mercury and Venus developed in a different way with respect to Earth. In the applied 2D convection model, basaltic crust that may be transported into the silicate mantle (e.g. by subduction) is traced over time. The hydrated basaltic crust behaves differently than mantle silicates when re-molten and granitic (felsic) crust is produced. Pre-continental roots may form few hundreds of Myr after accretion of Earth – depending on the initial conditions and applied rheology. At this time, however, the mantle is too hot to allow for subduction of the cold lithosphere into the mantle. After a longer time span, when the planet cools and the buoyancy of warm uprising mantle plumes is reduced, plate tectonics together with present-day-like subduction can initiate at the boundary between the pre-continental roots and the oceanic, basaltic crust.

Controls on Two-sided Subduction on Dry Planets

R. I. Petersen[1], D. R. Stegman[1] and P. J. Tackley[2]

[1] *Scripps Institution of Oceanography, University of California, San Diego*

[2] *GFD group, ETH Zürich, Switzerland*

Subduction on Earth is distinct in that it is single-sided. The development of numerical models wherein single-sided subduction is an emergent feature has been long sought after goal in the modelling community. The addition of a pseudo-free surface, or ``sticky-air layer'', a brittle ``weak crust'' and low viscosity mantle wedge resultant from de-watering of the down-going slab to numeric models promotes single-sided subduction. The presence of water on a planet makes available to the modeller features such as a low viscosity mantle wedge and a relatively thick weak layer composed of a brittle upper portion and low strength serpentinized portion bellow. On a dry planet these features are absent. There exists no hydrated wedge and any weak crustal layer at the surface is thinner than it's wet planet counterpart. Therefore two-sided subduction may represent the appropriate mode of subduction. Frequently double-sided subduction is treated as a symmetric feature with convergence rates divided equally between the dual subducting plates. However our models suggest a more continuous regime with single-sided subduction and symmetric double-sided subduction representing two end members. Using the finite volume code StagYY we develop two-dimensional models of subduction systems with parameters appropriate for dry planets. In these models we vary the background temperature, surface temperature and thickness of the initial boundary layer. We establish a minimum boundary layer thickness for the initial condition given the Rayleigh number of a model. The minimum thickness is scaled from a reference boundary layer thickness for a model with a background temperature of 1600 K, surface temperature of 300K and boundary layer thickness of 100 km. We measure the convergence rate, trench migration rate and strength of the slabs involved in the subduction system. Using these measurements we have developed a regime diagram that illuminates the controls on this style of subduction in the setting of a dry planet.

How Can We Constrain the Amount of Heat Producing Elements in the Interior of Mars?

A-C. Plesa[1], M. Grott[1] and D. Breuer[1]

[1]*German Aerospace Center, Institute of Planetary Research, Berlin, Germany*

The InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission to be launched in 2016 will study Mars' deep interior and help improving our knowledge about the interior structure and the thermal evolution of the planet; the latter is also directly linked to its volcanic history and atmospheric evolution. Measurements planned with the two main instruments, SEIS (Seismic Experiment for Interior Structure) and HP^3 (Heat Flow and Physical Properties Package) aim to constrain the main structure of the planet, i.e. core, mantle and crust as well as the rate at which the planet loses the interior heat over its surface. Since the surface heat flow depends on the amount of radiogenic heat elements (HPE) present in the interior, it offers a measurable quantity which could constrain the heat budget. Being the principal agent regulating the heat budget which in turn influences partial melting in the interior, crustal and atmospheric evolution, the heat producing elements have a major impact on the entire the present temperature thermal history of the planet. To constrain the radiogenic heat elements of the planet from the surface heat flow is possible assuming that the urey number of the planet, which describes the contribution of internal heat production to the surface heat loss, is known. We have tested this assumption by calculating the thermal evolution of the planet with fully dynamical numerical simulations and by comparing the obtained present-day urey number for a set of different models/parameters (Fig. B1). For one-plate planets like Mars, numerical models show - in contrast to models for the Earth, where plate tectonics play a major role adding more complexity to the system – that the urey ratio is mainly sensitive to two effects: the efficiency of cooling due to the temperature-dependence of the viscosity and the mean half-life time of the long lived radiogenic isotopes. The temperature-dependence of the viscosity results in the so-called thermostat effect regulating the interior temperature such that the present-day temperatures are independent of the initial temperature distribution. If the thermostat effect is efficient as we show for the assumed Martian mantle rheology, and if the system is not dominated by radioactive isotopes like Thorium with a half-life much longer than the age of the planet as in the model of Morgan and Anders (1979), all numerical simulations show similar today's values for the urey number (Fig. B1). Knowing the surface heat loss from the upcoming heat flow measurements planned for the InSight mission, one can distinguish then between different radiogenic heat source models (Treiman et al., 1986; Morgan and Anders, 1979; Wänke et al., 1994; Lodders and Fegley, 1997).

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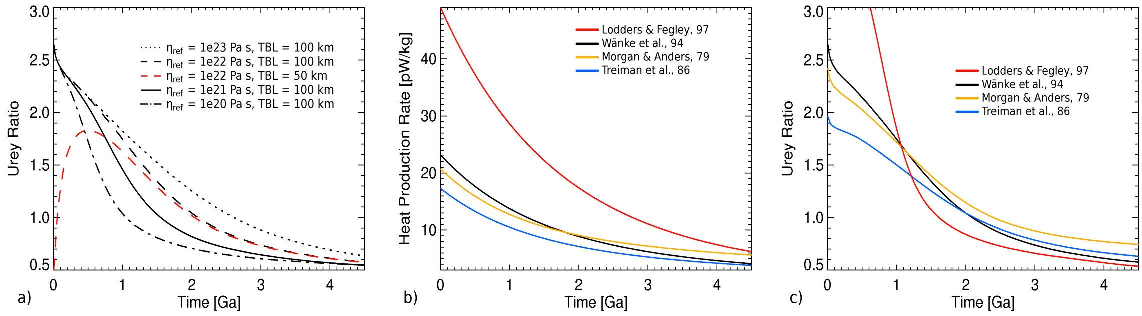

Figure B1. (a) The influence of the reference viscosity and initial upper thermal boundary layer (TBL) on the urey ratio using HPE density from Lodders and Fegley (1997). (b) Different models for HPE density. (c) The urey ratio for different HPE models and 1e22 Pa s reference viscosity.

Sheet-like and Plume-like Thermal Flow in a Spherical Convection Experiment Performed under Microgravity

A-C. Plesa[1], B. Futterer[2,3], A. Krebs[2], F. Zaussinger[2], D. Breuer[1] and C. Egbers[2]

[1]*German Aerospace Center, Institute of Planetary Research, Berlin, Germany*

[2]*Brandenburg University of Technology Cottbus, Department of Aerodynamics and Fluid Mechanics, Germany*

[3]*Otto von Guericke University, Institute of Fluid Dynamics and Thermodynamics, Magdeburg, Germany*

In mantle dynamics research, experiments, usually performed in rectangular geometries in Earth-based laboratories, have the character of 'exploring new physics and testing theories' (Davaille and Limare, 2009). In this work, we introduce our spherical geometry experiments on electro-hydrodynamically driven Rayleigh-Benard convection that have been performed for both temperature-independent (GeoFlow I), and temperature-dependent fluid viscosity properties (GeoFlow II) with a measured viscosity contrast up to 1.5. To set up a self-gravitating force field, we use a high voltage potential between the inner and outer boundaries and a dielectric insulating liquid and perform the experiment under microgravity conditions at the ISS (Futterer et al., 2010, 2012). Further, numerical simulations in 3D spherical geometry have been used to reproduce the results obtained in the GeoFlow experiments. For flow visualisation, we use Wollaston prism shearing interferometry, which is an optical method producing fringe pattern images. Flow pattern differ between our two experiments (Fig. C1). In GeoFlow I, we see a sheet-like thermal flow. In this case convection patterns have been successfully reproduced by 3D numerical simulations using two different and independently developed codes. In contrast, in GeoFlow II we obtain plume-like structures. Interestingly, numerical simulations do not yield this type of solution for the low viscosity contrast realised in the experiment. However, using a viscosity contrast of two orders of magnitude or higher, we can reproduce the patterns obtained in the

GeoFlow II experiment, from which we conclude that non-linear effects shift the effective viscosity ratio (Futterer et al., 2013).

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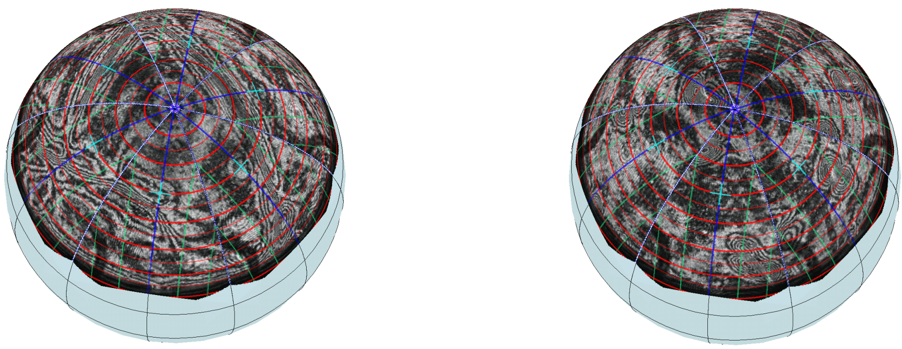

Figure C1. Sheet-like thermal flow in the GeoFlow I spherical experiment with silicone oil of temperature-stable properties (left, $Ra_E = 1.17 \cdot 10^6$) and plume-like dominated flow in the GeoFlow II experiment using a fluid with temperature dependent viscosity and volume expansion (right, $Ra_E = 1.87 \cdot 10^6$).

Modeling the India-Asia Collision Zone: 3D Simulations and Numerical Insights

A-E. Püsök[1], B. Kaus[1] and A. Popov[1]

[1]*Institute of Geosciences, Johannes-Gutenberg University, Mainz, Germany*

The dynamics of the India-Asia collision zone remains one of the most remarkable topics of the current research interest: the transition from subduction to collision and uplift, followed by the rise of the abnormally thick Tibetan plateau, and the deformation at its Eastern and Western syntaxes, are processes still not fully understood. Models that have addressed this topic include wholescale underthrusting of Indian lithospheric mantle under Tibet (Argand model), distributed homogeneous shortening or the thin-sheet model (England and Houseman, 1986), slip-line field model for lateral extrusion (Tapponier and Molnar, 1976) or lower crustal flow models for the exhumation of the Himalayan units and lateral spreading of the Tibetan plateau (Royden et al., 1998; Beaumont et al., 2004). Of these, the thin-sheet model has successfully illustrated some of the basic physics of continental collision and has the advantage of a 3D model being reduced to 2D, but one of its major shortcomings is that it cannot simultaneously represent channel flow and gravitational collapse of the mantle lithosphere (Lechmann et al., 2011), since these mechanisms require the lithosphere to interact with the underlying mantle, or to have a vertically non-homogeneous rheology. As a consequence, 3D models are emerging as powerful tools to understand the dynamics of coupled systems. However, because of yet recent developments and various complexities, the current 3D models simulating the dynamics of continent collision zones have relied on certain explicit assumptions, such as replacing part of the asthenosphere with various types of boundary conditions that mimic the effect of mantle flow, in order to focus on the lithospheric/crustal deformation (Yang and Liu, 2013). Here, we employ the parallel 3D code LaMEM (Lithosphere and Mantle Evolution Model), with a finite difference staggered grid solver, which is capable of simulating lithospheric deformation while simultaneously taking mantle flow and a free surface into account. We report qualitative results on lithospheric and upper-mantle scale simulations in which the Indian lithosphere is indented into Asia. Solving for the incompressible Stokes flow in 3D brings up new computational difficulties and we also present some numerical insights into solving the linear system of equations more efficiently and with larger computational power.

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The Timescales of Continental Drift Controlled by the Strength of the Lithosphere?

T. Rolf[1], N. Coltice[2] and P. J. Tackley[1]
[1]*Institute of Geophysics, ETH Zurich, Switzerland*
[2]*Laboratoire de Geologie de Lyon, Université Claude Bernard Lyon 1, France*

Since Alfred Wegener proposed his theory of continental drift and the formation of the supercontinent Pangaea about 100 years ago, quite some effort has been made to understand the dynamics of continental drift, including the collision and break-up of supercontinents. Although evidence from the Precambrian geological record is rather limited, the existence of several earlier supercontinents, e.g. Columbia or Rodinia, on Earth has been proposed, which lead to the idea of a supercontinent cycle during which the continental configuration alternates between dispersed and assembled states. Despite the progress made in this field, however, the dynamics of continental drift in the context of plate tectonics and its link to the underlying convection of Earth's mantle is so far only vaguely understood.

Which processes lead to the assembly of continental blocks? How can they be separated again? And how long do these processes take? Here we investigate the dynamic relation between continental and oceanic plates as well as mantle convection with a numerical model of mantle convection in spherical geometry that combines, as one of the very few, self-consistently generated plate-like behaviour and Earth-like continental drift. We focus on the conditions that favour (super-)continental cycles by varying the properties of mantle flow as well as the rheological properties of the lithosphere and derive timescale characteristics from statistical analysis of continental assembly and break-up. We propose that the strength of the lithosphere imposes a strong control on these timescales by varying the structure and wavelength of mantle flow.

Landscape Response to Lithospheric Strain Localization

S. G. Roy[1], P. O. Koons[1], P. Upton[2] and G. Tucker[3,4]

[1]*Earth and Climate Sciences, University of Maine, USA*

[2]*GNS Science, New Zealand*

[3]*Geological Sciences, University of Colorado Boulder, USA*

[4]*CIRES, USA*

We hypothesize that the crustal strength field influences the rate of landscape response to a perturbation, and that landscape anisotropy is attributable to the anisotropic strength fields generated by strain localization in the lithosphere. We model the influence of 3D strain-induced weakening on landscape by assuming that hydraulic erodibility is inversely proportional to cohesion for bedrock rivers. This assumption is valid for examples where bedload abrasion is the primary cause of river erosion. Crustal deformation is accommodated by localized and intense brittle disintegration of host rock within anisotropic fault zones. The density, position, and orientation of fault zones depend on the magnitude and orientation of strain transferred from an advecting mantle and the brittle crustal response. The rate of landscape response to tectonic activity is amplified by knickpoint migration into the fault zones and is dependent on the orientations established in the strength field. The rate of knickpoint migration depends on fault dip and cohesion, as well as the knickpoint relief and the amount of runoff channelled through the fault. The strength field influences the spatial distribution of erosion rate, generating a ridge-valley geometry that eventually dictates the spatial distribution of topography and surface water. The resulting drainage network pattern reflects the crustal strength field. Natural examples of this can be seen in the Southern Alps of New Zealand. Fault zones with subvertical dip host a single knickpoint, while those with shallow dip host a more complex double knickpoint morphology representative of a vertical transition in erodibility and lateral expansion of drainage area. Fault dip also influences the shape of the drainage area. Steeply dipping faults host rapid knickpoint migration and longitudinal expansion of drainage area along strike, while faults with shallow dip exert a similar influence but with a larger amount of lateral expansion by tributaries orthogonal to fault strike.

Internal Temperature and Heat Flux in a Super-Earth

A. Rozel[1] and P. J. Tackley[1]

[1]*Geophysical Fluid Dynamics, ETH Zurich, Switzerland*

The pressure-dependence of the rheology of large super-Earths has been an increasing matter of debate during the last years. There is no experimental consensus yet about the pressure-dependence of the viscosity of mantle material for pressure larger than ~100 GPa. Some numerical simulations of 2D and 3D convection have been published assuming very different assumptions. In this study, we present a new analytical model of internal temperature and heat flux at the equilibrium, based on the boundary layer theory. An important assumption, numerically confirmed, is that the energy dissipation is quite homogeneously distributed in the convecting region. Our theoretical model predicts then that the internal temperature of the mantle of a planet heated by its core depends on the Frank-Kamenetskii parameter, in agreement with classical boundary layer theory, but also on the lateral and vertical viscosity contrasts of the internal region. Since the mantle of super-Earths may contains very important viscosity contrasts if a large pressure-dependent rheology is assumed, the present study represents an important improvement. The new theoretical model is tested using a large number of 2D numerical simulations of mantle convection. Newtonian and non-Newtonian models have been run. The Frank-Kamenetskii approximation is confronted to the classical Arrhenius definition of the rheology. Temperature-dependent and pressure-temperature-dependent models are also confronted. All simulations largely confirm the new analytical model. Since our new formulation is based on equilibrium situations, it may not apply directly to time-dependent models. To check the validity of our theoretical requirements, we investigate the non-equilibrium dynamics of cooling super-Earths, focusing on the spatial distribution of energy dissipation, for different initial temperature fields and rheologies. Our analytical model applies to fully internally heated cases or bottom heated situation. We observe the time-dependent transition from internal to bottom heated condition. The surface stress is also tracked to see the impact of pressure-dependent rheologies on the question of the likelihood of plate tectonics.

3D Deformation Patterns in Accretionary Wedges: Effects of Strain and Velocity Weakening

J. B. Ruh[1], T. Gerya[1] and J-P. Burg[1]

[1]*ETH Zurich, Switzerland*

Active shear zones within upper crustal rock sequences are thought to be weaker than the surrounding, non-failed rocks. Whether weakening within a shear zone depends on accumulated plastic strain or strain rate is still under debate. We used a three-dimensional numerical model with a visco-plastic/brittle rheology to investigate the influence of strain and strain rate (velocity) weakening on the evolution of thin-skinned fold-and-thrust belts. Two geometrical model setups are studied: (i) A cylindrical setup (no lateral variation) to test the effects of the two weakening modes on the structural

evolution and dynamics of fold-and-thrust belts (Fig. D1). (ii) A setup with a sharp transition of décollement strength to investigate the structural weakening effect on laterally varying systems (Fig. D2). The influence of shortening velocity, cover sequence thickness, weakening style and weakening amount on the structural evolution across laterally varying systems is tested. Results show that deformation patterns in strain and velocity weakened fold-and-thrust belts differ remarkably. Whilst strain weakening needs an initial finite plastic strain to initially weaken material, velocity weakening starts immediately without precursory strain. Strain weakening also favours the reactivation of out-of-sequence shear zones. Furthermore, the occurrence of strike-slip shear zones is enhanced by velocity weakening and a decreased cover sequence thickness. Shortening velocity has a minor effect on the structural evolution along transition zones. We conclude that the two modes of weakening, strain and velocity dependent, strongly influence the evolution of thrust wedges in terms of fault patterns and dynamics. Alternatively, fault patterns are key to discriminate weakening processes. Discrete vertical strike-slip shear zones appear only in velocity weakened, laterally varying setups of thrust wedges.

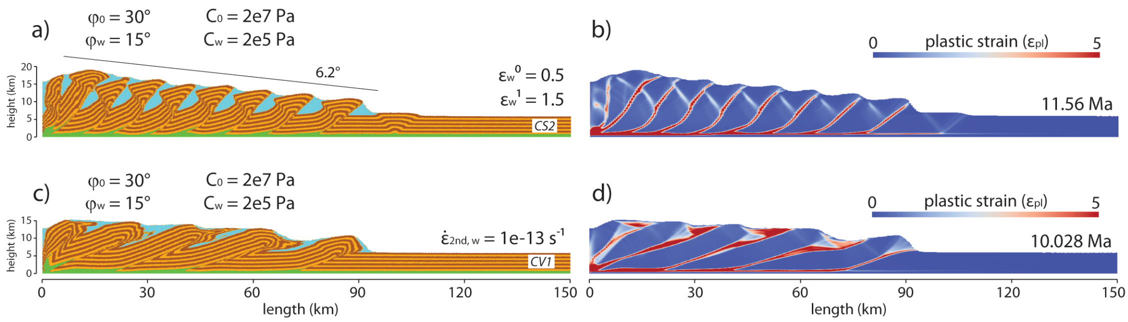

Figure D1. Profiles of cylindrical simulations with strain weakening (a, b) and velocity weakening (c, d). Left column: Deformed strata. Right column: Accumulated plastic strain.

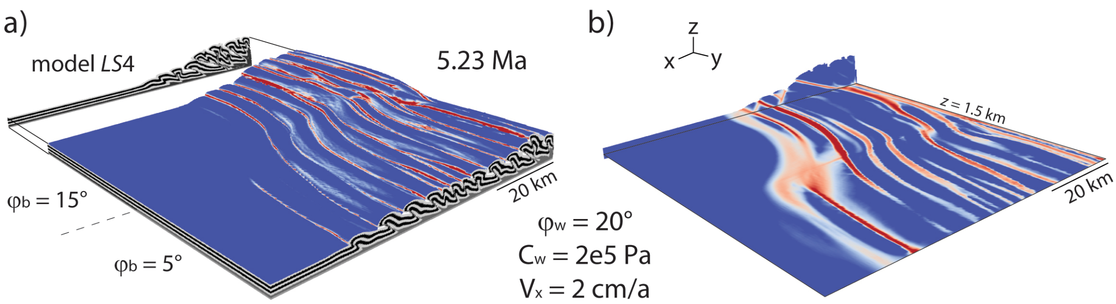

Figure D2. Simulations with lateral décollement strength variation and a cover sequence thickness of $H = 2.5$ km. (a) Accumulated strain with profiles of deformed strata (black/white) at $y = 0$ and $y = 100$ km. (b) Slices of the second invariant of the strain rate tensor at $z = 1.5$ km (horizontal slice) and $y = 0$ (vertical slice).

Symmetric Versus Asymmetric Spreading, Rifting, and Ridge Migration: The Role of Visco-plasticity

H. Schmeling[1], C. Weismüller[1], M. Shahraki[1] and S. Overmann[1]

[1]*Institute of Geoscience, Goethe-University Frankfurt, Germany*

Mid-oceanic ridges (MOR) usually appear as symmetric structures, i.e. they exhibit symmetric accretion and they migrate with half of the total spreading velocity. Observed deviations from this symmetry are minor, of the order of 10%. On the other hand, equivalent divergent features on lava lakes show both, symmetric and sometimes extremely asymmetric spreading zones. For continental rifts, asymmetric ("simple shear") and symmetric ("pure shear") modes are well known and their controlling mechanism has been identified as being strain softening (Huismans and Beaumont, 2003). Here we present several numerical experiments of continental and oceanic lithosphere extension assuming visco-plastic rheology (without strain softening) to study the conditions leading to symmetric or asymmetric rifting or spreading, including self-consistent ridge migration. In a first set of experiments we solve the time-independent momentum and mass equations for a simple isothermal homogeneous lithosphere with Mohr-Coulomb-plasticity and with a weak seed using COMSOL. The week seed is essential to generate ductile failure along shear zones initiated at the seed. We observe a transition from symmetric conjugate shear zones to a strongly asymmetric, single shear zone rifting mode when increasing the friction angle from almost zero to 0.6. This asymmetric mode is strongly enhanced for non-spherical seeds. In a second set of experiments using FDCON, MORs are modelled including also the heat equation and a non-linear olivine-based rheology together with a simplified Mohr-Coulomb plasticity (using the lithostatic pressure with a pore-pressure coefficient l_p instead of the full dynamic pressure). While in many previous models the MOR was positioned at the symmetry axis of the model box, we now place it deliberately at a prescribed offset. Applying a total spreading velocity v_0 as the lateral boundary condition, the ridge migrates with a velocity cv_0, where c varies between 0 (strongly asymmetric spreading) and 0.5 (symmetric spreading) when l_p is decreased from 1 to 0.001. As most MORs are close to symmetric spreading we therefore speculate that volatiles such as water or melts significantly weaken the rheology at MORs and effectively reduce the friction angle (unlike in lava lakes). In a third set of models focusing at continental rifting, we place a thermal anomaly at the base of a continental lithosphere with an offset with respect to the symmetry axis of the model box. In contrast to the MOR-models a symmetric continental rift forms similar to the rifts of Schmeling (2010), which migrates with a c-factor of about 0.5. However, lithospheric necking is less pronounced probably because sub-rift secondary convection cannot keep pace with the migrating rift, forcing the migrating rift to override cool downwelling regions having formed at the rift flanks. We conclude that symmetric/asymmetric rifting and spreading strongly depends on the friction angle or l_p and may be obtained also without invoking strain softening.

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Modelling the Influence of Faults on a Developing River System

S. Schroeder[1] and R. Gloaguen[2]

[1]*GFZ Potsdam, Germany*

[2]*Bergakademie Freiberg, Germany*

This numerical study aims to clarify if and how a system of faults may influence the development of a river network. We simulate the effect of varying angles between riverbed and fault on flow direction, and for which configuration a deflection of the river is possible. We also compare the influences of uplift and of high erodibility zones on the deviation of river networks. This study has a direct application. The highly active Pamir orogen is penetrated by sub-parallel faults. The main rivers of the Pamir flow from east to west, following the fault system. They join the river Panj, that abruptly turns at 71.5° longitude from east-west direction to the north. An old river bed in direction to south-west can be observed at the sudden turn. So far it is unknown, how strong such a fault system influences a river network. Is it possible that the east-west fault system forced the rivers in that direction? Might the Panj river have changed its direction due to a river capturing event, induced by a recently forming fault? We simulate an inclined plan with white noise and faults. The faults are modelled as regions of increased erodibility. We test the effect of fault-bounded block rotations on river captures. The uplift in the model is analytically imposed and coupled to a Surface Evolution Model (SEM). The supply limited surface model is designed for a coupling with any tectonic model. It follows the concept of the cellular automaton implemented on a regular Eulerian mesh. It incorporates an effective filling algorithm that guarantees flow direction in each cell, D8 search for flow directions, computation of discharges and bedrock incision. Additionally, the model implements hill slope erosion in the form of non-linear, slope-dependent diffusion. It offers a new feature that allows incision of not only a channel of one cell width, but of the whole river valley. This lateral abrasion routine avoids a time consuming multiple flow direction algorithm, but gives a more natural topography and allows working with real Digital Elevation Models. Furthermore, the new surface evolution model enables headward erosion.

Effects of Post-perovskite Phase Change on the Observed Geoid

M. Shahraki[1] and H. Schmeling[1]

[1]*Institut für Geowissenschaften, Facheinheit Geophysik, J.W. Goethe Universität, Frankfurt am Main, Germany*

Direct evidence for a phase transition from perovskite (Pv) to Post-perovskite (pPv) comes from both experiments and quantum mechanical calculations. In addition, seismic studies in the lower mantle also indicate the occurrence of this phase change in the lowermost mantle. A strong viscosity difference between Post-perovskite and perovskite is expected. However, the magnitude and even the sign of such viscosity contrast is a controversial issue. We have performed a series of instantaneous mantle flow simulations, by using density heterogeneities, inferred from a recent global seismic tomography model

S40RTS to determine how a phase transition of perovskite to Post-perovskite at lower mantle depths affects the geoid and dynamic topography. We introduced Post-perovskite viscosity beneath the slabs between 2560 km and core-mantle boundary. The low viscosity of the post-perovskite regions, obtained by a negative temperature dependent viscosity, and a normal temperature dependent viscosity assumed for the upper and lower mantle. We show that the viscosity of Post-perovskite phase can have large effect on the pattern and the amplitude of the geoid and dynamic topography. Nevertheless, after applying a viscosity contrast of at least two orders of magnitude any higher viscosity contrast does not affect the geoid any further.

Sinking of Spherical Slablets Through a Non-Newtonian Mantle

D. R. Stegman[1], F. Crameri[2] and P. J. Tackley[2]

[1]*Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California, San Diego, USA*

[2]*Institute of Geophysics, Department of Earth Sciences, ETH Zürich, Switzerland*

The dominant driving force for plate tectonics is slab pull, in which sinking slabs pull the trailing plate. Forward plate velocities are typically similar in magnitude (7 cm/yr) as estimates for sinking velocities of slabs through the upper mantle. However, these estimates are based on data for slabs that are coherent into the transition zone as well as models that considered the upper mantle to be entirely Newtonian. Dislocation creep in the upper mantle can strongly influence mantle flow, and is likely activated for flow around vertically sinking slabs in the uppermost mantle. Thus, it is possible that in some scenarios, a non-Newtonian mantle will have an influence on plate motions but it is unclear to what degree. To address this question, we investigate how the non-Newtonian rheology modifies the sinking velocities of slablets (spherical, negatively buoyant viscous blobs). The model set-up is similar to a Stokes sphere sinking, but is in 2-D cartesian with temperature-and stress-dependent rheology. For these numerical models, we use the StagYY code and also include a pseudo-free surface (‘sticky air’) with a thin surface thermal boundary. The sinking blob is compositionally dense but is the same temperature as the background fluid, which eliminates thermal diffusion and associated variations in thermal buoyancy. The model domain is 4x1 and allows enough distance to the sidewalls so that sinking velocities are not influenced by the boundary conditions. We compare our results with those previously obtained for salt diapirs rising through a power-law rheology mantle/crust (Weinberg, 1993; Weinberg and Podladchikov, 1994), which provided both numerical and analytic results. Previous results indicate a speed-up of an order of magnitude is possible.

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Possible Links Between Subduction History, Generation of Mantle Plumes, True Polar Wander, Core-mantle Boundary Heat Flux and Core Processes

B. Steinberger[1,2], A. J. Biggin[3] and T. H. Torsvik[2,4,5]

[1]*GFZ German Research Centre for Geosciences, Potsdam, Germany*

[2]*Centre for Earth Evolution and Dynamics, University of Oslo, Norway*

[3]*School of Environmental Sciences, University of Liverpool, United Kingdom*

[4]*Geological Survey of Norway, Trondheim, Norway*

[5]*School of Geosciences, University of the Witwatersrand, South Africa*

It is still an open question to what extent and in what way the core-mantle boundary (CMB) heat flux pattern influences core processes. According to current understanding, higher CMB heat flow – in particular, in near-equatorial regions – causes more magnetic field variability and higher reversal frequency. Here we compute CMB heat flux from a dynamical model of the mantle based on 300 Myr of subduction history. It includes a thermo-chemical layer at its base which – due to flow driven by subducted slabs – is shaped into piles resembling the two Large Low Shear-wave Velocity Provinces (LLSVPs). Predicted CMB heat flux is spatially very variable reaching several hundred mW/m^2 beneath subducted slabs, and remaining <10 mW/m^2 beneath piles. Due to induced large-scale mantle flow, CMB heat flux increases beneath a new subduction zone after a few tens of Myr, long before the slab has sunk to the lowermost mantle. But it remains high beneath paleo-subduction zones for hundreds of Myr, while the slab sinks to the CMB and subsequently heats up. Plume heads detaching from the lowermost mantle, primarily at the margins of piles, due to the thermal boundary layer being pushed sideways and piled up ahead of slabs, also remove heat and locally increase CMB heat flux. Accordingly, the number of Large Igneous Provinces (LIPs), offset by 50 Myr (plume rise time), is correlated with reversal frequency. But since plumes themselves are triggered by slabs, their effect on heat flux variations cannot be considered separately. Thermochemical piles and regions of low heat flux beneath appear to be more stationary. However, true polar wander (TPW) – wholesale rotation of the entire mantle relative to the core – can change core heat flux, even if the pattern remains constant in a mantle reference frame. Combining a heat flux pattern derived from LLSVPs fixed in the mantle with TPW, we compute heat flow between 10°N and 10°S through time and find some resemblance to reversal frequency.

Evolution of Mantle Convection and Plate Tectonics from a Hot/Molten Initial State on Earth and Super-Earths

P. J. Tackley[1]

[1]*ETH Zürich, Switzerland*

Planets of Earth size or above were/are likely completely molten early on, but evolution from such a very hot early state has not so far been considered in published studies of mantle convection and/or plate tectonics on super-Earths (e.g., van Heck and Tackley, 2011; Tackley et al., 2013). More generally, melting is a very important process in planetary evolution (Nakagawa and Tackley, 2012). However, previous studies have either focused on statistically steady-state solutions, or time evolution with a much reduced initial starting temperature. In this presentation, various considerations and preliminary numerical simulations of terrestrial planetary evolution from a mostly molten initial state will be presented. This requires several numerical advances but is an essential step because it reduces the arbitrariness of initial conditions for long-term evolution simulations (e.g., adiabatic and isochemical), facilitating a more integrated and self-consistent understanding of planetary evolution.

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DynEarthSol3D: An Efficient and Flexible Unstructured Finite Element Method to Study Long-term Tectonic Deformation

E. Tan[1]

[1]*Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan*

Many tectonic problems require treating the lithosphere as a compressible elastic material, which can also flow viscously or break in a brittle fashion depending on the stress level applied and the temperature conditions. We present a flexible methodology to address the resulting complex material response, which imposes severe challenges on the discretization and rheological models used. This robust, adaptive, 3D, finite element method solves the momentum balance and the heat equation in Lagrangian form using unstructured meshes. The solver uses contingent mesh adaptivity in places where shear strain is focused (localization) during remeshing. We detail the solver and verify it in a number of benchmark problems against analytic and numerical solutions from the literature.

A Discussion of Mantle Temperatures in Numerical Studies of Rift-to-drift Extension

J. Tétreault[1] and S. Buiter[1,2]

[1] *Geological Survey of Norway, Norway*

[2]*Centre for Earth Evolution and Dynamics, University of Oslo, Norway*

The thermal structure of the mantle is important for numerical studies that rely on the interaction of the lithosphere and asthenospheric mantle. Non-Newtonian rheologies for olivine are obviously dependent on the mantle temperature, and the resulting mantle viscosities will significantly affect the behavior of the numerical experiment. Typical upper mantle thermal parameters based on analytical, geochemical, and geophysical studies are; an upper mantle thermal conductivity of about 2.5–3.5 W/m K, 1300–1400 °C potential temperature, and an adiabatic gradient of 0.3–0.5 K/m. But in rift-to-drift numerical experiments a realistically low conductivity value in the asthenosphere can lead to fast cooling of the mantle adiabat and subsequent erroneous isotherms at the spreading ridge. Therein lies the dilemma: how to maintain the mantle adiabat and also produce a realistic mid-ocean ridge temperature structure? Various methods are utilized to solve this problem in numerical studies. In order to maintain the mantle adiabat, some authors have employed a high asthenospheric mantle conductivity (1–2 orders of magnitude higher). But high conductivities will promote speedy heat loss; therefore a low conductivity thermal buffer in the overlying lithosphere is necessary to maintain realistic values for surficial heat flow and the mantle thermal structure. In rift-to-drift experiments, the lithosphere breaks up, asthenosphere upwells to the surface, and the low conductivity buffer is no longer present. A crude workaround is to employ a depth-dependent or temperature-dependent conductivity for the mantle asthenosphere. Instead of using high mantle conductivities, several researchers use high mantle adiabats (an order of magnitude higher), therefore producing virtually linear viscous mantle material of low viscosities, which serves as a feedback system by transferring heat faster as convection is sped up. Another technique is to have an initial phase of convection, produced by a high basal temperature boundary condition that will eventually converge to a stable mantle adiabat. After hundreds of millions of years the model reaches steady state with a realistic mantle adiabat and then extension is started. In this poster, we explore the various numerical techniques for maintaining mantle thermal fields and how they influence the thermal structure of the mantle after continental breakup and sea-floor spreading. We would like this presentation to serve as a discussion point on what thermal parameters are realistic and which methods are best able to maintain a mantle adiabat in numerical experiments of passive margin evolution.

Multiphase Geodynamical Modelling Using ASPECT

C. Thieulot[1,2], A. Glerum[2], B. Hillebrand[2], A. Graas[2], W. Spakman[2] and T. H. Torsvik[1]

[1]*Centre for Earth Evolution and Dynamics, University of Oslo, Norway*

[2]*Earth Sciences, Utrecht University, The Netherlands*

ASPECT (Advanced Solver for Problems in Earth's ConvecTion) is a 2D/3D FEM code to simulate problems in thermal convection. It is a promising and powerful tool, implementing state-of-the-art numerical methods and is vowed to become a standard tool in the mantle convection numerical modelling community. Its primary focus is on the simulation of processes in the earth's mantle, but its design is more general than that and we therefore explore the (recent) algorithmic additions made to the code: these include for instance the ability to implement complex in/outflow boundary conditions, the tracking of any number of compositional fields which are passively advected by the computed velocity fields, and the use of various adaptive mesh refinement strategies. Several benchmarks of the geodynamical community involving multiphase flow will be shown and compared with results obtained with a FEM code using the particle-in-cell technique and a FEM code using the level set method. The use of ASPECT in the case when a free surface is present will also be investigated. Finally, preliminary results of multiphase thermo-mechanically coupled visco-plastic experiments will be shown.

Linking Mantle Dynamics to Plate Tectonics

T. H. Torsvik[1], P. V. Doubrovine[1], B. Steinberger[1,2] and K. Burke[3]

[1]*Centre for Earth Evolution and Dynamics, University of Oslo, Norway*

[2]*Helmholtz Centre Potsdam, GFZ, 14473 Potsdam, Germany*

[3]*Department of Geosciences, University of Houston, USA*

The calibration of longitude in the mid-eighteenth century by the invention of a sea-going chronometer gave mariners confidence that they could reliably calculate their absolute position on the Earth's surface. Until recently, Earth scientists have been in the comparable position of having no way of calculating the longitudes of continents before the Cretaceous, leaving paleomagnetism, which cannot determine longitude, as the only quantitative means of positioning continents on the globe before that time. However, by choosing a reference continent that has moved the least longitudinally (i.e. Africa), longitudinal uncertainty can be minimized. The analytical trick is to rotate all paleomagnetic poles to Africa and calculate a global apparent polar wander path in African co-ordinates, which serves as the basis for subsequent global reconstructions. This method is dubbed the 'zero-longitudinal motion' approximation for Africa, and has allowed us to confidently estimate true polar wander (TPW) since Pangea formation (320 Ma), and to demonstrate that ancient large igneous provinces and kimberlites have been sourced by plumes from the edges of the large low shear-wave velocity provinces (LLSVPs) on the core-mantle boundary beneath Africa and the Pacific. Using this surface-to-CMB correlation and a new iterative approach for defining a palaeomagnetic reference frame corrected for TPW, we have developed a model for absolute plate motion back to earliest Paleozoic time that maintains the remarkable link between surface volcanism and the LLSVPs. For the Paleozoic we have for the first time identified several phases of slow, oscillatory TPW (less than 1 degree/Myr) during which the Earth's axis of minimum moment of inertia was similar to that of Mesozoic times. We model ten phases of clockwise and counter-clockwise rotations since 540 Ma, which can be interpreted as oscillatory swings approximately around the same axis (11 degrees East at equator). Net TPW angles peaked at 22 degrees in the Mesozoic and 62 degrees in the Paleozoic, and paleomagnetic and TPW-corrected (mantle) reconstructions therefore differ significantly in the early Paleozoic.

Chemical Geodynamics of the NE Atlantic and Arctic Mantle

R. G. Trønnes[1,2], V. Debaille[3] , M. Erambert[4] , F. M. Stuart[5] and T. Waight[6]

[1]*Centre for Earth Evolution and Dynamics University of Oslo, Norway*

[2]*Natural History Museum, University of Oslo, Norway*

[3]*Département des Sciences de la Terre et de l'Environnement, Université Libre de Bruxelles, Belgium*

[4]*Department of Geosciences, University of Oslo, Norway*

[5]*Isotope Geoscience Unit, Scottish Universities Environmental Research Centre, East Kilbride, Scotland, UK*

[6]*Institute of Geography and Geology, University of Copenhagen, Denmark*

The NE Atlantic and Arctic spreading ridges and the volcanic zones in Iceland, Jan Mayen and northern Spitsbergen (Pleistocene basalts) record regionally variable geochemical interaction between the original asthenosphere (asthenospheric mantle, AM), material supplied by the Iceland plume and subcontinental lithosphere (SCLM) (Debaille et al., 2009; Goldstein et al., 2008; Trønnes et al., 2010). The SCLM-component was mixed with the local asthenosphere during and shortly after the continental rifting and ocean basin opening. Using combined Sr-Nd-Pb-Os-He-isotope systematics, the Iceland plume can be modelled as a mixture of 70% refractory and primordial lower mantle (LM) with high $^{3}He/^{4}He$-ratios, and 30% recycled oceanic crust (ROC). Low-degree melting of the NE Atlantic and Arctic mantle taps preferentially the enriched ROC and SCLM components. Further melting taps progressively the refractory LM and AM components. The estimated ROC/SCLM-ratio decreases from a maximum of about 2.3 at the Reykjanes Ridge, Reykjanes Peninsula and the Southern Volcanic Flank Zone in Iceland, via 1.2 at the Snæfellsnes peninsula, Western Rift Zone and Mid-Icelandic Belt and 0.7 at Jan Mayen and the Kolbeinsey, Mohns and Knipovich Ridges to less than 0.2 at Spitsbergen and the Gakkel Ridge. The minor element composition of olivine phenocrysts in primitive off-rift basalts in Iceland and Jan Mayen, sampling preferentially the enriched source components, indicate that the SCLM-lithologies are overwhelmingly peridotitic, in contrast to the ROC-lithologies, recording basaltic and hybridized pyroxenite lithologies. The Hf-Nd-isotope ratios also discriminate between these two enriched source components. The high proportion of the SCLM-component in the asthenosphere along the Kolbeinsey, Mohns, Knipovich and Gakkel Ridges reflects the young, narrow and slow-spreading character of the corresponding oceanic basins. The opening of the Kolbeinsey ridge basin 33 Ma ago, with the subsequent formation of the Jan Mayen microcontinent, also displaced fragments of continental crust to positions under E and SE Iceland (Torsvik et al., 2013). The spreading ridges north of Iceland appear to sample mantle sources with higher proportions of locally derived SCLM-material than other mid-ocean ridges.

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Interseismic and Postseismic Deformations Associated with 2011 Magnitude 9.0 Tohoku-Oki Earthquake: 2D And 3D Finite Element Models with a Viscoelastic Rheology

O. Trubienko[1], L. Fleitout[1] and J-D. Garaud[2]

[1]Laboratoire de Géologie, ENS, Paris, France

[2]Onera — The French Aerospace Laboratory, Châtillon, France

Elastic backslip models are very often used to study interseismic deformations associated with large subduction earthquakes. In these models, a peak in vertical velocity is predicted above the downdip end of the locked portion of the fault. However, in the case of Tohoku, the peak in vertical velocity was in the Western part of the district and an elastic backslip model would then imply strong coupling down to a depth of at least 100km which is unrealistic as already noticed by Savage (1983). We explain the observed horizontal and vertical velocity (GEONET network) with a 2D Finite element model with a viscoelastic mantle. We show that, in this case, a Low Viscosity Wedge (LVW) or Low Viscosity Channel (LVCh), a locking depth of the order of 40 km and an asthenosphere with a burger rheology with short-term viscosity of the order of 3×10^{18} Pas are compatible with the interseismic data (Trubienko et al., 2013). Japan March 11, 2011 great subducting earthquake offers an opportunity to study postseismic deformations due to the exceptional data coverage. GPS data from Russia and China show that the huge horizontal velocity perturbations can be seen more than 1000 km away from the rupture zone. With the help of 3D Finite-element model we first invert for coseismic slip on the subduction interface. Then we show that the far-field postseismic velocities can only be explained by viscoelastic relaxation in the asthenosphere. To explain the post-seismic observations in the close- and middle-field some slip on the subduction interface and presence of a LVCh are required. The shape and location of this LVCh (versus LVW) is determined via inversion of relaxation patterns given by elementary low viscosity zones within the overriding plate as well as upper part of asthenosphere. Furthermore, we show that the same viscoelastic properties of the mantle material can be used to fit both postseismic and interseismic deformations.

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Modeling Melting with Particles in Whole Mantle Convection

H. J. van Heck[1] and J-H. Davies[1]

[1]*School of Earth and Ocean Sciences, Cardiff University, UK*

Many outstanding problems in Earth science relate to the geodynamical explanation of geochemical observations. Nowadays, extensive geochemical databases of surface observations exist, but satisfying explanations of underlying processes are lacking. Longstanding problems such as; The possible existence and sustainability of chemically distinct reservoirs in the Earth's mantle; the possible need of layered convection through much of Earth's history to explain chemical observations; and the heat flow paradox remain unsolved. One way to address these problems is through numerical modeling of mantle convection while tracking chemical information throughout the convective mantle. In the past decade, both numerical mantle convection codes and computer power have grown sufficiently to begin to grasp much of the full problem of the complex interlocking physics, chemistry and thermodynamics of the convecting mantle, lithosphere, continents and atmosphere. We implemented a new way to track both bulk composition and concentration of trace elements in the well-developed mantle convection code TERRA. Our approach is to track bulk composition and trace element abundance via particles. One value on each particle represents bulk composition; it can be interpreted as the basalt component. The system is set up to track both radioactive isotopes (in the U, Th, K system) and noble gases (He, Ar). In our model, chemical separation on bulk composition and trace elements happens at self-consistent, evolving melting zones. Melting is defined via a composition dependent solidus, such that the amount of melt generated depends on pressure, temperature and bulk composition of each particle. A novel aspect is that we do not move particles that undergo melting; instead we transfer the chemical information carried by the particle to other particles. Molten material is instantaneously transported to the surface, thereby increasing the basalt component carried by the particles close to the surface, and decreasing the basalt component in the residue. For molten material that arrives at the surface, a fraction of its content of isotopes is moved into separate continent and atmosphere reservoirs. Results will be presented in which we test and show the success and limitations of our implementation. We choose to use a simplified setup with calculations of incompressible mantle convection in spherical geometry. In these we will avoid complexities such as phase changes and elastic/plastic deformation, and focus on different density and viscosity profiles. For these calculations we will show: 1. The evolution of bulk composition over time, showing the build up of oceanic crust (via melting induced chemical separation in bulk composition); i.e. a basalt-rich layer at the surface overlying a thin layer of depleted material (harzburgite), and the transportation of these chemical heterogeneities through the deep mantle. 2. The amount of melt generated over time. 3. The evolution of the concentrations and abundances of different isotopes of the elements: U, Th, K, Pb, He and Ar, throughout the mantle as well as the atmosphere and continent reservoir. 4. Numerical details on the splitting and merging of particles which is needed to ensure proper coverage at all times.

Numerical Model Exploration of a Movable Emplacement Zone for Melt Extraction in a Continental Lithospheric Extension Scenario

H. Wallner[1] and H. Schmeling[1]

[1]*Goethe-Universität, Frankfurt am Main, Germany*

Motivated by the special geological situation of the Rwenzori Moutains numerical modeling of its geodynamics led us to more fundamental questions on the structure and evolution of the continental lithosphere. The observation of a melt-infiltration front (MIF) (Wölbern et al., 2012) also considered as mid-lithospheric discontinuity (MLD) supports our concept of melt extraction and emplacement in lithospheric levels. Modeled physics is based on thermo-mechanics of visco-plastic flow. The equations of conservation of mass, momentum and energy are solved for a multi component (crust-mantle) and two-phase (melt-matrix) system. Rheology is temperature-, pressure-, and stress-dependent. In consideration of depletion and enrichment, melting and solidification are controlled by a simplified linear binary solid solution model. The Compaction Boussinesq Approximation and the high Prandtl number approximation are used, elasticity is neglected and geometry is restricted to 2D. Approximation is done with the Finite Difference Method in an Eulerian formulation (FDCON). A fast upwardly transport of melt is substituted by extraction and emplacement of melt and its heat in a given level. Extension is realized by a lateral outflow boundary condition. The geotherm, defining the initial temperature background, reaches the melting curve near the model bottom in the asthenosphere. Additional temperature anomalies in the asthenosphere focuses uprising melt batches; their amplitudes determine the time behavior and rifting style. Above a critical fraction limit melt is extracted and intruded above. Variations of these intrusion levels imply different convection patterns resulting in more or less active erosion of the lower lithosphere, doming of asthenosphere and melt-induced weakening - chimneys of increased enrichment evolving to narrow low viscous mechanical decoupling zones. A termination criterion – the melt front exceeds the top of emplacement zone (EZ) – stops models with deep-seated intrusion levels in an early transient state. To maintain the full evolution the top EZ boundary should ascent. Also the hypothesis of melt infiltrating the lithosphere expects an uprising front (MIF). Before developing a physical approach – aim of a future project – a preliminary study shall explore an (or several) empirical attempt(s) defining an upward moving EZ. Modeling is in progress.

Whether a moving EZ will influence erosion type and dynamic topography is open. The results will provide some expectations on future, more self-consistent physically based modeling of lithosphere evolution.

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The Earliest Evolution of Moon, Mars and Mercury – How Old Are Their Oldest Surfaces?

S. C. Werner[1]

[1]*Centre for Earth Evolution and Dynamics, University of Oslo, Norway*

Evidence of the late thermal evolution is recorded on the planetary surfaces in various expressions of volcanic landforms, which add material to the crust of the planetary body. While Earth and Venus have experienced significant crustal rejuvenation, the Moon, and perhaps Mars and Mercury carry remnants of primordial crust. The thermal and volcanic evolution can be read from their surfaces: Basin formation ages for Moon, Mars and Mercury are determined, compared and evaluated with respect to their maximum surface ages and available isotope ages. Both Mars and Mercury appear to have undergone global resurfacing even after magma ocean overturn, so that at least the first 200-400 millions of years are not recorded on their surfaces. Basin frequency (craters larger than about 250 km in diameter) and crater frequencies below 150 km indicate that the Moon has the oldest surface, Mars the youngest maximum surface age, while Mercury's maximum surface age lies somewhat in between. However, this also depends on the impact-rate ratios and average impact velocities during the first several hundreds of millions of years, which are poorly known and model dependent. A mismatch between the basin size-frequency distribution, the smaller crater size-frequency distribution and the main-belt asteroid size-frequency distribution is observed in all three cases, suggesting an off-set of about 150 Ma between basin distribution and maximum surface age distribution. This is preliminary interpreted as lack of understanding of the basin formation process: But one possible explanation for the apparently under-representative basin frequency could be a different (lower) average impact velocity compatible with the 'Nice' flux model (spiky flux behaviour instead of monotonic decay). The question is raised if the Moon due to its special formation history is a suitable analogue for the formation, evolution and cratering record of the other terrestrial bodies.

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