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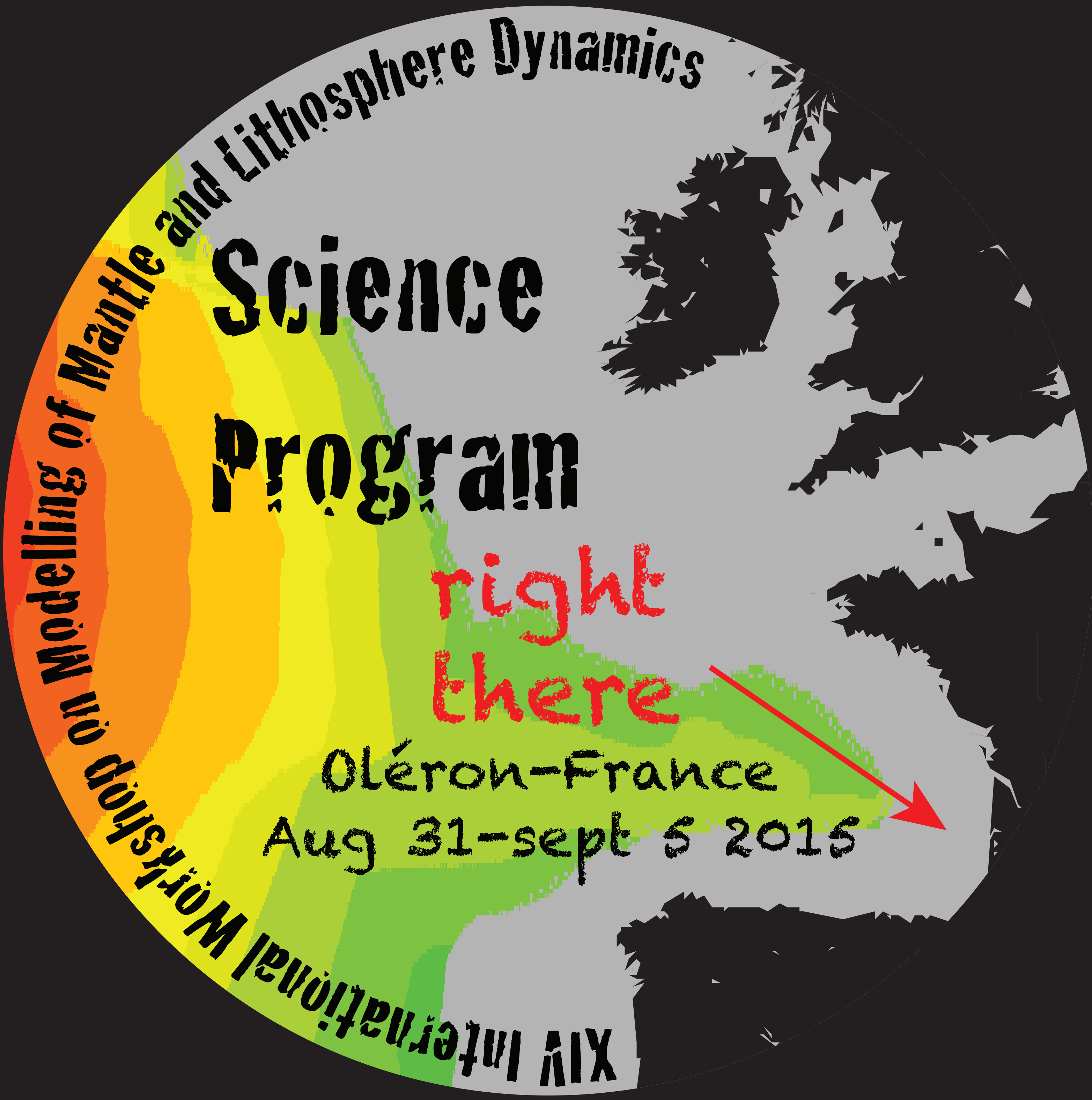

XIV International Workshop on Modelling of Mantle and Lithosphere Dynamics

Science Program

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Oral program

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TRADEOFFS IN DATA ASSIMILATION AND SOLVER DESIGN

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ABSTRACT:

Geophysical models never have complete input data and rarely is the solution of the forward model the primary quantity of interest. Instead, forward models are used to infer consistent inputs and quantitites of interest in a probabilistic sense. This information is ultimately used to inform decisions, often balancing expense with risk, and requiring more sophisticated statistical techniques. Suitable algorithms for these tasks depend critically on factors such as nonlinearity and dimensionality, and have consequences for the design of forward models. Throughout, we attempt to balance modeling error, discretization error, and stochastic error in order to maximize efficiency at any desired prediction accuracy. This talk will explore these issues via examples with discussion of tradeoffs and limitations in available methods and software and opportunities for improving efficiency on modern and emerging architectures.

NON-PERIODIC HOMOGENEIZATION FOR SEISMIC FORWARD AND INVERSE PROBLEMS

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ABSTRACT:

The modeling of seismic elastic wave full waveform in a limited frequency band is now well established with a set of efficient numerical methods like the spectral element, the discontinuous Galerking or the finite difference methods. The constant increase of computing power with time has now allow the use of seismic elastic wave full waveforms in a limited frequency band to image the elastic properties of the earth.

Nevertheless, inhomogeneities of scale much smaller the minimum wavelength of the wavefield associated to the maximum frequency of the limited frequency band, are still a challenge for both forward and inverse problems. In this work, we tackle the problem of elastic properties and topography varying much faster than the minimum wavelength. Using a non periodic homogenization theory and a matching asymptotic technique, we show how to compute effective elastic properties and local correctors and how to remove the fast variation of the topography. The implications on the homogenization theory on the inverse problem will be presented.

We will then discuss the potential application of such an homogenization to geodynamics problems, which are by far less
obvious than for the linear equation case.

GEODYNAMIC INVERSE MODELLING TO CONSTRAIN THE RHEOLOGY OF THE LITHOSPHERE

Kaus B.J.P. (1,2), Baumann T. (1), Reuber G. (1,2), Popov A. (1)

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ABSTRACT:

Better understanding the physics of the Earth is and will remains one of the goals of the solid Earth sciences. Whereas geophysical methods give a fair idea of the structure of the present-day Earth, geological data indicate that most processes occur over millions of years and thus tell us something on how the Earth behaved on a much longer timescale. If we want to reconcile both types of data, we need models that describe how the lithosphere deforms and results in mountain belts such as the Himalayas. Over the last decade, dynamic lithospheric models have become quite sophisticated. Typically such geodynamic models are used in a forward manner, in which various theoretical scenarios are simulated as a function of changing parameters such as plate speed, thermal structure of the lithosphere and rock rheology. The best fitting models are the ones that appear to be most consistent with the data. This does teach us something about how lithospheric collision could have occurred. Yet, since the number of model parameters is large and the models remain computationally intensive even in 2D, we cannot check every parameter combination. Moreover, the uncertainties in experimentally determined creep laws are very large and it is therefore desirable to have an independent method to constrain the rheology of the lithosphere.

Here, I will discuss inverse modelling approaches that combine lithosphere-scale dynamic forward models with geophysical observations (such as horizontal and vertical surface (GPS-) velocities, topography and gravity data) with the aim to better constrain the rheological parameters of the lithosphere and get a grip on how well the models fit observational constraints.

There are a number of ways in which the inverse problem can be formulated, of which I will discuss two in detail. The first method assumes that your model parameters are close to the “optimal” parameters and that there is only one solution to the inverse problem. In that case, one can use a gradient-based method to arrive at the “best-fit” solution with only a few iterations. Doing this requires computing the gradient of the misfit function versus the model

parameters. One way to do this, is to perturb each of the model parameters and compute the gradient in a finite-difference manner which requires n computations if we have more n model parameters. A different, and more elegant, way is to use a so-called adjoint formulation of the Stokes equations, which requires only a single additional solution and is thus independent of n. The price you have to pay for this, is that it requires an additional linear solve with the transpose of the jacobian which can be tricky to derive. Yet, a disadvantage of the gradient-based methods is that they assume that you are close to the optimal solution and that there is only one best-fit solution.

As this is not guaranteed to be the case for the lithosphere, the second method that will be discussed is a Bayesian inversion strategy. This method estimate probabilities of model parameters that affect the rheology of the lithosphere. As this requires many forward models (104 - 106), which increase with increasing n, it requires an efficient and parallel implementation which we recently showed to exist in 3D for linear viscous rheologies. Here, we examine how well this method is capable of resolving complex rheologies and address a few technical issues such as defining an appropriate stopping criteria for models with a free surface. We use synthetic models of intraoceanic subduction to demonstrate that the rheological parameters of the lithosphere can be recovered successfully even if rheologies are powerlaw viscous or plastic, provided that the temperature structure is known. A piece-wise linear lithospheric temperature parameterization as part of the inverse approach is shown to give reasonable results as well.

Furthermore, we apply the method to cross-sections of the Himalaya where we consider different geological interpretations as end-member cases. For each end-member, we estimate the probabilities of their rheological structure and plasticity parameterization and also obtain suitable temperature distributions. Results indicate that the Indian mantle lithosphere has a large effective viscosity whereas the Tibetan lower crust has small effective viscosities. Yet, the results also indicate that several regions in the model parameter space exist that fit the data nearly equally well, some of which have a high viscous mantle lithosphere underneath Tibet, whereas others prefer a weaker mantle lithosphere. If more data are included in the inversion approach, we might be able to further narrow the solution space. Simultaneously, we also obtain the uncertainties of each of the model parameters.

We conclude that geodynamic inversion is a powerful and very promising methodology to better constrain the rheology and the physics of the lithosphere.

Funding was provided by ERC Starting Grant agreement #258830

Data assimilation, efficient solvers and homogeneisation

INFERRING THE INITIAL CONDITIONS OF MANTLE CONVECTION FROM THE MANTLE TEMPERATURE STRUCTURE USING PATTERN RECOGNITION

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ABSTRACT:

Many of the parameters necessary for initiating mantle convection simulations are very poorly constrained, introducing large uncertainties and errors into the simulations. One obstacle to the constraint of these parameters is the non-linear nature of convection. Whist convection is fully deterministic, the non-linearity makes inversion difficult. Linear inversion techniques cannot be used to obtain initial model conditions over more than very short periods of time and require strong regularisation. We demonstrate a new method for inferring initial mantle convection model parameters from the mantle temperature structure. Our method is probabilistic, allowing us to consider the whole of Earth's history. We invert the temperature structure of the mantle produced by 4.5 Gy of convection for the initial convection model parameters. We are able to do this because we construct probability density functions for initial conditions, represented by neural networks, which take into account all of the non-linearity of convection. Our approach is very flexible because we sample in the prior rather than the posterior space, allowing us to make inferences from many different geophysical observations. We need relatively few samples to make inferences, making this approach much more computationally tractable than other probabilistic inversion methods, such as Monte-Carlo methods. From observations of the temperature structure from 2D convection simulations, calculated using the code StagYY, we find we can constrain yield stress, surface reference viscosity, viscosity activation volume, mantle radiogenic heating and the initial thickness of primordial material at the CMB. By adding other observations, such as density, the power of the inversion process improves further. We expect our approach to work in 3D, giving us a new method to make inferences about early Earth history and the evolution of the mantle.

European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013)/ERC Grant Agreement n. 320639, and the Netherlands Research Center for Integrated Solid Earth Science (ISES 2012-81)

A HIGH-RESOLUTION 3D GEODYNAMICAL MODEL OF THE PRESENT-DAY INDIA-ASIA COLLISION SYSTEM

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ABSTRACT:

We present a high-resolution, 3D geodynamic model of the present-day India-Asia collision system. The model is separated into multiple tectonic blocks, for which we estimate the first order rheological properties and the impact on the dynamics of the collision system. This is done by performing systematic simulations with different rheologies to minimize the misfit to observational constraints such as the GPS-velocity field.

The simulations are performed with the parallel staggered grid FD code LaMEM (Lithospheric and Mantle Evolution Model, Kaus and Popov et al.). To resolve dynamically important shear zones reasonably well, we use a minimum resolution of 512x512x256 FD-cells.

A fundamental part of this study is the reconstruction of the 3D present-day geometry of Tibet and the adjacent regions. Our interpretations of crust and mantle lithosphere geometry are jointly based on a globally available shear wave tomography (SL2013sv, Schaeffer and Lebedev, 2013) and the Crust 1.0 model (Laske et al. 2013). We regionally refined and modified our interpretations based on seismicity distributions and focal mechanisms and incorporated regional receiver function studies to improve the accuracy of the Moho in particular.

First results suggest that we can identify at least one “best-fit” solution in terms of rheological model properties that reproduces the observed velocity field reasonably well. We also present model covariances to illustrate the trade-offs between the rheological model parameters and their respective uncertainties.

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Schaeffer, A. J., & Lebedev, S. (2013). Global shear speed structure of the upper mantle and transition zone. Geophysical Journal International, ggt095.

Funding was provided by ERC Grant agreement #258830. Numerical computations have been performed on JUQUEEN of the Jülich high- performance computing center.

Data assimilation, efficient solvers and homogeneisation

APPLYING DATA ASSIMILATION TO MANTLE CIRCULATION AND SURFACE TECTONICS: A PROOF OF CONCEPT

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ABSTRACT:

Global mantle convection models are now able to solve for both the dynamics of the interior flow and the surface tectonics to first order.

Combining tectonic data (like surface kinematics and seafloor age distribution) with such models opens the way to a new generation of mantle circulation reconstructions, where tectonic data are not used as boundary conditions for the flow, but as data to invert. We explore this possibility by using a sequential data assimilation method, based on suboptimal schemes derived from the Kalman Filter. This method consists in assimilating data chronologically, by repeating two stages, an analysis and a forecast, for the time period during which data are available. Whenever an observation is available, the analysis evaluates the most likely state of the mantle at this time, considering a prior guess (supplied by the forecast) and the new observations at hand.

This evaluation is done by using the classical best linear unbiased estimate. The evolution of the mantle until the next observation time is then forecasted by the forward model of mantle convection. We conduct synthetic 2D spherical annulus mantle cases to evaluate the efficiency of this method. First, we compute reference evolutions, from which we extract synthetic surface data time series. Then, we assimilate these data to estimate the evolution of the system, and compare the result to the original reference evolution. The quality of the data assimilation depends on two parameters: the time between two analyses, and the amplitude of noise in the synthetic observations. We are able to retrieve the temperature field evolutions when the time between two analyses is less or equal to 10 My. Moreover, even with a noise on observations as high as 50%, our method is able to provide an estimate of mantle evolution with an error of less than 9% on the temperature field for time periods of around 150 My.

The research leading to these results has received funding from the European Research Council within the framework of the SP2-Ideas Program ERC-2013-CoG, under ERC grant agreement 617588. Calculations were performed on LGLTPE Seisglob high-performance computing cluster and using HPC resources from GENCI-IDRIS (grant 2014-047243).

Data assimilation, efficient solvers and homogeneisation

Another regional spherical grid

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Abstract:

A regional spherical grid is presented that spans over a desired fraction of a spherical shell while maintaining conformity and avoiding pole problems. This is achieved by projecting a rectangular grid with the stereographic projection onto a sphere. This way the rectangular angles remain the same on the sphere, enabling standard textbook discretization for finite-volume and -difference to be applied to spherical geometry without the need to take care of complex or varying stencils. The resulting grid has the same connectivity as a two- or three-dimensional box grid and is therefore perfectly parallelizable and suitable for multi-grid methods. Mantle convection benchmarks (natural convection Stokes-flow) for spherical shells with strong variable viscosity have been used to test and benchmark the grid and to demonstrate applicability.

Newton versus Drucker-Prager

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ABSTRACT:

Plasticity models that describe rock failure are essential ingredients in geodynamic models as terrestrial rocks do not possess an infinite yield strength. Numerous physical mechanisms have been proposed to limit the strength of rocks, including low temperature plasticity and brittle fracture. While ductile and creep behavior of rocks at depth is largely accepted, the constitutive relations associated with brittle failure, or shear localisation, are more controversial.

In practice, only a few macroscopic constitutive laws for visco-plasticity regularly used in geodynamics models. Such formulations can be cast as simple effective viscosities which act as stress limiters with different choices for yield surfaces; the most common being a von Mises (constant yield stress) or Drucker-Prager (pressure dependent yield stress) criterion. The choice of plasticity model, however, can have significant consequences for the degree of non-linearity in a problem and the robustness of non-linear solvers.

Here we describe a series of simplified 2D model problems to elucidate several issues associated with obtaining accurate description and solution of visco-plastic problems. We demonstrate that (1) Picard schemes for solution of the non-linear problems can often stall at large values of the non-linear residual, thus producing spurious solutions; (2) combined Picard/Newton schemes can be effective for a range of plasticity models, however, they can produce serious convergence problems for strongly pressure dependent plasticity models such as Drucker-Prager; (3) when used with strong materials, the Drucker-Prager plasticity model or strong materials as the dynamic pressures produced in these layers can develop pathological behavior resulting in stress strengthening rather than a stress weakening behavior.

Theoretical considerations associated with incompressible media with a pressure dependent viscosity are discussed which reveal that there are well defined regimes in which the non-linear visco-plastic formulation is not well-posed, and thus no solution can exist. These theoretical findings can be used to guide the definition of well-posed geodynamic models.

MODELLING IN TOMORROW'S TECHNOLOGICAL LANDSCAPE - UNVEILING UNDERWORLD2

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ABSTRACT:

Understanding of mantle and lithosphere dynamics, distinct or coupled, attracts certain modes of scientific discovery. It is not only engineering - as the constitutive laws for minerals under these conditions are difficult to measure in the laboratory. It is not only geology - as the precise characterisation of the Earth is impossible without interpretations on sensor observations. Further it is intrinsically multi-scale, where chemical and physical effects at the centimetre scale effect structures as broad as plates and mantle flow. The mode of "modelling" dominates our discovery process. Do we understand how this mode will continue in the changing technological landscape?

Over the period of two decades ago to one decade ago, increased accessibility to personal computing led to a golden age of Earth dynamics discovery. Fundamental processes were contributed by many, all relying on computation of numerical systems of scale or complexity that required a computer. Invariably we must thank the innovation of Moore's Law - over 50years of sustained 50%-compounded yearly growth in computing capability - for enabling such computing at this time.

Increasingly a sole phd student could no longer write their own code in isolation and from scratch. Despite the readily available computing power, the total model required had become sufficiently complex that collaboration about codes became necessary. About a decade ago, the very first versions of software Underworld was released. And along with other codes, a second golden age was born, where many discoveries about 3-dimensional effects together with processes across scales have arisen. Hence innovations of Underworld were enabled by software for complexity - allowing more expertise and more libraries to readily contribute. Underworld in particular focused on distributed parallel computing, increasingly complex numerical methods, and increasingly complicated physics. It is by no means perfect, but has pioneered avenues of methods and discoveries.

Today, Moore’s Law is ailing, and the only man-made innovation that is remotely close to it is the Internet of Things. Sensor capabilities are an honourable second (approximately 25%-compounded yearly growth over the last couple of decades). Together with increasing storage technologies, they are fuelling the data-deluge, and in-turn, data-driven scientific discovery (clearly being enjoyed by the geophysical disciplines). They are also fuelling organisational and asset (code in our case) permeability. We are no longer needing just massive amounts of computing for the complex numerical system, but an eco system of computing that enables rapid experimentation and high throughput on data. In short, increasingly innovation at large will drive towards codes and environments that assimilate with data, and codes and environments that have accessible insides (rather than those that are one monolithic box or function).

Here we unveil Underworld2, a cloud ready, python-based code for mantle and lithosphere dynamics discovery, spanning tutorials, data assimilation and in-line analysis. We hope that nothing is lost from Underworld1 but that Underworld, and its subparts, are accessible to the researcher with data.

Data assimilation, efficient solvers and homogeneisation

ON THE USE OF THE STABILISED Q1P0 ELEMENT FOR GEODYNAMICAL SIMULATIONS

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ABSTRACT:

Many Finite Element geodynamical codes (Fullsack,1995; Zhong et al., 2000; Thieulot, 2011) are based on bi/tri-linear velocity - constant pressure element (commonly called Q1P0), because of its ease of programming and rather low memory footprint, despite the presence of (pressure) checker-board modes. However, it is long known that the Q1P0 is not inf-sup stable and does not lend itself to the use of iterative solvers, which makes it a less-than-ideal candidate for high resolution 3D models.

Other attempts were made more recently (Burstedde et al., 2013; Le Pourhiet et al., 2012) with the use of the stabilised Q1Q1 element (bitri-linear velocity and pressure). This element, while also attractive from an implementation and memory standpoint, suffers a major drawback due to the artificial compressibility introduced by the polynomial projection stabilization. These observations have shifted part of the community towards the Finite Difference Method while the remaining part is now embracing inf-sup stable second-order elements [May et al., 2015; Kronbichler,2012).

Rather surprinsingly, a third option exists when it comes to first-order elements in the form of the stabilised Q1P0 element, but virtually no literature exists concerning its use for geodynamical applications. I will then recall the specificity of the stabilisation and will carry out a series of benchmark experiments and geodynamical tests to assess its performance.

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Data assimilation, efficient solvers and homogeneisation

Deep Earth and Planetory Bodies

Oral program

Subduction History and the Evolution of Earth's Lower Mantle
Bull, A. L. , Shephard, G. E. , Domeier, M. , Torsvik, T. H.

From defects to mantle flow
Cordier P.

The deep mantle large low shear-velocity provinces - largely thermal features?
Goes, S , Davies, D.R.

Poster program

How can initially stagnant slabs sink into the lower mantle?
Agrusta R. , Goeas S. , van Hunen J.

Compositional mantle layering revealed by slab stagnation at ~1,000 km depth
Ballmer, M. D. , J. Ritsema , T. Nakagawa , N. C. Schmerr

Geodynamic modelling of a mantle plume under La Réunion
Bredow E. , Steinberger B. , Sigloch K.

A benchmark initiative on mantle convection with melting and melt segregation
Dohmen J. , Schmeling H. , Dannberg J. , Maurice M. , Noack L. , Plesa A.C. , Thieulot C. , Tosi N., Wallner H.

Melting at the mantle conditions
Fomin I., Tackley P.

Towards coupled giant impact and long-term interior evolution models
Golabek G. J. , Jutzi M. , Emsenhuber A. , Gerya T. V. , Asphaug E. I.

Reconciling observations of PKIKP precursors and thermochemical convection models
Haugland S. , Ritsema J.

Grain-size dependent transition between dislocation and diffusion creep
Huettig C , Breuer D , Plesa A

Is there any correlation between continents and elevated temperatures in the subcontinental mantle?
Jain C., Rozel A., Tackley P.

Stability of convection patterns in 3D and implications for benchmarking
Kellogg L.H. , Arrial P.A. , Flyer N. , Wright G.B.

Early evolution and dynamics of Earth from a molten initial stage
Lourenço D.L. , Tackley P.J.

Delamination of the Mafic Subducting Crust
Maunder B. , van Hunen J. , Magni V. , Bouilhol P.

Detailed program

Consequences of magma ocean solidification
Maurice M. , Tosi N. , Plesa A.-C. , Breuer D. , Huettig C.
Does Earth’s Hot Accreted Core Power Mantle and Core Convection?
Morgan, J.

The effect of viscosity variations in determining dynamic topography from seismic tomography models
O'Farrell, K. , Lithgow-Bertelloni, C.

Semi analytical model for the effective grain size profile in the mantle of the Earth
Rozel A. , Golabek G. , Thielmann Marcel , Tackley P.

Evidence for and dynamical consequences of a viscosity increase in the mid-mantle
Rudolph, M.L. , Lekic, V. , Lithgow-Bertelloni, C.

Temporal variation of the geoid and dynamic topography inferred from geodynamics modeling
Shahraki M. , Schmeling H.

Generating dynamos in basal magma oceans
Stegman D. , Ziegler L. , Davies, C.

The key influence of magmatism on the thermo-chemical-tectonic evolution of terrestrial planets
Tackley P. J. , Lourenco D. , Nakagawa T. , Rozel A.

Mercury's low-degree geoid and topography controlled by insolation-driven elastic deformation
Tosi N. , Cadek O. , Behounkova M. , Kanova M. , Plesa A. , Grott M. , Breuer D. , Padovan S. , Wieczorek M.

On Evolving Lid-States, Bi-Stability, and the Evolution of Terrestrial Planets: Pathways and Divergences in Planetary Evolution
Weller M.B. , Lenardic, A.

Detailed program

SUBDUCTION HISTORY AND THE EVOLUTION OF EARTH'S LOWER MANTLE

Bull, A. L. (1), Shephard, G. E. (1), Domeier, M. (1), Torsvik, T. H. (1-3)

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ABSTRACT:

Understanding the complex structure, dynamics and evolution of the deep mantle is a fundamental goal in solid-Earth geophysics. Seismic tomography has revealed Earth's mantle to be a complex system - a result of 4,56 billion years of evolution, gravitational settling, convection and crustal recycling. Close to the core-mantle boundary, seismic images reveal a mantle characterised by (1) higher than-average shear wave speeds beneath Asia and encircling the Pacific, consistent with subducting lithosphere beneath regions of ancient subduction, and (2) large regions of anomalously low seismic wave-speeds beneath Africa and the Central Pacific. The anomalously slow areas, which cover nearly 50% of the core-mantle boundary and extend ~1000 km upward from their base, are often referred to as Large Low Shear Velocity Provinces (LLSVPs) due to the reduced velocity of seismic waves passing through them. The origin, composition and long-term evolution of the LLSVPs remains enigmatic. Geochemical inferences of multiple chemical reservoirs at depth, strong seismic contrasts, increased density, and an anti-correlation of shear-wave velocity to bulk sound velocity in the anomalous regions imply that heterogeneities in both temperature and composition may be required to explain the seismic observations. Consequently, heterogeneous mantle models place the anomalies into the context of thermochemical piles, characterised by an anomalous component whose intrinsic density is a few percent higher relative to that of the surrounding mantle.

Several hypotheses have arisen to explain the LLSVPs in the context of large-scale mantle convection. One end-member scenario suggests that the LLSVPs are relatively mobile features over short timescales and thus are strongly affected by supercontinent cycles and Earth's plate motion history. In this scenario, the African LLSVP formed as a result of return flow in the mantle due to circum-Pangean subduction (~240 Ma), contrasting a much older Pacific LLSVP, which may be linked to the Rodinia supercontinent and is implied to have remained largely unchanged since Rodinian break-up (~750–700 Ma). This propounds that Earth's plate motion history plays a controlling role in LLSVP development, suggesting that the location, geometry and morphology of lower mantle structures can be influenced by the movement of subducting slabs, and thus by the motions of tectonic plates at the surface. Alternatively, a long-term stability for both LLSVPs, which would suggest a first-order

dissociation from the effects of surface plate motions, is hypothesised by recent studies which propose a geographic correlation between the reconstructed surface eruption sites of kimberlites and Large Igneous Provinces with the margins of the LLSVPs. If the surface volcanism was sourced from the lower mantle, such a link would suggest that the LLSVPs may have remained stationary for at least the age of the volcanic rocks (> 500 Myr) and further that the anomalies were largely insensitive to the formation and subsequent break-up of Pangea, and thus to Earth's plate motion history.

Here we discuss the evolution of lower mantle structure and LLSVPs in terms of subduction dynamics. We integrate plate tectonic histories and numerical models of mantle convection and perform a series of 3D spherical calculations with Earth-like boundary conditions to investigate the role that subduction history plays in the development and evolution of lower mantle structures. To test whether such an interaction exists, and if so, to what degree over time, we apply varying shifts to the absolute reference frame of the plate reconstruction. We incorporate global shifts in both longitude and latitude, with the correction applied over timescales of 230 - 50 Myrs. With this method, we are able to change the location of subduction at the surface and thus the global flow field. This in turn affects the time-dependent sinking of lithospheric slabs and may affect their interaction with the lower mantle and the LLSVPs at both their margins and top surfaces. We aim to understand how the subduction history has affected mantle structure on a global scale. Preliminary results show that shifts to the surface history of subduction, even for extreme and unrealistic cases, lead to minimal changes in LLSVP geometry and position, suggesting that the LLSVPs may be long-lived features (> 250 Ma).

FROM DEFECTS TO MANTLE FLOW

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ABSTRACT:

Large scale flow in the Earth's mantle involves plastic deformations of rocks and of their constitutive minerals. Due to the extremely slow strain rate conditions in the Earth's mantle, it is very challenging to identify the fundamental mechanisms controlling such processes. The extreme pressures that build up with increasing depth in the Earth’s mantle (and more generally in planetary interiors) also affect strongly the electronic structure of solids, hence the mechanical properties. Thus, the development of a multi-scale approach linking the atomic scale properties and the microscopic elementary mechanisms to the macroscopic behavior is needed (Cordier et al. 2012).

One of the key steps in this approach is the description of dislocation-based intra-crystalline plasticity. Three important stages must be addressed:

- Dislocation modeling. The dislocation core, i.e. the atomic configuration close to the dislocation line has strong implications on the mobility of dislocations. To address this issue one can either perform full atomic scale modeling or use semi-continuous models like the Peierls-Nabarro model. In any case, it is necessary to rely on first-principles calculations to account properly for the influence of pressure.
- Dislocation mobility. Lattice friction, i.e. the force opposed to dislocation glide by the crystal is the first consequence of the dislocation core structure. Its magnitude has implications on the mechanical properties. It is however necessary to describe the thermally-activated mechanism by which the dislocation overcomes lattice friction under applied stress: the kink-pair mechanism.
- Collective behavior. The mechanical properties result from the collective behavior of a large number of interacting defects. The simplest approach involves the Orowan equation. Alternatively, we use dislocation dynamics modeling to describe intra-crystalline plasticity.

Cordier P. et al., Nature 481, 177 (2012)

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THE DEEP MANTLE LARGE LOW SHEAR-VELOCITY PROVINCES - LARGELY THERMAL FEATURES?

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ABSTRACT:

The two large low shear-wave velocity provinces (LLSVPs) that dominate lower-mantle structure may hold key information on Earth's thermal and chemical evolution. It is generally accepted that these provinces are hotter than background mantle and are likely the main source of mantle plumes. Increasingly, it is also proposed that they hold a dense (primitive and/or recycled) compositional component. The principle evidence that LLSVPs may represent thermo-chemical `piles' comes from seismic constraints. To test these constraints, we compare imaged seismic structures with synthetic seismic structures from a set of thermal and thermo-chemical mantle convection models that are constrained by ~ 300 Myr of plate motion histories. Modelled physical structure is converted into seismic velocities via a thermodynamic approach that accounts for elastic, anelastic and phase contributions and, subsequently, a tomographic resolution filter is applied to account for the damping and geographic bias inherent to seismic imaging. We find that anomaly shapes, amplitudes and gradients, (relative) variation of shear, compressional and bulk-sound speeds, and a relation between LLSVPs and the distribution intraplate volcanism can be equally well explained with thermal and thermo-chemical models. Only an anti-correlation between shear-wave velocity anomalies and density, found by some studies but questioned by others, would provide unambiguous evidence for chemical heterogeneity. In any case, imaged distributions of lower-mantle shear-velocity anomalies allow at most very low-volume piles of dense chemical heterogeneity in the deep mantle. Such heterogeneity, although geochemically significant, would exert little control on large scale geophysical structure and mantle dynamics.

Early evolution and dynamics of Earth from a molten initial stage

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Abstract:

Most of the terrestrial planets underwent a magma ocean stage during their evolution. On Earth, it is probable that at the end of accretion, giant impacts like the Moon-forming impact, together with other sources of heat, melted a substantial part of the mantle. Considerable research has been done on magma oceans using simple 1-D models (e.g.: Abe, PEPI 1997; Solomatov, Treat. Geophys. 2007; Elkins-Tanton, EPSL 2008). However, some aspects of the dynamics may not be adequately addressed in 1-D and require the use of 2-D or 3-D models.

The goal of our study is to understand the influence of melting on the long-term thermo-chemical evolution of rocky planet interiors, starting from an initial molten state. Our approach is to model viscous creep of the solid mantle, while parameterizing processes that involve melt as previously done in 1-D models, including melt-solid separation at all melt fractions, the use of an effective diffusivity to parameterize turbulent mixing, coupling to a parameterized core heat balance and a radiative surface boundary condition. These enhancements were made to the numerical code StagYY (Tackley, PEPI 2008).

We will present results for the evolution of an Earth-like planet from a molten initial state to present day, while testing the effect of uncertainties in parameters such as melt-solid density differences, surface heat loss and efficiency of turbulent mixing. Our results show rapid cooling and crystallization until the rheological transition then much slower crystallization, large-scale overturn well before full solidification, the formation and subduction of an early crust while a partially-molten upper mantle is still present, transitioning to mostly-solid-state long-term mantle convection and plate tectonics or an episodic-lid regime.

HOW CAN INITIALLY STAGNANT SLABS SINK INTO THE LOWER MANTLE?

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ABSTRACT:

It is generally accepted that subducting slabs can either sink into the lower mantle, lie down in the mantle transition zone, or even stagnate beneath it. Several studies have looked at correlations between subduction zone parameters and the ability of their slabs to penetrate into the lower mantle. These studies have suggested that the key parameters to control whether slabs stagnate or penetrate are trench motions, slab strength, buoyant features and/or the overriding plate. For example, there is evidence that older lithospheres show significant trench retreat, and tend to lie down flat above the transition zone (northwest Pacific), whereas younger lithospheres, less able to drive trench retreat, tend to sink into the lower mantle (central America). Moreover, numerical modelling studies have shown further correlations with parameters that cannot be directly observed. For example, slab penetration is inhibited by density and viscosity increases associated with post-spinel phase transition.

Numerical modelling has been one of the key tools to investigate slab penetration, and a lot of insight has been gained from these studies. But most of these studies assume (statistical) steady-state scenarios, in which slab stagnation or slab penetration is more or less a permanent feature. However, how an initially stagnant slab will eventually begin to sink into the lower mantle is unclear. In this study, using 2D self-consistent numerical subduction models, we test various changes in forcing of downgoing plate, upper plate and mantle to see if any can trigger lower mantle penetration of previously stagnating slabs.

COMPOSITIONAL MANTLE LAYERING REVEALED BY SLAB STAGNATION AT ~1,000 KM DEPTH

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ABSTRACT:

Improved constraints on lower-mantle composition are fundamental to understand the accretion, differentiation and thermochemical evolution of our planet. Whereas cosmochemical arguments indicate that lower-mantle rocks may be enriched in Si relative to upper-mantle pyrolite, seismic tomography images suggest whole-mantle convection and efficient mantle mixing. This study reconciles cosmochemical and geophysical constraints using the stagnation of some slab segments at ~1,000 km depth as the key observation. Through numerical modeling of subduction, we show that lower-mantle enrichment in intrinsically dense basaltic heterogeneity can render slabs neutrally buoyant in the uppermost lower mantle. Slab stagnation (at ~660 and ~1,000 km depth) as well as unimpeded slab sinking to great depth can only coexist if the basalt fraction is ~8% higher in the lower than in the upper mantle, equivalent to a lower-mantle Mg/Si of ~1.18. Geodynamic models demonstrate that such a moderate compositional gradient can persist in the presence of whole-mantle convection, due to compositional filtering of both slabs and plumes as they cross the transition zone. Whereas basaltic heterogeneity tends to get trapped in the transition zone and ultimately sink into the lower mantle, harzburgitic heterogeneity tends to rise into the uppermost mantle.

GEODYNAMIC MODELLING OF A MANTLE PLUME UNDER LA RÉUNION

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ABSTRACT:

The French island La Réunion is located in the Indian Ocean, about 700 kilometers east of Madagascar. The Piton de la Fournaise at Réunion is one of the most active volcanoes worldwide with approximately one eruption per year. Although the existence and mechanisms of mantle plumes have remained very controversial, the plume beneath Réunion is one of the most likely candidates for a "classical" oceanic hotspot created by a deep plume from the base of the mantle. The hotspot track can be followed back to the Indian Deccan Traps, one of the world's largest flood basalt provinces that was created 65 Ma ago during the first eruptions of the Réunion volcano. Yet the genesis and the origin at depth of the hotspot and mantle upwelling leave many questions unresolved. The intention of this research is the creation of new geodynamic models with a range of realistic parameter sets that take into account the specific setting of the Réunion plume with subduction zones to the north and east and the African Large Low Shear Velocity Province to the south and west. For the numerical modelling, the mantle convection code ASPECT (Advanced Solver for Problems in Earth’s ConvecTion) is used, which is well-suited for this task, as the mesh can be adaptively refined at particularly interesting regions (i.e., the plume and slabs). The scheduled models can be divided into three categories: numerical models of the upper mantle, models based on present-day seismic tomography and forward calculations that are based on subduction history. This work is closely related to the German-French passive seismic experiment RHUM-RUM (Réunion Hotspot and Upper Mantle - Réunions Unterer Mantel) which aims at a seismological image of the entire structure of the plume from crust to core and a better understanding of the complex heat flow, material and plume dynamics. As soon as tomography models from the seismic data are available, the parameters of the geodynamic models will be modified to improve the fit between the model prediction and the tomography results. Most of the studies so far dealt with general plume models, so this will be one of the first works on a specific plume that considers its actual position within global mantle flow and inhomogeneities.

A Benchmark Initiative on Mantle Convection with Melting and Melt Segregation

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Abstract:

In recent years a number of mantle convection models have been developed which include partial melting within the asthenosphere, estimation of melt volumes, as well as melt extraction with and without redistribution at the surface or within the lithosphere. All these approaches use various simplifying modelling assumptions whose effects on the dynamics of convection including the feedback on melting have not been explored in sufficient detail. To better assess the significance of such assumptions and to provide test cases for the modelling community we initiate a benchmark comparison. In the initial phase of this endeavor we focus on the usefulness of the definitions of the test cases keeping the physics as sound as possible. The reference model is taken from the mantle convection benchmark, case 1b (Blanckenbach et al., 1989), assuming a square box with free slip boundary conditions, the Boussinesq approximation, constant viscosity and a Rayleigh number of 105. Melting is modelled using a simplified binary solid solution with linearly depth dependent solidus and liquidus temperatures, as well as a solidus temperature depending linearly on depletion. Starting from a plume free initial temperature condition (to avoid melting at the onset time) three cases are investigated: Case 1 includes melting, but without thermal or dynamic feedback on the convection flow. This case provides a maximum melt fraction □max and total melt volume Vftot in a steady state. Case 2 is identical to case 1 except that latent heat is switched on. Case 3 includes batch melting, melt buoyancy (melt Rayleigh number Rm) and depletion buoyancy (depletion Rayleigh number Rd), but no melt percolation. Output quantities are the Nusselt number (Nu), root mean square velocity (vrms), □max , and Vftot approaching a statistical steady state. □max , and Vftot are significantly smaller compared to Case 1. Case 4 includes two-phase flow, i.e. melt percolation, assuming a constant shear and bulk viscosity of the matrix and a specific melt retention number (Rt). This case is calculated either with the full compaction formulation or the Compaction Boussinseq Approximation (Schmeling, 2000). A quasi-steady state is reached with □max , and Vftot smaller than in case 3. So far 4 to 5 codes are involved in Cases 1-3, while 2 codes solve Case 4. First tests show that satisfactory agreement can be reached, but further

refinements and resolution tests are needed.. A case 5 is planned where all melt will be extracted, so depleted mantle will be left behind. In a case 5b the extracted melt shall be reinserted in a shallow region. The motivation of this presentation is to summarize first experiences and call interested modelers to join this benchmark exercise.

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MELTING AT THE MANTLE CONDITIONS

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ABSTRACT:

Buoyancy and viscosity play a major role in the dynamics of terrestial planets' deep interior. Buoyancy is mainly defined by density contrast. One of the most important elements is iron, because it is almost two times heavier, than other major elements (Si, Al, Mg). During melting iron accumulates in liquid, so ultrabasic rocks produce dense rocks. Density contrast between melt and solid controls direction of matter redistribution and flow rate. Viscosity of melt is ~20 orders of magnitude less than viscosity of solid. Theoretical (e.g. [Abe, 1993]) and experimental (e.g. [Martin et al., 2006]) studies show, that total viscocity of rock remains almost constant until 30-40 vol.% of melt is reached, and then decreases according to Einstein-Roscoe Equation. 30-40%-limit comes from geometry factor: crystals tend to form a connected (and so rigid) framework. If amount of liquid is less then several percent, it can be locked by surface tension forces, if more – then Darcy filtration flow will control the phase differentiation.

How wide spread are liquids in the deep Earth? The first stage of terrestial planets' evolution is magma ocean, when up to all mantle is molten. It's solidification can form initially heterogeneous solid planet (e.g. [Labrosse et al., 2007], [Elkins-Tanton et al., 2005]). Also formation of crust, especially continental, requires significant chemical melting-induced differentiation. “Recent” and “modern” deep-Earth melting zones include ULVZ (e.g. [Garnero et al., 1998]), subducting slabs and under mid-ocean ridges. Episodic kimberlitic and similar magmas evidence depthes up to the lower mantle. So melting take place in a wide range of conditions.

An important question is composition of subducting slab sucked to the lower mantle. Now most of models to describe LSVP and other seismic features suppose presence of MORB piles in the lower mantle (and this idea has proves in seismic and geodynamic models). But recent data on solidus profiles, such as [Ghosh, Schmidt, 2014], [Litasov, Ohtani, 2007], [Litasov et al., 2011] shows melting temperatures to be much lower than mantle adiabat. Such dehydratation and melting can alter basalt composition.

Study of [Kato et al., 2013] shows, that K-rich NAL phase can be stable at pressures up to 144 GPa (below CMB) at moderate temperatures. These temperatures are below mantle adiabat, but higher than values proposed by numerical simulations of thermal structure of

subducting slabs.

These data (1) show a mechanism to carry sufficient amounts of K and Na in the Lower Mantle and (2) propose melting of slab, when it will heat up to adiabatic temperatures. Corrections of basalt's properties (such as elastic constants) according to chemical and phase composition can provide better fits for the deep Earth.

All these issues are not covered by existing well-known geodynamics codes: in the best case they deal with prescribed components such as basalt and harzburgite. It does not allow to study behavior of independent composnents, such as SiO2 and FeO.

By the way, numerous experimental and numerical studies of the lower mantle phases provide sufficient amount of data to build up a thermodynamic model of melting. Molecular Dynamics of [de Koker et al., 2013] provides data on thermodynamic properties of liquids (ρ, CP, α, latent heat of melting etc.). Absence of many components (iron, alkali etc.) makes it to overestimate melting temperatures significantly (up to 20-30%). So melting temperatures are corrected along Clausius-Clapeyron slopes to agree with modern experimental data ([Andrault et al., 2011], [Andrault et al., 2014], [Fiquet et al., 2010], [Hirose et al., 1999], [Mosenfelder et al., 2007], [Nomura et al., 2014], [Zerr et al., 1998]).

Because iron partitioning between solid and liquid phases is crucially important to understand planetary dynamics, we used database from [Tateno et al., 2014] to build up a pressure-dependent model for iron KD.

Our model was implemented into StagYY software (e.g. [Tackley, 2008]). It is a finite-volume discretization code for advection of solid and liquid phases in a planetary scale. A principal new feature of our code is separated variables for chemical compounds: SiO2, FeO, MgO and other (list can be extended according to purpose of specific study and computational resourses). So it is possible to trace mantle heterogeneities produced by melting and solidifying events.

Calculations predict appearing and disappearing batches containing up to 5-7% of melt (CMB temperature 4000-4400 K). Amount of FeO in liquid is up to 18%, so melts are 2 % denser than solid counterpart, resulting in total density increase up to 1 %. This data fits properties proposed for Ultra-Low Velocity Zones (melt fraction between 5 and 30 % [Garnero et al., 1998], and density increase of at least 1% [Beuchert & Schmeling, 2013]).

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Towards coupled giant impact and long-term interior evolution models

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Abstract:

The crustal dichotomy [1] is the dominant geological feature on planet Mars. The exogenic approach to the origin of the crustal dichotomy [2-6] 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 [7], suggesting a degree-1 mantle upwelling underneath the southern highlands [8-11], 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 [12-15], 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 [16,17] serially coupled with geodynamical computations performed using the code I3VIS [18] to improve the latter approach and test it against observations. We are exploring collisions varying the impactor velocities, impact angles and target body properties.

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Reconciling observations of PKIKP precursors and thermochemical convection models

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Abstract:

Observations of wave scattering of high-frequency body waves provide a constraint on the distribution of small-scale heterogeneity in the deep mantle. Precursory signals of high-frequency precursors (~ 1 Hz) to the PKPdf (or PKIKP) phase provide unequivocal evidence for deep-mantle scattering. While these signals have been modeled using stochastic distributions of small-scale (~ 10 km) heterogeneity, the origin of the scatterers has remained uncertain.

We are investigating the contribution of subducted eclogite fragments in the deep mantle to scattering. We use (i) high-resolution finite-element models of long-term thermochemical mantle circulation, (ii) mineral physics constraints to relate the mineralogical and seismic structure of the mantle, and (iii) AxiSEM wavefield simulations of high-frequency body-wave propagation to determine whether the inferred strength and distribution of scattering is compatible with models of thermochemical convection in the mantle. Our poster will present preliminary results.

Grain-size dependent transition between dislocation and diffusion creep

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Abstract:

We investigate quasi-steady-state mantle convection with varying Rayleigh numbers for an Arrhenius-type rheology. The deformation is usually dominated by either dislocation or diffusion creep, depending on the present strain-rates. If the Rayleigh number is increased, the deformation mechanism transitions to dislocation creep. We present a parameter study with Rayleigh numbers up to 1e10 to determine this transition zone between the two mechanisms and its consequences. An important factor that influences this transition is the largely unknown pre-factor for the Arrhenius law, mainly associated with grain-size. We have varied this factor in our study and carried out simplified thermal evolution models to investigate the impact of the transition to these models.

IS THERE ANY CORRELATION BETWEEN CONTINENTS AND ELEVATED TEMPERATURES IN THE SUBCONTINENTAL MANTLE?

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ABSTRACT:

Rolf et al. (EPSL, 2012) and Coltice et al. (Science, 2012) have previously shown that continents exert a first order influence on Earth's mantle flow by affecting convective wavelength and surface heat flow. However, how continents influence the development and location of mantle plumes remains a topic of considerable debate.

Continental motion is attributed to the viscous stresses imparted by the convecting mantle and the extent of this motion depends on the heat budget of the mantle. Core-mantle boundary (CMB) heat flux, internal heating from decay of radioactive elements, and mantle cooling contribute to this heat budget. Out of these sources, CMB heat flux is not well defined. However, the recent determination of core's high thermal conductivity requires a CMB heat flow of at least 12 TW (de Koker et al., PNAS 2012; Pozzo et al., Nature 2012; Gomi et al., PEPI 2013). Thus it is necessary to characterize the impact of basal heating on mantle dynamics with continents and self-consistent plate tectonics.

By systematically varying parameters such as CMB temperature, continental size, mantle heating modes (basal and internal), and Rayleigh number; we model Boussinesq, incompressible, thermo-chemical mantle convection using StagYY (Tackley, PEPI 2008). We observe correlation between continents and elevated temperatures in the subcontinental mantle irrespective of the variations in basal heating and continental size (except for very small continents). Moreover, with increasing Rayleigh number, correlation still exists with episodes of anticorrelation. We will also show first results for continental growth as opposed to having prescribed continents in StagYY.

STABILITY OF CONVECTION PATTERNS IN 3D AND IMPLICATIONS FOR BENCHMARKING

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ABSTRACT:

Fully 3-D numerical simulations of thermal convection in a spherical shell have become a standard technique for studying the dynamics of mantle convection in the Earth and in the interiors of other planets. Models often include highly complex material properties, phase changes, and strongly varying rheology to represent planetary physics. Scientific software is verified and validated through community benchmarks, in which codes are used to compute the solutions to agreed-upon models, in order to determine both accuracy and performance. When possible, benchmarks use cases that have analytical solutions or compare with experimental results for validation; however, for codes intended to model naturally-occurring processes such as mantle convection, this approach is not possible, and comparisons between are required. Moreover, the governing equations are nonlinear, and the evolution of the convection system can be sensitively dependent on initial conditions, which are unknown for the Earth and planets. We carried out models of isoviscous convection in a spherical shell using codes with different numerical discretization schemes – a widely used finite-element code (CitComS), a code using spectral method that combines Chebyshev polynomials with radial basis functions (RBFs), and a new adaptive mesh finite-element code (Aspect), to investigate the dominant modes of convection and especially the stability of the known modes to perturbations of various magnitudes and degree. Our goal is to determine whether and how the discretization of the governing equations affects the outcome and thus any physical interpretation. We consider isoviscous Rayleigh–Bénard convection at infinite Prandtl number, where the aspect ratio between the inner and outer shell is 0.55, starting with the low-order convection patterns predicted by theory at low Rayleigh number that forms the basis of the earliest published 3-D spherical shell benchmarks. As anticipated, all methods first converge to the same pattern (i.e. spherical harmonics of degree 4 or 6). However, these well-known solutions are not always stable in the presence of certain perturbations. Over long periods of computation, perturbations cause instabilities to develop which break the symmetry of the convection pattern and 'kick' the convection into another pattern (i.e. tetrahedral forms.) At approximately 70 times the critical Rayleigh number, an unusual five-cell or hexahedral pattern emerges. This exploration of

long-term changes in the convection pattern is enabled by increased availability of computational power, which did not allow such investigation at the time when initial theory and benchmarks were established (circa 1970 – 1995). These results demonstrate the impact of numerical discretization on the observed patterns, and can form the basis for discussion of new accuracy benchmarking efforts for 3-D spherical mantle convection codes.

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Delamination of the mafic subducting crust

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Abstract:

It is commonly accepted that the building of continental crust is linked to subduction zone processes, but the refining mechanism isolating the felsic product from its basaltic counterpart, leading to a stratified crust, remains poorly understood. Upward delamination of subducting material from the slab, its subsequent melting and segregation, with the felsic part being underplated and added to the overriding crust from below has been suggested to be a viable scenario.

In this study we use thermo-mechanical numerical models of subduction to explore the possibility of delamination of the mafic part of the slab crust and determine the conditions that are required by varying key parameters, such as subduction speed and angle, slab age, crustal thickness and density, overriding plate thickness, mantle temperature, depth of eclogitisation and the rheological properties for crustal and mantle material.

Our preliminary models demonstrate that, for present day mantle potential temperatures and average slab crustal thickness, only the uppermost 2-3km of mafic slab crust may delaminate and only for extreme rheologies (i.e very weak crust) or very slow subduction (~2cm/yr convergence), making slab mafic crust delamination unlikely. Contrastingly, in an early earth setting (High mantle temperature potential and thicker mafic slab crust) we find that delamination of the subducting mafic crust is a dynamically viable mechanism for a reasonable rheology under a wider range of subduction conditions and that when it does occur, it can be much more extensive, with the entire crust able to delaminate from the slab in some cases.

consequences of magma ocean solidification

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Abstract:

Energy sources involved in the early stages of planetary formation could have caused partial or possibly entire melting of the mantle of terrestrial planets and moons (Elkins-Tanton ,2008). Global or local liquid magma oceans could thus have formed, whose solidification, from the bottom upwards, upon planetary cooling could have exerted a significant impact on the differentiation and subsequent evolution of the interior of terrestrial bodies. Initial compositional stratification of the solid mantle, as a result of magma ocean crystallization can play an important role for the subsequent planetary evolution and surface tectonics (Tosi et al., 2013; Plesa et al.,(2014).

In this study, we investigate the cooling and crystallization of a whole-mantle magma ocean and in particular the conditions for the onset of solid-state thermal convection before complete mantle solidification. To this end we employ two-dimensional Cartesian box simulations using the finite-volume code Gaia (Hüttig et al.,2013). We assume an adiabatic temperature profile in the magma ocean and various cooling rates of the surface temperature according to coupled magma ocean-atmosphere models (Lebrun et al., 2013). Upon reaching a critical melt fraction that marks the formation of the so-called rheological front (Solomatov,2007), we self-consistently solve the conservation equations of solid-state mantle convection in the partially molten domain assuming a viscosity strongly dependent on temperature and melt content. By varying the reference Rayleigh number between 106 - 109 and the magma ocean cooling rate between 100 - 0.01 Ma, we show that, even for a rapidly decreasing surface temperature, a sufficiently high Rayleigh number guarantees the onset of solid-state convection prior to complete crystallization of the mantle. This finding can have important consequences for the initial distribution of compositional heterogeneities generated through the magma ocean fractional crystallization.

Elkins-Tanton (2008) Annual Review of Earth and Planetary Sciences 40, 113-139.
Hüttig et al. (2013) PEPI 220, 11-18.
Lebrun et al. (2013) JGR: Planets 118, 1155-1176.
Plesa et al. (2014) EPSL 403, 225-235.
Solomatov (2007) Treatise on Geophysics 9, 91-119.

Tosi et al. (2013) JGR: Planets 118(7), 1512-1528.

Dynamics of deep earth and planetary body

DOES EARTH'S HOT ACCRETED CORE POWER MANTLE AND CORE CONVECTION?

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ABSTRACT:

Earth's mantle and core are convecting planetary heat engines. The mantle convects to lose heat from slow cooling, internal radioactivity, and core heatflow across its base. Its convection generates plate tectonics, volcanism, and the loss of ~35 TW of mantle heat through Earth's surface. The core convects to lose heat from slow cooling, small amounts of internal radioactivity, and the freezing-induced growth of a compositionally denser inner core. Core convection produces the geodynamo generating Earth's geomagnetic field.

Here I explore the likely range of core temperatures that resulted from Earth accretion and core segregation processes. Cosmochemical pallasite trace element partitioning constraints imply that <300km diameter planetessimals and/or the upper ~200km of larger bodies formed with >~1000C temperatures, likely more. With this constraint on Earth accretion, Earth's mantle and core are also likely to have formed hot even if their only heating were due to adiabatic pressure-loading and and the gravitational energy released by core segregation. In this case, it is plausible that the core segregated with an early temperature contrast across the CMB, and that it could have cooled secularly by ~800K over Earth's evolution, with core convection transferring >15 TW to the CMB. This would be sufficient energy to drive both a strong 'bottom-heated' plume mode of mantle convection and a geodynamo in a highly conductive iron core. In this evolution scenario, the primary difference between Earth and Venus could be that Earth's plate tectonics cools the mantle and core at a high enough rate for core convection to occur, while Venus's thick 1-plate lithosphere does not allow its core to cool quickly enough to power a Venusian magnetodynamo.

THE EFFECT OF VISCOSITY VARIATIONS IN DETERMINING DYNAMIC TOPOGRAPHY FROM SEISMIC TOMOGRAPHY MODELS

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ABSTRACT:

Seismic tomography can be used to investigate radial viscosity variations on instantaneous flow models by predicting the global geoid and comparing with the observed geoid. This method is one of many that has been used to constrain viscosity structure in the Earth's mantle in the last few decades. Examining 60 tomographic models we found notable differences by comparing a synthetically produced geoid with the observed geoid. Comparing S- and P-wave tomographic models, the S-wave models provided a better fit to the observed geoid. Using this large suite of 60 tomographic models, we have been able to constrain the radial viscosity structure of the Earth. We found that two types of viscosity profiles yielded equally good fits. A viscosity profile with a low transition zone viscosity and a lower mantle viscosity equal to the upper mantle, or a profile with a large lower mantle viscosity and a transition zone viscosity similar to the upper mantle. This suite of tomographic models and our constrained viscosity profiles can further be used to investigate the effect on dynamic topography generated at the Earth's surface. Dynamic topography is the residual topography of the Earth after removing the isostatic topography. This dynamic topography is generated by the flow of the mantle. Being able to constrain the dynamic topography on the surface requires good constraints on the internal structure and dynamics of the Earth. Here, we present the tomographic models which produce more realistic amplitudes for dynamic topography based on the range of viscosity profiles we have previously constrained.

SEMI ANALYTICAL MODEL FOR THE EFFECTIVE GRAIN SIZE PROFILE IN THE MANTLE OF THE EARTH

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ABSTRACT:

We present a semi analytical model of mantle convection able to predict the grain size profile of the present day Earth. Grain size evolution has been studied with increasing interest over the last decades but its behavior in both mantle and lithosphere remains largely misunderstood due to its non-linearity. Several recent studies suggest that it might play a fundamental role in localization of deformation in the lithosphere but we focus here on the mantle in which we also observe important processes. We propose a 1D compressible thermal convection model based on the equality of advective heat flux and the integral of viscous dissipation in the whole domain. Imposing mass conservation, our model is able to predict all rheological parameters able to produce both present day average surface velocity and lower mantle viscosity. Composite rheologies involving dislocation creep and grain size dependent diffusion creep are considered. The effect of phase transitions on the grain size is also explicitely taken into account. We present the family of solutions for the activation volume and the viscosity jump at the 660 discontinuity according to any initial choice of activation energy. The scaling laws for rheological parameters obtained are compared to self-consistent evolutionary simulations of mantle convection considering grain size dependent diffusion creep in 2D spherical annulus geometry.

The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 320639 project iGEO

Evidence for and dynamical consequences of a viscosity increase in the mid-mantle

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Abstract:

The viscosity structure of Earth's deep mantle affects the thermal evolution of Earth, the ascent of mantle plumes, settling of slabs, and the mixing of compositional heterogeneities in the mantle. Based on a re-analysis of the long-wavelength non-hydrostatic geoid, we infer viscous layering of the mantle using a transdimensional, hierarchical Bayesian method that allows us to avoid a priori assumptions about the number and locations of changes in mantle viscosity. We find evidence for an increase in viscosity at 800-1200 km depth, significantly deeper than the mineral phase transformations which define the mantle transition zone. The viscosity increase is coincident in depth with regions where seismic tomography has imaged slab stagnation, plume deflection, and changes in large-scale structure, manifested in the mantle radial correlation function for the lowest spherical harmonic degrees. In addition to presenting new solutions for the mantle radial viscosity structure, we explore the dynamical consequences of simplified representations of these viscosity profiles, including the long-wavelength structure of the lower mantle, the mantle radial correlation function, and the fate of downwellings, using 3D spherical geometry simulations of mantle circulation with imposed velocity boundary conditions based on plate reconstructions for the past 200-450 Myr.

Temporal variation of the geoid and dynamic topography inferred from geodynamics modeling

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Abstract:

Although tomography based models are useful to explain the geophysical observables such as the geoid and dynamic topography, they are limited to the extent that they only provide a snapshot of the present- day mantle convection.

In order to providing a time-dependent evaluation of the mantle structure that is as realistic as possible we have constructed a time-dependence (3D spherical model of) mantle circulation by advecting density heterogeneities, inferred from a recent global seismic tomography model S40RTS.

We have determined the longevity of structures in the present-day mantle by (tracking) estimate the temporal variations of the geoid and dynamic topography as the two major geophysical observables. We found that a common feature is a rise of geoid undulation around the strong subduction regions, especially, in the West Pacific and South America. The global temporal geoid undulations obtained from our geodynamic models are of the order of   to   which is close to the resolution limit of GRACE. Thus, the magnitude of the geoid signals produced by mantle convection processes in our models is one to two order smaller than other dynamic processes such as post glacial rebound and mean sea-level changes. On the other hand, dynamic topography variations are correlated to the geoid undulation and exhibit one order of magnitude larger temporal variations.

Generating Dynamos in Basal magma oceans

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Abstract:

Observations of Earth's magnetic field extending back to 3.45 billion years ago indicate that generation by a core dynamo must be sustained over most of Earth's history. However, recent estimates of thermal and electrical conductivity of liquid iron at core conditions from mineral physics experiments indicate that adiabatic heat flux is approximately 15 TW, nearly 3 times larger than previously thought, exacerbating difficulties for driving a core dynamo by convective core cooling alone throughout Earth history. A long-lived basal magma ocean in the lowermost mantle has been proposed to exist in the early Earth, surviving perhaps into the Archean. While the modern, solid lower mantle is an electromagnetic insulator, electrical conductivities of silicate melts are known to be higher, though as yet they are unconstrained for lowermost mantle conditions. Here we explore the geomagnetic consequences of a basal magma ocean layer for a range of possible electrical conductivities. For the highest electrical conductivities considered, we find a basal magma ocean could be a primary dynamo source region. This would suggest the proposed three magnetic eras observed in paleomagnetic data originate from distinct sources for dynamo generation: from 4.5-2.45 Ga within a basal magma ocean, from 2.25-0.4 Ga within a superadiabatically cooled liquid core, and from 0.4-present within a quasi-adiabatic core that includes a solidifying inner core. We present a new code, Dynamantle, a model with an entropy-based approach commonly used in core dynamics models, to assess the conditions under which basal magma oceans can generate positive ohmic dissipation. This is more generally useful than just considering the early Earth, but also for many silicate exoplanets in which basal magma oceans are even more likely to exist.

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THE KEY INFLUENCE OF MAGMATISM ON THE THERMO-CHEMICAL-TECTONIC EVOLUTION OF TERRESTRIAL PLANETS

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ABSTRACT:

Melting and resulting differentiation play a large role, starting from the magma ocean phase and continuing through long-term evolution with the production of different types of crust (oceanic and continental on Earth). We can now numerically model the evolution of a terrestrial planet from the magma ocean stage to the present day using a 2D or 3D model of the mantle-lithosphere system couped to a parameterized model of the core (and sometimes, atmosphere), including the effects of magmatism and variations in tectonic mode. Such models will be presented here. Our recent models find that melting has several key effects on planetary evolution. Firstly, it produces compo-sitional heterogeneity in the lithosphere, including continental cratons [Rolf & Tackley, 2011 GRL] and basaltic crust [Lourenco et al. submitted], which facilitate plate tectonics by focussing or producing stresses, making it “easi-er” for the lid to break. Thus, scaling laws that are based on purely thermal convection cannot be literally applied to planetary evolution. Secondly, magmatism acts as a thermostat on mantle temperature, losing large amounts of heat when the mantle is hot, such as when internal heat production is high early in a planet’s evolution [Nakagawa & Tackley, 2012 EPSL] or in a stagnant-lid mode – indeed [Armann & Tackley, 2012 JGR] showed that in a stagnant-lid Venus-like planet most of the heat loss is accommodated by magmatic heat pipe volcanism. Thirdly, magmatism can produce compositional stratification in the deep mantle, which modules heat flux from the core, determining geodynamo evolution [Nakagawa and Tackley, 2010 GCubed]. Fourthly, intrusive magmatism can weaken the crust and lithosphere. On Earth most magmatism is intrusive rather than extrusive. This tends to warm and weaken the crust, resulting in substantial surface deformation even if modern-day plate tectonics did not operate (e.g. Gerya, 2014 EPSL).

Mercury's low-degree geoid and topography controlled by insolation-driven elastic deformation

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Abstract:

Mercury experiences an uneven insolation that leads to significant latitudinal and longitudinal variations of its surface temperature. These variations, which can be expressed in terms of degree-2 and 4 spherical harmonics, propagate to depth imposing a long-wavelength thermal perturbation throughout the mantle. We computed the accompanying density distribution and used it to calculate the mechanical and gravitational response of a spherical elastic shell overlying a quasi-hydrostatic mantle. We then compared the resulting geoid and surface

deformation at degree-2 and 4 with Mercury's geoid and topography derived from MESSENGER data. More than 95% of the data can be accounted for if the thickness of the elastic lithosphere were between 110 and 180 km when the thermal anomaly was imposed. The obtained elastic thickness implies that Mercury became locked into its present 3:2 spin-orbit resonance about 1 Gyr after planetary formation.

ON EVOLVING LID-STATES, BI-STABILITY, AND THE EVOLUTION OF TERRESTRIAL PLANETS: PATHWAYS AND DIVERGENCES IN PLANETARY EVOLUTION

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ABSTRACT:

We use 3D mantle convection and planetary tectonics simulations to explore the links between tectonic regimes, lithospheric yield strength, the age of a planet, and thermal histories. At both high and low values of internal heating a single hot or cold stagnant-lid end state prevails. For lower initial and/or depleted radiogenics (e.g. thermal ageing) hot stagnant-lid states can yield through an episodic-lid, into a mobile-lid regime. Further reducing radiogenics leads the mobile-lid transitioning back into a (now) cold stagnant-lid. While high and low temperature tectonic end states may be fixed, the intermediate parameter range – a significant span of a planet's thermal evolution – may be governed by the thermal history of the system (e.g. initial conditions) allowing for regions of multiple stable tectonic states, or bi-stability. Within the bi-stability window, the tectonic regime becomes a function of a planet's specific geologic and climatic history. The timing of transitions in tectonic regimes is linked to internal temperature variations, which are a function of the lid-state evolution. Transitions from an initial stagnant-lid state are delayed (requiring a larger decrease in radiogenics) as a function of increasing yield strength and surface temperature, indicating that a system with a different thermal evolution has the potential to migrate through tectonic regimes at the same 'thermal time' (e.g. temperature), but very different 'temporal times'. Our results indicate that multiple modes of convection and surface tectonics can potentially operate on a single planetary body at different times in its evolution, as consequence of changing internal parameters, surface temperatures, and differing thermal histories, implying terrestrial worlds can alternate, and be offest between multiple tectonic states over giga-year timescales. Cases for the divergence of Venus and Earth will be discussed.

Strain localization in the crust and lithosphere

Oral program

Strain localization in the continental lithosphere

Gueydan F.

Modes of extension and oceanization at magma-poor margins: an example from the Brazilian-African margins

Perez-Gussinye, M , Araujo M. , Ros E., , Andres-Martinez, M. , Morgan J.

Fundamental strain localization mechanisms during lithospheric deformation

Schmalholz, S.M.

Poster program

Making Coulomb angle-oriented shear bands in numerical tectonic models

Choi, E. , Petersen, K. D.

Numerical thermo-mechanic 3D modeling of the India-Asia collision

Dargère L. , Burov E. , Jolivet L. , Gerya T.

Lower crustal viscosity and modes of continental lithospheric extension

Elena Ros , Marta Pérez-Gussinyé , Jason Phipps Morgan , Miguel Andrés-Martínez

Pattern formation in 3D numerical models of down-built diapirs initiated by a Rayleigh–Taylor instability.

Fernandez N., Kaus, B.J.P.

Impact of fluid circulation on the symmetry of detachments

Mezri L., Le Pourhiet L., Wolf S., Burov E.

Numerical simulation of Glacial Isostatic Adjustment

Miglio E. , Penati M.

The role of elasticity in simulating long-term tectonic extension

Olive J.-A. , Behn M. D. , Mittelstaedt E. , Ito G. , Klein B. Z.

Does the inherited composition of the crust controls the symmetric or asymmetric exhumation of continental core complex?

Plunder A. Mezri L., Le Pourhiet, L. and Burov, E.

Submarine Mass-waste Events caused by Seamount Subduction

Ruh, J.B. , Gerya, T.

The impact of the initiation phase in numerical models of continental rifting

Susanne Buiter and Joya Tetreault

Intermediate-depth earthquake generation and shear zone formation caused by grain size reduction and shear heating

Thielmann M., A.Rozel, B.J.P. Kaus and Y.Ricard

Detailed program

Using naturally deformed peridotites to constrain models of shear localization
Warren J.M. , Hansen L.N. , Kumamoto K.M. , Skemer P

Dynamic and structural setting of the Marlborough Fault Zone, New Zealand
Willis D. , Betts P. , Ailleres L., Moresi L.

Detailed program

STRAIN LOCALIZATION IN THE CONTINENTAL LITHOSPHERE

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ABSTRACT:

No single rheological model is up-to-now comprehensive enough to simultaneously describe weak behaviour of plate boundaries and rigid-like behaviour of plate interiors. The extrapolation of laboratory flow laws to geological scale suggests a complex layering of brittle and ductile layers in which the upper mantle is brittle and support high stresses. Such a rheological layering is moreover important to reproduce first-order patterns of lithosphere deformation. By contrast, recent geophysical studies suggest a high-strength lower crust and a weak ductile upper mantle.

Geological constraints on lithospheric strength and large strain numerical experiments reveal that the development of layers containing weak minerals and the onset of grain boundary sliding upon grain size reduction in olivine cause strain localisation and reduce strength in the crust and subcontinental mantle, respectively. The positive feedback between weakening and strain localization leads to the progressive development of weak plate boundaries while plate interiors remain strong.

MODES OF EXTENSION AND OCEANIZATION AT MAGMA-POOR MARGINS: AN EXAMPLE FROM THE BRAZILIAN-AFRICAN MARGINS

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ABSTRACT:

It is well known that the amount of magmatism and occurrence of serpentinised mantle at rifted margins and oceanic ridges fundamentally depends on spreading rate and mantle potential temperature (McKenzie and Bickle, 1988). Here we show that during continental extension, in addition, the rheology of the continental lower crust is a key factor in determining the onset and amount of melting and serpentinisation. Furthermore, using numerical modeling constrained by multi-channel seismic reflection and wide-angle data from the magma-poor margins of Brazil and Africa, we also show that it is possible to associate margin architectural styles to types of ocean-continent transitions. Observed margin architectural styles can be explained by a combination of extensional modes: core-complex, wide and narrow (Buck, 1991), with a fourth mode, sequential faulting, that accounts for conjugate margin asymmetry (Ranero & Perez-Gussinye, 2010, Brune et al., 2014). The prevalence of any of these modes during extension depends on lower crustal rheology, which controls the coupling between crust and mantle deformation, and hence mantle uplift velocity and type of oceanization. For a given extension velocity, a weak lower crust leads to small degree of coupling between crust and mantle, to ultra-wide hyper-extended margins and also to slower mantle uplift, inhibiting melt production and serpentinisation. Hence, ultra-wide hyper-extended margins (North Santos-South Kwanza conjugates, or the Campos-Kwanza conjugates) will tend to present an abrupt transition to thin oceanic and magmatic crust. On the other hand, if lower crust is stronger, mantle uplift velocity and crustal thinning will be fast and effective, leading to the formation of narrow conjugates and a continent-ocean transition that may consist of exhumed and serpentinised mantle, if horizontal extension velocity is slow enough (e.g. as in the Camamu-Gabon margins).

Fundamental strain localization mechanisms during lithospheric deformation

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ABSTRACT:

During the deformation of the lithosphere strain is often localized on many scales, ranging from the millimetre to the kilometre scale. Strain localization is responsible for many tectonic features such as tectonic plate boundaries, orogenic and accretionary wedges and tectonic nappes. However, the mechanisms controlling strain localization are still debated. This contribution focuses on mechanisms which can generate ductile shear zones with continuous deformation, that is, discontinuous deformation due to for example fracturing or frictional sliding is not considered. Three strain localization mechanisms are discussed which may be considered as fundamental mechanisms because (1) they operate for basic rheologies (such as linear and power-law viscous flow laws, or linear viscoelastic flow law), (2) the material properties remain constant during localization (no material softening) and (3) they can occur in single-phase material (i.e. no porous material, no softening due to fluid-rock interaction or mineral reactions etc.). The three mechanisms are (1) kinematic strain localization, (2) structural softening due to geometric instabilities, and (3) thermal softening. For kinematic strain localization the geometrical configuration or the kinematics outside the ductile material can impose a localization of strain, for example, the flow around mechanically strong objects or a brittle fault (velocity discontinuity) above or below the ductile material. Kinematic strain localization is independent of the material properties and flow laws. Kinematic strain localization is here applied to the formation of thrust nappes (such as the Helvetic nappes in Switzerland) which are sheared-off from half-grabens during orogeny. Geometric instabilities such as necking (continuous boudinage) cause strain localization during extension. In viscous multi-layers localized shear zones can develop (additionally to necking) when both stiff layers and weak matrix are power-law viscous. The strength of the multi-layer decreases due to shear zone formation although material parameters (stress exponent and reference viscosity) are constant (no material softening). Such localization occurs due to a structural softening and is applied here to outcrop scale shear zones found in deformed sedimentary rock. (3) Thermal softening is based on the conversion of mechanical work into heat and the decrease of ductile rock strength (effective viscosity) with increasing temperature. Thermal softening can generate shear zones with an

intrinsic thickness of several kilometres for typical lithospheric deformation conditions. Thermal softening can be intensified in viscoelastic material when stored elastic strain energy is released during shear zone formation. Thermal softening is applied to explain the self-consistent formation of orogenic wedges during continental collision and the propagation of thrust-type shear zones. Two-dimensional numerical simulations of the three strain localization mechanisms will be presented and applications to structures and observations in the Alps will be discussed.

Strain localization in the crust and lithosphere

THE IMPACT OF THE INITIATION PHASE IN NUMERICAL MODELS OF CONTINENTAL RIFTING

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ABSTRACT:

When investigating continental extension geodynamically, numerical experiments often start from laterally homogeneous crustal layers with a prescribed heterogeneity to initiate deformation. These heterogeneities represent thermal or structural remnants from previous deformation phases and are imposed as a thermal anomaly, a variation in Moho geometry, or an inherited weak region. This approach allows a control over the initial location of deformation and the time it takes for deformation to localise. Such simplified models are well suited to testing the sensitivity of a rift system to controlling parameters such as extension velocity and crustal rheology. However, imposed initial heterogeneities do not fully capture the structural and thermal complexities of the continental lithosphere observed in nature. In addition we observe that passive margins tend to originate on continental collision zones and that collisional structures are not small and simple blocks like in typical 2D experiments. Collision zones can act as intrinsic rift-localisers for several reasons: rifting may be initiated by extensional collapse of the orogen, the thicker crustal root of orogens and their associated increase in heat producing elements makes orogens thermally weak, and inherited thrust faults form large-scale heterogeneities. We attempt to better approximate the role of structural inheritance in extensional tectonics by examining these three scenarios.

We present three series of 2-D numerical experiments that investigate the role of inherited structures in continental rifting and passive margin formation. We first examine experiments in which continental extension is initiated at a single simple heterogeneity in the crust or lithospheric mantle, represented by a small area of weak frictional properties or elevated temperatures. We find that the depth and shape of the heterogeneity affect rift duration and geometry. In the second series of experiments we explicitly prescribe collisional structures in the initial setup, such as increased Moho depth and inherited thrust faults. Various prescribed collisional structures result in different rift to break up durations, crustal shear zone patterns, and margin widths. In our third series of experiments we create an inherited collision zone through subduction and closure of an ocean. We use this set-up to investigate how extension localises on a continental collision zone. The former weak subduction interface and the elevated temperatures in the crustal nappe stack work in tandem as prime deformation localisers. Mantle flow in the rift region enhances crustal extension and contributes to lithosphere delamination. We find that the different approaches to initiating a continental rift result in significantly different dynamics of the crust and mantle, thereby impacting rift geometry, rift to break-up duration, and exhumation of subduction-related sediments and oceanic crust. This implies that rift experiments aimed at regional studies would benefit from considering geological history when designing the initial setup.

Strain localization in the crust and lithosphere

MAKING COULOMB ANGLE-ORIENTED SHEAR BANDS IN NUMERICAL TECTONIC MODELS

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ABSTRACT:

Localization of shear strain induced by strain weakening plasticity in continuum models are often used to represent faults of various scales. The orientation of the shear bands is thus required to be consistent with those observed from natural faults and with simple theories of brittle failure. Although the Coulomb angle is widely used as an assumed fault orientation, the currently available numerical techniques do not always produce shear bands oriented at this angle. We demonstrate that, under an associated plastic flow rule where dilation and friction angles are equal, the Coulomb angle becomes a unique initial shear band orientation regardless of the numerical methods employed and model resolution. The known problem of overly expanding shear bands in case of a constant dilation angle is preventable if dilation angle is reduced as shear strain along the shear band increases. This treatment corresponds to natural processes reducing roughness of a fault plane.

Numerical Thermo-mechanic 3D modeling of the India-Asia collision

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ABSTRACT:

The onset of the India-Asia collision zone (early Eocene) has led to the formation of a complex geodynamic collisional system. Surface deformation of the upper plate is characterized by important and varied tectonic structures such as the Himalayan moutains, the Tibetan plateau, and large-scale strike-slip fault allowing the spreading of strain across a wide area, far from the collision zone.

Recent 3D numerical models show that such a system is best viewed as the subduction of a heterogenous plate, that is to say an oceanic plate with a buoyant continental domain, under a continental plate.

The subduction of a buoyant lithosphere induces a wide range of dynamic responses whether it be in the deeper level of the system (e.g slab tear, mantle flow) or in the crustal part of the upper plate (e.g, continental indentation, orogen and plateau build-up, oceanic domain retreat, back-arc extension, lateral extrusion, large-scale strike-slip faulting).

In this study, we modelise this tectonic setting numerically for the first time, in 3D, in high-resolution, at the scale of the India-Asia collision with realistic, non-newtonian rheologies.

Among all the tectonic features of this collisional system, the formation and evolution of the Tibetan Plateau is a probably the most controversial topic. The different proposed views have strong implications on the mechanism of plateau formation which lead to opposite understandings of the rheology of the continental lithosphere : from a strong and plastic lithosphere to a weak and ductile lithophere.

The high resolution used in this study will allow us to discuss the topography evolution of the model in order to get a better understanding of the Tibetan plateau problems.

Pattern formation in 3D numerical models of down-built diapirs initiated by a Rayleigh-Taylor instability.

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ABSTRACT:

Many salt diapirs are thought to have formed as a result of down-building, which implies that the top of the diapir remained close to the surface during syn-halokinetic sediment deposition. Down-building is largely a 3-D process and in order to better understand what controls the patterns of the diapirs that form by this process, we here perform 3-D numerical models of down-built diapirs initiated by the gravity instability in linear viscous materials and compare the results with analytical models. We vary several parameters of the numerical models such as initial salt thickness, sedimentation rate, salt viscosity, salt-sediment viscosity ratio as well as the density of sediments. Down-building of 3-D diapirs only occurs for a certain range of parameters and is favored by lower sediment/salt viscosity contrasts and sedimentation rates in agreement with analytical predictions and findings from previous 2-D models. However, the models show that the sedimentation rate has an additional effect on the formation and evolution of 3-D diapir patterns. At low sedimentation rates, salt ridges that form during early model stages remain preserved at later stages as well. For higher sedimentation rates, the initial salt ridges are covered up and finger-like diapirs form at their junctions, which results in different salt exposure patterns at the surface. Once the initial pattern of diapirs is formed, higher sedimentation rate can also result in covered diapirs if the diapir extrusion velocity is insufficiently large. We quantify the effect of sedimentation rate on the number of diapirs exposed at the surface as well as on their spacing and we explain the observations with analytical predictions using thick-plate analytical models. In some cases, this final pattern is distinctly different from the initial polygonal pattern.

Fernandez, N., and Kaus, B. J .P., 2015, Pattern formation in 3D numerical models of down-built diapirs initiated by a Rayleigh–Taylor instability: Geophysical Journal International, v. 202, no. 2, p. 1253-1270, http://doi.org/10.1093/gji/ggv219.

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Impact of fluid circulation on the symetry of detachments

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ABSTRACT:

Metamorphic phase changes have a strong impact on the physical and mechanical properties of rocks including buoyancy (body forces) and rheology (interface forces). As such, they exert important dynamic control on tectonic processes. It is generally assumed that phase changes are mainly controlled by pressure (P) and temperature (T) conditions. Yet, in reality, whatever the PT conditions are, phase changes cannot take place without an adequate amount of the main reactants. It is generally assumed that water is always available in quantities sufficient for thermodynamic reactions to take place at minimal Gibbs energy for given P, T conditions and a constant chemical composition. However, petrologic studies point out that water, as a limiting reactant, is responsible for the lack of retrograde metamorphic reactions observed in exhumed tectonic units outside of shear zones.

Present day geodynamic models neglects the limiting influence of water content. As a result, no high-grade metamorphic rocks actually make there way to the surface of the models, since they are all retro-morphed to low-grade state during their exhumation. In order to study the impact of fluid content on the structure of metamorphic core complexes, we have coupled a geodynamic thermo-mechanical code Flamar with a fluid-transport and water-limited thermodynamic phase transition algorithm. We have introduced a new parameterisation of Darcy flow that is able to capture source/sink and transport aspects of fluid transport at the scale of the whole crust with a minimum of complexity. Within this model, phase transitions are controlled by pressure temperature and the local amount of free fluid that comes from both external (meteoric) and local (dehydration) sources. The new implementation is tested with an application to granitic core complexes.

The numerical experiments suggest a strong positive feedback between the asymmetry of the tectonic structures and the depth of penetration of meteoric fluids. In particular, bending-stress distribution in asymmetric detachment zones drives the penetration of meteoric fluids to greater depths. However, thermal weakening and/or slow re-equilibration of the protolith rocks at depth tends to decrease the asymmetry of structure, changing the orientation of the bending stresses and shutting down the activity of asymmetric

detachments in favor of spreading structures.

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Strain localization in the crust and lithosphere

NUMERICAL SIMULATION OF GLACIAL ISOSTATIC ADJUSTMENT

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ABSTRACT:

In the Earth's crust, stress can be subdivided into tectonic background stress,overburden pressure, and pore-fluid pressure. The superposition of the first two and the variation of the third part are key factors in controlling movement along faults. Furthermore, stresses due to sedimentation and erosion contribute to the total stress field. In deglaciated regions, an additional stress must be considered: the rebound stress, which is related to rebounding of the crust and mantle after deglaciation. During the growth of a continental ice sheet, the lithosphere under the ice load is deformed and the removal of the ice load during deglaciation initiates a rebound process. The uplift is well known in formerly glaciated areas,e.g.North America and Scandinavia, and in currently deglaciating areas,e.g.Alaska, Antarctica, and Greenland. The whole process of subsiding and uplifting during the growth and melting of an ice load and all related phenomena is known as glacial isostatic adjustment (GIA). During the process of glaciation, the surface of the lithosphere is depressed underneath the ice load and compressional flexural stresses are induced in the upper lithosphere, whereas the bottom of the lithosphere experiences tensional flexural stresses. An additional vertical stress due to the ice load is present and it decreases to zero during deglaciation. During rebound, flexural stresses relax slowly. These stresses are able to change the original stress directions and regime.

In this work we aim to study the effect of the GIA process in the context of petroleum engineering. The main aspect we will focus on is the mathematical and numerical modeling of the GIA including thermal effects. We plan also to include a preliminary study of the effect of the glacial erosion. All these phenomena are of paramount importance in petroleum engineering: for example some reservoir have been depleted due to tilting caused by both GIA, erosion and thermal effects.

THE ROLE OF ELASTICITY IN SIMULATING LONG-TERM TECTONIC EXTENSION

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ABSTRACT:

While elasticity is a defining characteristic of the Earth's lithosphere, it is often ignored in numerical models of long-term tectonic processes in favor of a simpler visco-plastic description. Here we assess the consequences of this assumption on a well-studied geodynamic problem: the growth of individual normal faults at an extensional plate boundary. We conduct 2-D numerical simulations of extension in elasto-plastic and visco-plastic layers using a finite difference, particle-in-cell numerical approach. Our models simulate a range of faulted layer thicknesses and extension rates, allowing us to quantify the role of elasticity on three key observables: fault-induced topography, fault rotation, and fault life span. In agreement with earlier studies, simulations carried out in elasto-plastic layers produce rate-independent lithospheric flexure accompanied by rapid fault rotation and shorter fault life spans in thicker faulted layers. By contrast, models carried out with a visco-plastic lithosphere produce results that depend strongly on the extension rate. At slow extension rates fault evolution is qualitatively similar to the elasto-plastic cases. However, fast rates generate little deformation of the footwall and hanging wall blocks, suppress fault rotation, and promote long-lived faults associated with unrealistically flat topography. To interpret these results, we adapt a classic analytical model for fault-induced elastic flexure to a thin viscous plate. By doing so we elucidate the rate-dependence of the flexural wavelength of a viscous plate, and quantify the length scale over which topography decays away from the fault as a function of the extension rate. We show that visco-plastic numerical simulations qualitatively mimic the behavior of their elasto-plastic counterparts only if the horizontal dimension of the model domain accommodates ~2 viscous flexural wavelengths. When this criterion is not met, the rate-dependence of visco-plastic plate behavior produces unrealistic deformation patterns that can hinder geological interpretations, especially in models of long-term lithosphere evolution that involve sequential strain localization.

This work was supported by NSF grants OCE-11-54238 (JAO, MDB), EAR-10-10432 (MDB), and OCE-11-55098 (GI), as well as a WHOI Deep Exploration Institute grant and start-up support from the University of Idaho (EM).

DOES THE INHERITED COMPOSITION OF THE CRUST CONTROLS THE SYMMETRIC OR ASYMMETRIC EXHUMATION OF CONTINENTAL CORE COMPLEX?

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ABSTRACT:

Continental core-complexes are both characterized by distributed strain/high temperature rocks in their inner parts (or core) and by localized/low temperature rock in the outer part (or envelope). Such core-complexes are exhumed along detachment faults that participate to crustal thinning. The style of exhumation most likely dependent on lithology because: (1) localized asymmetric crustal deformation on the field is generally associated to brittle-ductile coupling; (2) the flow in ductile layer depends primarily on the creep parameters which varies with the minerals contained in the rock. In most models, it is shown that the rheology of the continental crust is determined by the initial geothermal gradient and the pre-existing structures. However, lithological metamorphic stratification of the crust with respect to tectonometamorphic history is rarely explicitly tested in thermo-mechanical models. Pressure-temperature-time-fluid history of related to previous events reveals two major inherited chemical end-members given different consequences on the mechanical behaviour of continental crust. Here, we use coupled hydro-thermo-mechanical modelling (code Flamar) to investigate the impact of “compositional inheritance” on the behaviour of continental exhumation. The model results show that the development of a weak mid-crustal shear zone is: (1) strongly dependent on the inherited chemical composition; (2) triggered by metamorphic reactions limited by water content. As a result, symmetric or asymmetric exhumation pattern emerge naturally from the chemical composition.

Lower crustal viscosity and modes of continental lithospheric extension

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ABSTRACT:

Extension of the continental lithosphere undergoes a range of different extensional modes: core-complex, wide and narrow (Buck, 1991). The selection of the extensional mode depends on the effective viscosity of the lower crust (Bird, 1991; Buck, 1991). With progressive cooling during extension, transitions may occur between these extensional modes (Hopper and Buck, 1996). We suggest that combinations of these extensional modes with a fourth one, sequential faulting mode (Ranero and Pérez-Gussinyé, 2010; Brune et al., 2014), may explain the different architectonical styles and asymmetry degree observed at conjugated margins. The predominance of any of these modes during extension also determines the onset and distribution of melting and serpentinisation.

In our project we use a 2D thermo-mechanical model based on the MILAMIN code (Dabrowski et al., 2008). We have included visco-elasto-plastic non-newtonian rheologies, free-surface stabilisation algorithm (Andrés-Martínez et al., 2015), melting and serpentinisation. Through a systematic study of crustal thicknesses, crustal rheologies and extension velocities we show that the prevalence of any of the extensional modes during extension depends on the strength of the lower crust at the start of rifting and during extension. We also present whether there is a viscosity value and distribution in the lower crust that characterizes the switch from one mode of extension to the other. We observe a different spatial distribution of the underplated melt and serpentinization for each of the tests. Our preliminary results show that the transit from one mode to the other depends on the spatial distribution and the thickness of a low viscosity channel (<1021.5 Pa s) at the base of the crust. For instance, sequential faulting mode occurs when there is a pocket of low viscosity lower crust at the tip of the active fault, which prevents faulting from mechanically breaking-up the crus. Besides, sequential faulting mode leads to a wider area of underplated melt since the migration of the rift centre extends the area where the melt is emplaced during the evolution of the model.

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Strain localization in the crust and lithosphere

SUBMARINE MASS-WASTE EVENTS CAUSED BY SEAMOUNT SUBDUCTION

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ABSTRACT:

Large areas of subducting oceanic plates obtain a rough topography due to the occurrence of submarine seamounts. At subduction zones, such seamounts often leave traces of destruction within the upper plate accretionary wedges, causing strong variations in wedge morphology and stress distribution. Resulting normal faults lowering surface tapers towards a critical wedge slope can trigger large submarine gravity flows. We present new insight into the mechanical and dynamic consequences of seamount collision into accretionary wedges with already developed imbricate thrust sheets by using numerical modelling tools. Large-scale 3D me¬chanical models (100 * 100 * 15 km; 9 million nodes; 36 million markers) based on finite difference, marker-in-cell technique, are applied to test how incoming seamounts connected to the lower plate change the stress regime in accrectionary wedges and specifically how they control the surface topography of accretionary wedges during col¬lision. We introduced different sizes for seamounts, which are either peaked or flat-topped. Furthermore, different seamount rheologies are tested.

Results show that seamounts underthrusting accretionary wedge systems are triggering out-of-sequence thrusts, rooted at their caps. Larger seamounts (peak or plateau elevation at least equal to stratigraphic thickness) lead to gravitational collapses of accreted material. Such mass-waste events sliding along normal faults lower critical tapers towards a stable value, according to the critical wedge theory. The volume of such submarine landslides depends on the seamount height and whether it has a flat-topped or a conical shape.

Intermediate-depth earthquake generation and shear zone formation caused by grain size reduction and shear heating

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Abstract:

The underlying physics of intermediate-depth earthquake generation has remained an enigmatic topic, with several studies supporting either thermal runaway or dehydration reactions as viable mechanisms. Here we present fully coupled thermo-mechanical models that investigate the impact of microstructural (grain size) and energy (shear heating) feedbacks on shear zone and pseudotachylite formation.

Our results indicate that grain size reduction i) weakens the rock prior to thermal runaway and ii) significantly decreases the critical stress needed for thermal runaway, which makes it more likely to result in intermediate-depths earthquakes at shallower depths. Furthermore, grain size is reduced in and around the shear zone, which agrees with field and laboratory observations where pseudotachylites are embedded in a mylonite matrix which agrees with field and lab observations.

The decrease in critical stress to initialize localization also has important implications for large-scale geodynamics, as this mechanism might induce lithosphere-scale shear zones and subduction initiation. We suggest that the combination of grain size reduction and shear heating explains both the occurrence of intermediate-depth earthquakes and the formation of large-scale shear zones.

USING NATURALLY DEFORMED PERIDOTITES TO CONSTRAIN MODELS OF SHEAR LOCALIZATION

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ABSTRACT:

Models of mantle shear localization rely on estimates of olivine rheology that are constrained by laboratory experiments. These experiments are necessarily performed at different temperatures and orders-of-magnitude higher strain rates than occur in the Earth. Field outcrops of naturally deformed peridotites provide a way to test the validity of extrapolating laboratory data to mantle conditions. Mantle shear zones exposed in the Josephine Peridotite in SW Oregon, USA, represent one such opportunity to improve existing constraints on mantle rheology. A series of ~10 shear zones are exposed in a kilometer-wide section, ranging in width from 1 to 60 m and representing small-scale deformation in the mantle at lithospheric conditions (Kelemen and Dick, 1995; Warren et al., 2008). These shear zones are useful for exploring mantle deformation, as the presence of a foliation provides a strain marker. Individual shear zones have maximum shear strains that range from 5 to >20.

The largest of the shear zones consists of inter-layered harzburgites and dunites, with both lithologies showing a similar evolution in olivine lattice-preferred orientation as a function of shear strain, but differences in their grain size evolution (Hansen and Warren, 2015). As laboratory experiments containing orthopyroxene are difficult, the contrast between orthopyroxene-bearing and orthopyroxene-free lithologies provides an alternate technique to constrain its rheology. The set of paired dunite-harzburgite samples are used to calculate a viscosity ratio of ~3 for pyroxene relative to olivine. However, increased viscosity in the harzburgites due to higher pyroxene contents than dunites is offset by a decreased grain size of olivine and deformation by a grain-size dependent mechanism.

To further investigate mechanisms of shear localization, we measured the water content in orthopyroxenes from samples across three shear zones. The water content is lowest at the center of shear zones, in contrast to preliminary results from Skemer et al. (2013) and to the expectation that water localizes deformation. Observations of melt at the center of one shear zone may provide a mechanism for water transport out of the shear zone, as well as a mechanism for shear localization. In addition, mechanical anisotropy – due to olivine alignment at the center of the shear zones – also plays a role in localizing shear (Skemer et al., 2013).

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Strain localization in the crust and lithosphere

Dynamic and structural setting of the Marlborough Fault Zone, New Zealand

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ABSTRACT:

The Marlborough Fault Zone provides the critical structural link between the Hikurangi Subduction Zone and the Alpine Fault within the obliquely convergent New Zealand plate boundary. We present numerical models explaining the geodynamic context for the progressive faulting and rotations within the Marlborough Fault Zone, and link this context to a field based structural geology study to understand how this strain is being accommodated. The Marlborough Fault Zone records a steady south-east ward propagation of dextral reverse faulting since ca. 7 Ma. The Wairau Awatere (Little & Jones 1998), Clarence (Browne 1992) and Hope Faults (Wallace et al 2007) have all undergone ~1.5 Myrs of high slip motion > 25 mm/yr. Further south the Porter Pass-Amberley Fault Zone appears to be propagating as the next active fault in the series (Cowan 1992). The Marlborough Fault Zone has a map width of ~100 km with active tectonics occurring in a 60km wide zone (Lietner et al. 2001; Wilson e. al. 2004; Savage et al. 2007), with no discernible offset in the lithosphere. The north-eastern half of the Marlborough Fault System is undergoing clockwise vertical axis rotations up to 1.2 °/my (Wallace et al. 2007), whilst the axis of maximum shortening displays a southward clockwise rotation from ENE-WSW to NW-SE (Bourne et al. 1998). The Marlborough Fault Zone overprints an Early Cretaceous NE verging duplex within the interbedded Early Cretaceous sandstone and mudstone lithofacies of Pahau Terrane. The Pahau Terrane is overlain by late Cretaceous sandstones of the Muzzle Group and cherts and limestone of the contiguous Paleogene Seymour Group to the NE.

Finite-element visco-elastic numerical models computed in Underworld (Moresi et al. 2007) have been used to explore the geodynamic setting of the Marlborough Fault System over geological time frames. The Hikurangi Subduction Zone is set up to provide the forces that drive New Zealand tectonics, with Hikurangi plateau included to reduce roll-back at its southern terminus. As the subduction zone undergoes asymmetric roll-back due to the presence of the Hikurangi Plateau, the Chatham Rise is thrust into the Australian Plate, increasing the lateral distance between the subduction zone and Alpine Fault. This increasing lateral distance combined with oblique dextral nature of displacement at the plate boundary appears to drive the southward propagation of faulting in the Marlborough Region

to maintain a continuous plate boundary, effectively accreting slices of the Pacific Plate to the Australian Plate. The models indicate that the vertical axis rotations in northern Marlborough form due to escape tectonics at the edge of the Chatham Rise. North-South extension develops with a steadily increasing strain rate as the Hikurangi Plateau delaminates from the Chatham Rise, matching earthquake focal mechanism active along the central Chatham Rise (Litchfield et al. 2014).

Structural mapping of Eastern Marlborough shows shortening has been strongly partitioned into the Pahau Terrane with extensive dextral-reverse listric faulting. Faulting has occurred contemporaneously with folding of the Paleogene with the Seymour Group Cherts and Limestone providing a strong rheology contrast to the heavily deformed Pahau Terrane, and possibly influences the location of the Clarence and Kekerengu Faults adjacent to the Ben Moore Anticline. In southern Marlborough the reactivation of earlier ramp structures in the Pahau Terrane as transfer faults at ~90° to the primary Marlborough Fault is consistent with a lack of vertical axis rotation. To the north the Clarence and Hope Faults rotate to a more northerly strike, developing riedel faults that allow vertical axis rotations to be accommodated. Extension is accommodated by east-west striking normal faults overprinting the reverse listric faults, indicating that extension is more widespread than recorded in New Zealand's active fault data-base (Litchfield et al. 2014). The lack of discernible offset along the lithosphere boundary is possibly linked to the geologically quick relocation of the plate boundary and a mid-crustal detachment for the fault system. The structural development of the Marlborough Fault Zone is forming in response to a strain field controlled by a specific geodynamic setting – the edge of a subduction zone under highly asymmetric rollback. This work demonstrates that structures in the field should be reproducible through numerical modelling, whilst understanding the geodynamic context of a regions greatly improves the interpretation of its structural development.

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Strain localization in the crust and lithosphere

Coupling physics and Linking Time scales : New frontiers and problems

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Detailed program

WHAT CONTROLS THE THICKNESS OF THE SEISMOGENIC LAYER? NEW INSIGHTS FROM HIGH-TEMPERATURE ROCK FRICTION EXPERIMENTS.

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ABSTRACT:

The deep limit to seismicity in most of the tectonically active continental lithosphere is typically around 12-15 km, and is thought to correspond to a transition from the velocity-weakening to the velocity-strengthening behavior of typical crustal rocks such as granite. However, a recent study by Mitchell et al. (2013) revealed velocity-weakening behavior of Westerly granite at temperatures up to 450 deg. C. These results were obtained using a heated direct shear apparatus, and solid samples under dry conditions and low (5 MPa) normal stress. I will present results from recent experiments done on thick gouge at both dry and wet conditions at temperatures up to 600 deg. C and normal stresses up to 40 MPa. We find that the rate dependence parameter (a-b) of the rate-state friction progressively decreases with temperature over the entire temperature range, leading to more unstable slip at higher temperature. This tendency is enhanced at hydrothermal conditions. Similar results are also obtained for gabbro (a rock representative of the oceanic crust). These results challenge the traditional view on the mechanisms responsible for the termination of seismicity in the middle continental crust and on the nature of the brittle-ductile transition. However, they may help explain deep crustal seismicity in regions of active extension (e.g. East Africa and Baikal) and convergence (Himalayas and Andes).

GEOLOGICAL CONSTRAINTS ON THE CONSTITUTIVE LAWS THAT GOVERN DEFORMATION OF THE CRUST AND LITHOSPHERE

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ABSTRACT:

The understanding of silicate deformation mechanisms is well-developed after decades of experimental rock mechanics studies that encompass stable and unstable slip mechanisms on fault surfaces and a range of ductile mechanisms that cause continuum deformation, including diffusion and dislocation glide and climb. A considerable extrapolation is involved, however, from the length and time scale of laboratory deformation experiments (~cm and ~days) to those scales on which crust and lithosphere deform (up to ~1000 km and ~10 Myr). It is worth bearing in mind that this extrapolation across 8 or 9 orders of magnitude in both dimensions creates some uncertainty when it comes to modelling regional geological deformation. Many studies are published in which the rheological parameters obtained from deformation experiments are assumed to apply to regional scale deformation of crust and lithosphere, but one of the most important roles for modelling of tectonic processes is to provide an independent test of these rheological laws by comparing modelled behaviour with geological observations.

Some geological processes may be interpreted as natural experiments that allow estimates of stress and strain-rates from which effective constitutive laws can be determined directly for geologically relevant time and length scales. Where the large-scale deformation of continental and oceanic plates can be measured geodetically, or otherwise, we can obtain a depth-averaged constitutive law that appears to hold on length scales of ~1000 km and time scales of ~10 Myr. The geodetic strain-rate field for Anatolia and the Aegean appears to be simply explicable in terms of the gradients of lithospheric gravitational potential energy driving deformation of a thin viscous sheet that deforms according to a power-law relation between stress and strain-rate, with an exponent n that may be significantly greater than 3. The deformation field of the Central Indian Ocean can be well represented by a thin viscous sheet with a power-law exponent n of 30 or more. Such large n-values are not necessarily inconsistent with sample-scale measurements of olivine deformation, but they do represent a significant constraint on the mix of deformation mechanisms that apply in such cases.

Another type of natural experiment is revealed by deformation that is measured on the scale of 10's of km, and months or years, as the Earth's crustal stress field re-equilibrates after a large earthquake. Such measurements can reveal a complex rheological response that is a function of position within the crust and possibly varies with time also. Some authors have appealed to a Burger's-type linear viscoelastic law to explain multiple time-scales evident in the relaxation data. Others have appealed to a non-Newtonian law in which viscosity increases as stress differences are relaxed. In fact, after-slip on the fault in the months following an earthquake may be the biggest factor in the early post-seismic response curves and it remains unclear whether a simple Maxwell-type viscoelastic law (incorporating spatial variation of viscosity) may be generally applicable to the post-seismic response of the crust. Analysis of post-seismic relaxation after the 1997 Manyi earthquake of Tibet using a Maxwell-type visco-elastic constitutive law implies a depth-dependence of crustal viscosity that is broadly consistent with deformation experiments on crustal materials. On the other hand, a localized mid-crustal low-viscosity zone beneath the North Anatolian Fault interpreted from fault-perpendicular profiles of geodetic displacement before and after the 1999 earthquakes, is difficult to explain using any simple model.

Coupling physics and Linking Time scales : New frontiers and problems

SEISMO-THERMO-MECHANICAL MODELING OF SUBDUCTION ZONE SEISMICITY

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ABSTRACT:

Recent megathrust earthquakes, e.g., the 2011 M9.0 Tohoku and the 2004 M9.2 Sumatra events, illustrated both their disastrous human and economic impact and our limited physical understanding of their spatial occurrence. To be able to better assess earthquake hazard, it is necessary to improve our physical understanding of what drives these extraordinary events. One increasingly important tool to improve our understanding is numerical modeling. However, there was no numerical subduction model that a) includes the three key ingredients of seismic cycle modeling in subduction zones -rate dependent friction, slow tectonic loading, and visco-elastic stress relaxation of medium and mantle- (Wang, 2007), b) allows for the spontaneous propagation of ruptures along naturally emerging paths, also outside the megathrust interface, nor c) links long-term subduction dynamics and relating deformation to the short-term seismogenesis. To improve long-term seismic hazard assessment by overcoming the restricted direct observations in time and space, we developed such a seismo-thermo-mechanical (STM) model by starting from models typically applied to long-term lithospheric deformation (Gerya & Yuen, PEPI, 2007). In this presentation we will first briefly show that we can simulate processes operating at seismic cycle time scales and how we can to this. Than we will focus at two specific applications that illustrate the type of problems that can be tackled using this approach that links geodynamic and seismological time scales.

How do we simulate seismic cycles?

Our 2D continuum-mechanics based finite difference framework uses a marker-in-cell formulation to solve for both spontaneous fault evolution and large deformation. It implicitly solves the Navier-Stokes equations for an incompressible medium with a visco-elasto-plastic rheology. Brittle failure is mimicked through Drucker-Prager plasticity. To simulate rapid earthquake-akin slip transients we mainly introduced a local, invariant implementation of strongly rate-dependent friction and inertia.

Can we really simulate seismic cycles?

This approach was first and formally validated by showing a first order agreement with source and recurrence parameters obtained in a gelatin analogue model (van Dinther et al., JGR, 2013a). Its capability was than extended to a more realistic setup to show agreement with a range of seismological, geodetic, and geological observations of megathrust and off-megathrust earthquakes, albeit at lower coseismic speeds (van Dinther et al., JGR, 2013b). The occurrence of splay and normal faulting events within the sedimentary wedge was moreover shown to agree with analytical predictions based on dynamic Coulomb wedge theory (van Dinther et al., GRL, 2014).

What can we learn by applying STM models?

In this presentation we will highlight two applications that demonstrate the strength and potential of our new modeling direction. The first application highlights the role of large-scale subduction processes for short-term coseismic displacements. A wide range of large-scale and laboratory-scale models demonstrated that oceanic slab penetration into the mantle and its internal elastic deformation cause a secondary zone of coseismic uplift at distances beyond 250 km from the trench. Observations of 4 out of 4 megathrust earthquakes confirm the presence of this secondary zone of uplift in nature, albeit to different extents and at different distances from the trench.

The second application illustrates that our originally long-term models can indeed help to improve long-term seismic hazard assessment. Even in a simplified analogue modeling setup we recognized that increasing the down-dip width of a seismogenic zone introduces a transition from ordinary to super cycles (Herrendoerfer et al, Nat. Geo., 2015). Super cycles start with small subcritical events near the downdip limit, where stresses accumulate fastest due to differential displacements. These stresses, along with subsequent larger pulse-like events and continuous tectonic loading, increase stresses within the center of the seismogenic zone. When the whole seismogenic zone experiences a low strength excess, a crack-like super event can propagate over its complete width and lead to a larger than historically observed, devastating event, such as the Tohoku earthquake. The potential relevance of this stress evolution hypothesis was supported by our recognition that in nature only subduction zones with a larger than average downdip width are suggested to show super cycles.

Despite current 3D and temporal limitations, these seismo-thermo-mechanical model results captured a wide range of natural observations and dynamic features. With two examples we demonstrated the potential of these physically-consistent models, which open a world of interdisciplinary research between geodynamics and seismology. This can relate both to the generation and characteristics of megathrust earthquakes and beyond.

Seismo-thermo-mechanical modeling of collisional margins

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Abstract:

Earthquakes in continental collision regions, such as the Alps and Himalayas, have long recurrence intervals due to typically low convergence rates and more widespread deformation. Since part of these mountains belts are densely populated, small and shallow earthquakes already represent a considerable seismic important hazard. The restricted direct observations in time and space in combination with the geometrical and rheological complexities, however, pose a difficult problem for both modeling efforts and seismic hazard assessment. We for the first time simulate cycles of spontaneous earthquake-like ruptures of non a-priori faults, using a newly developed seismo-thermo-mechanical (STM) numerical modeling approach. This modelling approach is based on continuum, viscoelastoplastic code I2ELVIS (Gerya and Yuen, 2007) and validated for seismic cycle applications against a laboratory model (van Dinther et al., 2013a) and natural observations (van Dinther et al., 2013b).

This approach may help to shed light onto the interaction between collision dynamics, crustal and lithospheric deformation and associated seismicity. The two-dimensional model setup consists of two continental plates separated by an oceanic plate, in which the incipient subduction phase is followed by continent-continent collision. From that, we evaluate a non-associative Drucker-Prager plasticity with pressure dependent yield strength and a strongly rate-dependent friction formulation, which takes into account both velocity-weakening and velocity-strengthening frictional behaviours. In this way, earthquake-like ruptures initiate, propagate and arrest spontaneously.

Our results show physically consistent emergence of complex curved rupture paths, both on- and off-main frontal thrust, thus reflecting first-order complexities of collisional margins. We investigate the spatiotemporal evolution assuming different frictional and rheological properties of tectonic nappes. Our findings suggest that the main-thrust seismic cycle affects the frequency and magnitude of events on the accretionary wedge. While thrust-faulting events mainly occur on the main frontal thrust and back-thrust, normal-faulting events spread throughout the orogenic belt as a consequence of gravitational extension. Their occurrence is in agreement both in terms of analytical predictions of dynamic Coulomb wedge theory and short-term quasi-static stress changes resulting from the triggering of main-thrust events.

Gerya, T. V., and Yuen, D. (2007), "Robust characteristics method for modelling multiphase visco-elasto-plastic thermo-mechanical problems." Physics of the Earth and Planetary Interiors 163.1: 83-105.
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van Dinther, Y., et al. (2013b), "The seismic cycle at subduction thrusts: Insights from seismo-thermo-mechanical models." Journal of Geophysical Research: Solid Earth 118.12: 6183-6202.

3D COMPRESSIBLE MELT TRANSPORT WITH MESH ADAPTIVITY

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ABSTRACT:

Melt generation and migration have been the subject of numerous investigations, but their typical time and length-scales are vastly different from mantle convection, which makes it difficult to study these processes in a unified framework. The equations that describe coupled Stokes-Darcy flow have been derived a long time ago and they have been successfully implemented and applied in numerical models. However, modelling magma dynamics poses the challenge of highly non-linear and spatially variable material properties, in particular the viscosity. Applying adaptive mesh refinement to this type of problems is particularly advantageous, as the resolution can be increased in mesh cells where melt is present and viscosity gradients are high, whereas a lower resolution is sufficient in regions without melt.

In addition, previous models neglect the compressibility of both the solid and the fluid phase. However, experiments have shown that the melt density change from the depth of melt generation to the surface leads to a volume increase of up to 20\%. Considering these volume changes in both phases also ensures self-consistency of models that strive to link melt generation to processes in the deeper mantle, where the compressibility of the solid phase becomes more important.

We describe our extension of the finite-element mantle convection code ASPECT that allows for solving additional equations describing the behaviour of silicate melt percolating through and interacting with a viscously deforming host rock. We use the original compressible formulation of the McKenzie equations, augmented by an equation for the conservation of energy. This approach includes both melt migration and melt generation with the accompanying latent heat effects. We evaluate the functionality and potential of this method using a series of simple model setups and benchmarks, comparing results of the compressible and incompressible formulation and showing the potential of adaptive mesh refinement when applied to melt migration.

Our model of magma dynamics provides a framework for modelling processes on different scales and investigating links between processes occurring in the deep mantle and melt generation and migration. This approach could prove particularly useful applied to modelling the generation of komatiites or other melts originating in greater depths.

COUPLING A GEODYNAMIC SEISMIC CYCLING MODEL TO RUPTURE DYNAMIC SIMULATIONS

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ABSTRACT:

The relevance and results of dynamic rupture scenarios are implicitly linked to the geometry and pre-existing stress and strength state on a fault. The absolute stresses stored along faults during interseismic periods are largely unquantifiable. They are, however, pivotal in defining coseismic rupture styles, near-field ground motion, and macroscopic source properties (e.g., Gabriel et al., 2012). Obtaining these in a physically consistent manner requires seismic cycling models, which directly couple long-term deformation processes (over 1000 year periods), the self-consistent development of faults, and the resulting dynamic ruptures.

One promising approach to study seismic cycling enables both the generation of spontaneous fault geometries and the development of thermo-mechanically consistent fault stresses. Such seismo-thermo-mechanical model are based on continuum visco-elasto-plastic Lagrangian-Eulerian models typically used to study long-term deformation (van Dinther et al., 2013a,b, using I2ELVIS of Gerya and Yuen, 2007).

Here, we innovatively include the absolute stress and strength values along physically consistent evolving non-finite fault zones from the 2D geodynamic seismic cycle model into dynamic rupture simulations as an initial condition. The dynamic rupture simulations are performed using SeisSol, an arbitrary high-order derivative Discontinuous Galerkin (ADER-DG) scheme (Pelties et al. 2012, 2014). The dynamic rupture models are able to incorporate the large degree of fault geometry complexity arising in naturally evolving geodynamic models. The software has recently proven to be highly scalable on current and future HPC infrastructure. It reached multi-petaflop/s performance on some of the largest supercomputers worldwide and is a Gordon Bell prize finalist application (Heinecke et al., 2014).

We focus on subduction zone settings to further our understanding of the fundamental conditions and underlying physics of earthquakes capable to generate devastating tsunamis. We succeeded to overcome the first methodological challenges relating to the synchronization of both methods regarding the nucleation of events, the localization of fault

planes, and are working on the incorporation of similar frictional constitutive relations. Once we obtain comparable initial and strength conditions, we will compare the slow earthquake-akin events developing in the quasi-static geodynamic model to fully dynamic ruptures in terms of coseismic slip, surface displacements and stress changes. Furthermore, we will verify the importance of physically consistent fault stress, strength, and geometry input for dynamic rupture propagation in terms of rupture path and dynamics.

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Heinecke, A. (2014), A. Breuer, S. Rettenberger, M. Bader, A.-A. Gabriel, C. Pelties, A. Bode, W. Barth, K. Vaidyanathan, M. Smelyanskiy and P. Dubey: Petascale High Order Dynamic Rupture Earthquake Simulations on Heterogeneous Supercomputers. In Supercomputing 2014, The International Conference for High Performance Computing, Networking, Storage and Analysis. IEEE, New Orleans, LA, USA.

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van Dinther, Y. (2013b), T.V. Gerya, L.A. Dalguer, P.M. Mai, G. Morra, and D. Giardini, The seismic cycle at subduction thrusts: insights from seismo-thermo-mechanical models, J. Geophys. Res., 118, 6183-6202.

Mapping the subsurface with seismic and GPS data - example of Japan

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Abstract:

Acquiring more data has always been necessary to increase our knowledge of the interior structure of the Earth: to enhance models, explore new areas, and increase the resolution. Introducing a new type of data can give a new insight and a different perspective of the already explored territories.

We propose to use GPS waveforms as well as seismic waveforms when modeling the interior structure of the Earth. GPS receivers record a measurement of the displacement occurring at the ground due to the earthquake. GPS observations do not clip at large ground motions, therefore capable of recording an earthquake of any magnitude at any distance from the epicenter when the ground motion exceeds the nominal GPS noise level (2 mm).

We present the first results of mapping the subsurface with a dataset that is a combination of broadband seismometer and GPS observations. We show comparison of subsurface models from the Japan area.

Links between long term and short term rheology of the lithosphere

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Abstract:

The long term tectonic community philosophy is to incorporate the knowledge we have about the complex rheology of rocks to try produce self-consistent models of plate tectonics. Over years of practice, it appears that introducing realistic behaviour of rocks, realistic boundary conditions and more complexity in the physics was generally solving paradoxes that were before introduced by over-simplifications. The results of long-term geodynamic models of localisation, all show that localisation over few million years modifies locally the rheological architecture of the lithosphere and allow to maintain strong plate interiors bounded by weak plate boundaries which are necessary to the very existence of plate tectonics.

Alternatively, the general philosophy of the short-term tectonic community is that if a simple stratified model can reproduce the geodetic data set there are no reasons to add complexity in the rheology or the geometry of the models. The advantage of these extremely simplified models of earth is that they can reproduce data and permits to pause the inverse problem to deduce the effective properties of the earth. The inconvenient are that it is non trivial to interpret these effective properties. Using the popular visco-elastic relaxation model however reaches a paradox.

One must either admit that the rheology of the lower crust changes with time from very strong long after an earthquake and to very weak during the early post-seismic period or that the lithosphere is as weak as 10^18 Pa.s. Short-term tectonics community together with seismologist community prefer this second hypothesis because 1) within the frame of the visco-elastic relaxation model of the earthquake cycle, they obtain a better fit to data, using a strong lower lower crust and a week upper mantle and 2) most of shallow the earthquakes are located in the crust and very few in the lithospheric mantle.

However, this crême brulée rheology has been shown not to be able produce plate tectonics on Earth. Rather than assuming that the rheology of the lithosphere changes with time (hypothesis 1), and aiming at explaining seismic cycle observation in the frame of plate tectonics, I propose that steep velocity gradient recorded across faults late in their cycle reflects secular strain localisation rather than the visco-elastic relaxation response to the last earthquakes (Traoré et al 2014). The local long-term elastic weakening of the plate boundary is indeed found to be very efficient when the upper mantle is strong outside the plate boundary and post-seismic transients are equally well explained by weak lower crustal layer than a weak lithosphere (Le Pourhiet et al. 2014).

After reviewing in short our knowledge about lithospheric rheology and how we implement it in numerical models. I will argue my point with the presentation of long term tectonic models and short-term elastic and visco-elastic models which converge toward a similar rheology valid across time scales (Lecomte et al. 2012).

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TOWARDS CONTINUUM MODELS OF LATERAL RUPTURE PROPAGATION IN A SEGMENTED MEGATHRUST

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ABSTRACT:

At subduction megathrusts, propagation of large ruptures may be confined between the up-dip and down-dip limits of the seismogenic zone. This opens a primary role for lateral rupture dimensions to control the magnitude and severity of subduction zone earthquakes. The goal of this study is to improve our understanding of the ways in which the inherent variability of the subduction interface may influence the degree of interseismic locking and the propensity of a rupture to propagate over regions of variable slip potential. We focus in particular on the roughness of the incoming seafloor, which we expect to be of primary importance.

The global absence of a historic record sufficiently long to base risk assessment on, makes us rely on numerical modelling as a way to extend our understanding of the spatio-temporal occurrence of earthquakes. However, the complex interaction of the subduction stress environment, the variability of the subduction interface, the structure and deformation of the crustal wedge, and the large range of physical time scales has made it very difficult to construct comprehensive numerical models able to study megathrust segmentation. We intend to develop and exploit the power of a visco-elasto-plastic 3D continuum representation of the subduction megathrust, as well as off-megathrust faulting, to model the long-term tectonic build-up of stresses, and their sudden seismic release.

The sheer size of the 3D problem, and the time scales covering those of tectonics as well as seismology, force us to explore efficient and accurate physical and numerical techniques. So far, we have focused our efforts on developing a staggered grid finite difference code that makes use of the PETSc library for massively parallel computing. The code incorporates a newly developed automatic discretization algorithm, which enables it to handle a wide variety of equations with relative ease. What remains now is combining the physics that act on the different spatial and temporal scales. To this end we explore new constitutive models that enable adaptive time stepping, artificial damping of waves, and allow us to make a stable transition from implicit to explicit solution methods.

SEA LEVEL CHANGES INDUCED VARIATIONS IN MID-OCEAN RIDGE AND HOTSPOT VOLCANO CO2 DEGASSING

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ABSTRACT:

Earth’s geosphere and climate have long been thought of as independent sub-systems with few interactions on sub-orbital time scales of several thousand to ten thousand years. Here show evidence for a possible negative feedback mechanism during interglacial-glacial transitions via sea level modulated mantle melting and associated CO2 release at hotspot volcanoes and mid-ocean ridges.

During the climate system’s descent into the last ice age, sea level dropped by approximately 60 m over a time period of 5,000 years. When corrected for the contrasting densities of mantle rocks and seawater, this still implies a significant increase above the steady mantle decompression rate at mid-ocean ridges and hotspot volcanoes. In order to quantify the possible global increases in magma and CO2 fluxes, we have performed a series of geodynamic simulations. Two-dimensional mid-ocean ridge simulations show that the relative significance of sea level changes scales inversely with opening rates. For the present global distribution of spreading rates, which is dominated by slow spreading ridges, a ~50% increase in magma and CO2 flux is predicted in response to the sea level drawdown during the last glacial-interglacial transition. Likewise, oceanic hotspot volcanoes may be sensitive to sea level changes. We have performed 3D simulations for about 40 oceanic hotspots and find a ~60% increase in magma and CO2 flux in response to the sea level drawdown associated with the last interglacial-glacial transition. This points to the intriguing possibility that the combined increase in CO2 emissions from mid-ocean ridges and hotspot volcanoes may have caused a negative feedback that hampered the climate system’s descent into the last ice age.

OCEAN DEPTH THROUGH DEEP TIME

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ABSTRACT:

The Earth's oceans have played an important role in the evolution of life and tectonics on Earth, and yet our understanding of basic connections between these remains limited. One of the central, and still unanswered questions, is whether Earth's oceans have been present over all of Earth's history, and how deep were any oceans that may have existed. Global tectonics provides a large influence on the long term fluctuations in sea level through varying the volume of ocean basins. The volume of ocean basins over time can be estimated from the seafloor age distribution as observed in plate reconstructions, which gives the proportion of younger, elevated seafloor to older, subsided seafloor.

Muller et al. (2008) reported that 200m of sea level variation over the past 140 Myr may be associated with changes in global tectonics and associated seafloor age distributions, while also accounting for other major contributions such as the volume of ice sheets, the presence of large igneous provinces on the seafloor and thickness of sediments on the seafloor. Plate reconstructions show periods during the Cretaceous with a larger number mid-ocean ridges and correspondingly larger areal extent of younger, elevated seafloor that produce shallower ocean basins and an associated rise in sea level (Muller et al., 2008). We reproduce their results by constructing the plate age-area histograms (areal extent of seafloor with a particular age vs age) for oceanic crust from the dataset for each million year. From the plate age-area distributions, we calculate the depth-area distribution of oceanic crust using plate cooling models and thus the volume of water that can be accommodated by the ocean basins. Assuming that the oceanic volume of water has not changed, we can calculate the sea level from the assumed total volume of oceanic water and the amount of water that can be accommodated by oceanic basins. As a result, we establish a relationship between sea level and the age-area distribution of oceanic plates.

We then extend this methodology back into earlier times during Earth's history by using synthetic plate reconstructions derived from numerical models of mantle convection in 3D spherical geometry. To approximate conditions for earlier in Earth's history, we consider that both the Rayleigh number would have been higher in the past, resulting in faster surface velocities and, on-average, younger seafloor. Thus, we vary the surface velocity from the modern day value of 4cm=yr to what is predicted for early Earth conditions of 80cm=yr (corresponding to Rayleigh number of 108 to 1010, respectively). Coltice et al. (2014)

showed that the shape of seafloor age distribution is influenced by the growth of continental area over time, with an increasingly younger-aged, triangular shaped distribution favored for increasing continental surface. We also vary the amount of continents on Earth between 0, 10%, and 30% continents.

These models are based upon those previously done by Coltice et al. (2012, 2014). Further details about the model are provided in supplementary materials of Coltice et al (2012). The dierence between the model in this study and the ones done in previous studies is that these include 30% basal heating, a viscosity jump of 30 between upper and lower mantle, and more than 6 orders of magnitude of viscosity variations with temperature. In order to generate enough statistics to indicate the natural variability of the system, we perform 5 billion year long time-integrations generating hundreds of age-area distributions for each of the scenarios we consider. Using those, we can calculate the sea level associated using similar principals.

Mantle Lithosphere Interaction

Oral program

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Detailed program

MOUNTAIN BUILDING AND MANTLE DYNAMICS

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ABSTRACT:

Mountain building at convergent margins requires tectonic forces that can overcome frictional resistance along large-scale thrust faults, and that can support gravitational potential energy stored within the thickened crust once the orogen has formed. A general, dynamic model for this process is still lacking. Here, we suggest that mountain belts can be classified between two end-members. Firstly, those of “slab pull” type, where subduction is mainly confined to the upper mantle, and rollback trench motions lead to moderately thick crustal stacks, such as in the Mediterranean. Secondly, those of “slab suction” type, where whole mantle convection cells (“conveyor belts”) lead to the more extreme expressions of orogeny, such as the large thickness crust and high plateaux of present-day Tibet and the Altiplano. The slab suction type of deep mantle convection produces the unique conditions to drag plates toward each other irrespective of their nature and other boundary conditions. We support our arguments by analyzing the convective, orogenic, and volcanic history associated with the formation of the Andes and Himalayas. The formation of these orgenic belt started in the Tertiary, the Himalaya after collision around ~55 and the Central Andes slightly after around ~40. Based on mantle circulation modeling and tectonic reconstructions, we speculate that the forces necessary to sustain slab suction mountain building in those orogens derive, after transient slab ponding, from the mantle drag induced upon the penetration of slabs into the lower mantle, and an associated surge of mantle upwelling beneath Africa. This process started first at ~ 65-55 Ma for Tibet, when the Tethyan slab penetrated the lower mantle, and later at ~ 50-40 Ma for the Antiplano, when the Nazca slab did. This vigorous surge of mantle convection drag plates one against each other, generating the necessary protracted compressional stresses to sustain orogen, generating the Himnalayan-Tibetan belt and the Andes, both from ~50-40 Ma onward. If our model is correct, the geological record of orogeny can be used to decipher time-dependent mantle convection, with implications for plate tectonic heat transport and the super-continental cycle.

Earth Before Plate Tectonics: Questions and answers

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ABSTRACT:

In contrast to modern-day plate tectonics, currently there is no agreement upon paradigm concerning the global style of geodynamics and lithosphere tectonics for the early Earth. How and when plate tectonics started and what geodynamic regime was before remains enigmatic and controversial. Understanding viable scenarios for starting subduction and plate tectonics is hampered by the fact that subduction initiation mechanisms should be markedly different in the case of globally absent vs. globally active plate tectonics. Most present-day subduction initiation mechanisms require acting plate forces and/or pre-existing zones of lithospheric weakness, which are themselves the consequence of plate tectonics. Here, we focus on plume-lithosphere interactions and spontaneous plume-induced subduction initiation, which does not require pre-existing lithospheric fabric and is viable for both stagnant lid and mobile/deformable lid conditions. We present results of 2D and 3D numerical modeling of plume-induced deformation and associated crustal growth resulting from tectono-magmatic interaction of ascending mantle plumes with oceanic-type lithosphere. We demonstrate that weakening of the lithosphere by plume-induced magmatism is the key factor allowing for its internal deformation and differentiation resulting in continental crust growth. We also show that plume-lithosphere interaction can enable subduction and rudimentary plate tectonics initiation at the margins of a crustal plateau growing above the plume head. We argue that frequent plume-arc interactions recorded in Archean crust could reflect either short-term plume-induced subduction or plume-induced episodic lithospheric drips. We furthermore suggest a distinct plume-tectonics regime operated on Earth before plate tectonics, which was associated with widespread tectono-magmatic heat and mass exchange between the crust and the mantle. This regime was characterized by weak deformable plates with low topography, massive juvenile crust production from mantle derived melts, mantle-flows-driven crustal deformation, magma-assisted crustal convection and widespread development of lithospheric delamination and crustal drips. Plume tectonics also resulted in growth of hot depleted chemically buoyant subcrustal proto-cratonic mantle layer. Later, this layer rapidly cooled by internal convection and consolidated to form long-living cratonic roots.

3D THERMO-MECHANICAL NUMERICAL MODELLING OF CONTINENTAL RIFTING VIA PLUME-LITHOSPHERE INTERACTION IN PRESENCE OF FAR-FIELD FORCES

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ABSTRACT:

The role of mantle–lithosphere interactions in rifting processes has long been debated. Identification of mantle contribution to rift topography and structure is difficult, especially in the continents. At the same time, the volcanic activity, which is commonly considered a prime signature of mantle upwellings, is not systematically detected in the areas of presumed active rifting. It can be argued therefore that complex brittle-ductile rheology and stratification of the continental lithosphere result in screening and deviation of mantle upwellings as well as in short-wavelength modulation and localization of surface deformation induced by mantle flow. This deformation should also be affected by far-field stresses and, hence, interplays with the “tectonic” topography. Testing these ideas requires fully-coupled high-resolution “tectonic grade” 3D numerical modelling of mantle-lithosphere interactions, which is so far has not been possible due to the conceptual and technical limitations of earlier approaches.

Here we present fully-coupled high resolution 3D thermo-mechanical numerical models to investigate the impact of the laterally heterogeneous structure and rheological stratification of the continental lithosphere on the plume activated rifting and continental break-up processes in presence of preexisting far-field tectonic stresses. In our experiments, the “plumes” represent short-lived diapiric upwellings that have no continuous feeding from the depth. Such upwellings may be associated with “true” plumes but also with various instabilities in the convective mantle. The models demonstrate that the prerequisite of strongly anisotropic strain localization during plume-lithosphere interaction (linear rift structures instead of axisymmetric radial faulting) refers to simultaneous presence of a mantle upwelling and of (even extremely weak) directional stress field produced by far-field tectonic forces (i.e. ultra-slow far field extension at < 3 mm/y). Although in all experiments the new-formed spreading centers have similar orientations perpendicular to the direction of the main far-field axis, the models with homogeneous lithosphere show that their number and spatial location is different for various extension rates and thermo-rheological structures

of the lithosphere: relatively slow extension (3 mm/year) and colder isotherm (600-700C at Moho depth) at the crustal bottom lead to the development of single rifts, whereas “faster” external velocities (6 mm/year) and “hotter” crustal geotherm (800C at Moho depth) result in dual (sometimes asymmetric) rift evolution. On the contrary, the models with heterogeneous lithosphere (thick cratonic block with cold and thick depleted mantle embedded into «normal» lithosphere) and the plume centered below the craton, systematically show similar behaviors: two symmetrical and coeval rifting zones embrace the cratonic micro-plate along its long sides.

The experiments where the initial plume position has been laterally shifted with respect to the craton center, demonstrate a fundamentally different development, since in this case the upwelling plume is deflected by the cratonic keel and preferentially channeled along one of its sides, leading to formation of a large rift zone, characterized by important magmatic activity with substantial amounts of melts derived from mantle plume material. The assumption of rheologically weak vertical interface (inherited suture zone) along other side of the craton or the presence of a second smaller plume initially shifted in opposite direction permit us to reproduce the first-order features observed in dual asymmetric (amagmatic western versus magmatic eastern branch) Central East-African rift system. Moreover, this contrasted double rifting and asymmetric distribution of the hot material on either side of the craton may be also a result of unequal splitting of relatively big plume which initial position is slightly shifted to the eastern side of the craton (in this case, neither a particular weakness of the interface between the craton and the embedding lithosphere nor a presence of second small plume is required).

The series of models with more geologically consistent structure of «normal» lithosphere (thickness is different for western and eastern segments: 200 km and 150 km, respectively) provide the best fit with the observations, further increasing rift asymmetry, favoring intensive magmatism at the eastern border of the Tanzania craton.

Our results reconcile the active (plume-activated) and passive (far-field tectonic stresses) rift concepts demonstrating that both magmatic and a-magmatic rifts may develop in identical geotectonic environments.

This study is co-funded by the Advanced ERC Grant 290864 RHEOLITH to E. Burov and A. Koptev, by the UPMC Invited Professor Grant to T.Gerya and by the ETH Invited Professor Grant to E. Burov. The numerical simulations were performed on the ERC-funded SGI Ulysse cluster of ISTEP.

HOW TO MODEL AN INCIPIENT SUBDUCTION ACROSS A TRANSFORM FAULT?

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ABSTRACT:

This study is a preliminary work to contrain modelling with observations with the aim to understand the processes of evolution from a transform fault (TF) or a fracture zone (FZ) to subduction initiation.

We first focus on three natural examples : for mature subduction : Izu-Bonin-Mariana (IBM) and for incipient to young subductions : Puysegur and Hjort. IBM subduction initiated around 50 Myr ago (Deschamps and Lallemand, 2002) along a transform fault separating the paleo-Pacific plate (45 to 65 Myr old) (Sdrolias and Müller, 2006) on one side and the proto-Philippine sea plate (PSP). The proto-PSP is composed of an alternance between remnant arcs and young oceanic lithosphere (Deschamps and Lallemand, 2002).

South of New Zealand, several subduction zones initiated since 20 Myr starting with Puysegur (Lebrun PhD, 1996) and then southward with North Hjort around 11 Myr ago and South Hjort ~6 Myr ago (Meckel et al., 2005). On one side of the transform fault, the Australian plate was ~0-10 Myr old whereas on the other side, the Pacific plate was ~5-30 Myr old (Meckel PhD, 2005).

To better constrain our modeling, we explore the rheology and structure of modern transform faults before subduction initiation. We notice that ridge spreading rate modifies the structure of the TF or FZ. Slow-spreading ridges display deeper TF than for fast-spreading ridges. The total width of the TF zone associated with fast-spreading ridges is often larger than those with slow-spreading ridges.

Both TF and FZ display brittle deformation. Intense hydrothermal alteration yields serpentinization of the mantle under ~600°C that strongly weakens the fault zone.

To model the process of subduction initiation at a TF, we use in our simulations a thermo-chemico-mechanical code of convection (Christensen, 1992) that solves equations of momentum, energy and mass conservation. The simulated rheology combines viscous (non-Newtonian) and brittle behaviors. Plates are made of two layers, one shallow oceanic crust overlying the mantle part, both characterised by their own rheology and density.

The model investigates two types of mantle structure. The thermal mantle structure is made up of small-scale convection patterns in the first one, while in the second one, the thermal

structure neglects small-scale convection. The first thermal state results from the thermal equilibrium between the convective asthenosphere and the surface lithospheric conductive cooling, yielding small-scale convection. In the second hypothesis, the lithospheric gradient is derived from Turcott and Schubert (1982) while the deep mantle geotherm corresponds to an adiabatic gradient. The model juxtaposes two plates of different ages separated by a weakness zone made of the simulated weak oceanic crust. We test two different settings : 4 vs 9 Myr and 10 vs 30 Myr. Plate kinematic conditions are not applied symetrically. We impose a total convergence rate of 8 mm/yr in all cases. We perform a preliminary parametric study by changing the following parameters : age of plates, thermal transition zone width, deep mantle structure, weakness zone depth, and applied kinematics.

The weakness zone depth controls subduction initiation at least for 10 vs 30 Myr old plates. The depth of the weakness zone must reach the 1000°C isotherm of the young plate to trigger the localisation of convergence at the TF. As a result, the young plate subducts beneath the old one. Based on our 4 vs 9 Myr experiments, the width of the thermal transition zone controls the subduction vergence. The mantle structure strongly affects subduction initiation. Further experiments are needed to confirm these results. The setting of the plates (i.e., 4 vs 9 or 9 vs 4) does not affect the result. We also verify that the subduction initiation process is not modified if total convergence rate is applied on one plate only.

We plan to further explore : thermal structure (cited above), hydration and convergence velocity. We apply hydration to simulate serpentinisation in the weakness zone. For example, we will test the influence of the ridge spreading rate which controls the hydration and the rheology of the TF, on the processes of subduction initiation. We will also test various convergence velocities.

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Assessing the long-term structural deformation of the crust-mantle boundary beneath the lunar basins

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Abstract:

The topography of the crust-mantle interface underlying the lunar basins is well resolved in crustal thickness models derived from inversion of gravitational and topographical data (Wieczorek et al., 2013). These models show that there is a region of high density material located under the central portion of all except the very oldest basins. This feature has generally been interpreted as an upward perturbation of the Moho as a result of the basin-forming impact (Dombard et al., 2013; Freed et al., 2014; Melosh et al., 2013; Neumann et al., 1996; Wieczorek & Phillips, 1999; Williams & Zuber, 1998). The vertical magnitude of this Moho uplift, as well as its horizontal extent, has been observed to vary widely between basins and was previously believed to be representative of both the age of the basin and the extent to which the local thermal environment has enhanced the rheological creep of the lower crust and upper mantle in the vicinity of the basin (Dombard et al., 2013; Mohit & Phillips, 2006; Namiki et al., 2009). That is, older basins or those hosted in a region of elevated heat production appear to have broader and shallower central uplifts than those that are younger and/or situated in a cooler region of the Moon.

Our primary goal was to determine the conditions under which the current topographic character of the basin may be used as a proxy for previous thermal conditions of the hosting region of the Moon. In order to accomplish this we first created a database of the Moho uplift heights and widths below all measureable lunar basins. This allowed for the comparison of specific subsurface topographic characteristics to basin age and diameter. We then used a 2-layer finite element viscoelastic model to investigate the lateral topographic relaxation of the Moho of an 1000 km diameter basin in response to a range of initial thermal environments. These thermal conditions consist mainly of radiogenic decay of heat-producing elements and remnant heat from the impact event. In order to isolate lateral deformation from the much faster buoyancy-driven vertical deformation (Zhong, 1997), we enforce an initial condition of isostatic balance. Thus, late-stage deformation is driven only by the lateral pressure gradient created by the initially displaced mantle. All models were run for a simulated time of at least 1 billion years. We used the dry rheologies of diabase (Mackwell et al., 1998) or anorthosite (Rybacki & Dresen, 2000) for the crust, and olivine

(Karato et al., 1993) for the mantle.

We found that the widths of present-day Moho uplifts have some correlation with basin diameter, as expected from crater scaling relationships. However, the magnitudes of vertical uplifts (and thickness of the crust below the basin) have no obvious relationship to basin diameter. This implies that some aspects of sub-basin Moho topography may either be due to varying amounts of thermally-driven structural deformation, or alternatively to different initial impact conditions with little subsequent change. The results of our finite element models are able to provide further insight. Even the most permissive thermal cases result in negligible amounts of crustal flow and thickening of the crust below the basin. That is, the initial Moho topography is preserved through geologic time and suggests that present-day differences between basin sub-surface topography is a result of the impact event, rather than structural deformation during the last several billion years.

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Mantle Lithosphere Interactions

3D GEODYNAMIC MODELS OF ALPINE TYPE COLLISIONS AND DETAILS OF A NEW METHOD TO CREATE 3D INPUT GEOMETRIES FOR PARTICLES-IN-CELL BASED CODES

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ABSTRACT:

We present preliminary results of three-dimensional forward numerical models for the evolution Alpine-type collision. In particular we investigate the non-trivial 3D geometric effects of 3D subduction. The evolution of the model is then compared to geodynamic paleo-reconstructions of the Alpine and Western Mediterranean region. The simulations were performed using LaMEM and take into account visco-elasto-plastic temperature dependent rheology and free surface.

We also present a new easy-to-use method to create complex 3D input geometries. We use a well-established vector graphics software (Inkscape, www.inkscape.org) to draw geological interpretations on multiple cross sections. The drawings are converted into 3D volumes using the MATLAB-based library GeomIO (Geometry I/O). The output files contain 2D slices of 3D volumes, which are used to assign phases to particles within 3D domains. The output files are lightweight (~10 Mb) and phase assignment can efficiently be performed in parallel (successfully tested on over 8000 CPUs). GeomIO is planned to be released as an open-source library in the coming months.

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THERMAL RECONSTRUCTION OF THE SOUTH ATLANTIC CONJUGATE MARGINS: COUPLING GEODYNAMIC MODELLING WITH PETROLEUM SYSTEM MODELLING

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ABSTRACT:

Since a decade, oil exploration in the deep offshore of the conjugate margins of the southern Atlantic deals with petroleum systems with syn-rift and sag-basin associated source rocks and reservoirs. There is still a lot of uncertainty about the oil potential of the source rocks. One of the main concerns is the risk of too early maturation due to continental stretching and subsequent hydrocarbon leakage prior to the formation of oil traps. This possibility has not yet been explored to its fullest. This work couples geodynamic modeling with petroleum system modeling in order to get more insight into the thermal-mechanical evolution of the South Atlantic conjugate margins. Large-scale long time period (100 Ma) models have been developed to reproduce the thermal evolution related to the overall response of the basin accompanying its thermal subsidence. With this timeframe it is impossible to evaluate the thermal evolution resulting from crustal stretching, syn-rifting and continental break-up since these processes happen very fast in only few ten millions of years. Coupled phenomena on large-scale asthenospheric ascent, lateral flow of ductile materials in the lower crust and brittle structure of the upper crust are at the base of this relative fast thermal evolution. Knowledge on these processes can only be gained through the use of numerical codes dedicated to the thermo-mechanical study of the lithosphere. The thermo-mechanical evolution of the South Atlantic lithosphere will therefore be modeled with 1) the Flamar code with geometries over geological times of the 1300 oC isotherm at the base of the lihospheric mantle. The outcome will then be used as input for 2) Temis, a basin modeling software, to estimate what the results of thermo-mechanical calculations can contribute to the description of lithosphere dynamics of a petroleum system. Furthermore, an investigation with already available analytical solutions in Temis is also an option.

SIMULTANEOUS WIDE-SPREAD INTRA-PLATE NORMAL FAULTING AND ULTRA-SLOW OCEANIC SPREADING IN ARCTIC OCEAN: INSIGHTS FROM 3D MODELS

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ABSTRACT:

The Arctic Ocean and its continental shelf has recently attracted growing attention due to its estimated natural resources potential, observed climate and environmental changes and its puzzling tectonic evolution. The active plate boundary that runs through its youngest oceanic basin - the Eurasia Basin, includes the slowest spreading system in the world : the Gakkel Ridge. While the western part of this ridge has been explored by various Arctic expeditions, its eastern segment and associated conjugate margins are practically unexplored.

Here we present new data from the first systematic, high-resolution, 20560 km long seismic Arctic survey which image the two flanks of the basin, the slowest part of the Gakkel Ridge and the adjacent continental margins and basins. Interpretation of several seismic profiles, together with magnetic and gravity data analysis suggest that the ultra-slow spreading regime that started in the Late Eocene coincides not only with a change in the structure and bathymetry along the ridge, but also with faulting and doming in remote areas, particularly within adjacent continental blocks. Numerical 3D thermo-mechanical numerical modelling experiments suggest that this deformation is partly due to the bi-directional (transpression) active plate boundary stresses that are remotely transmitted. They show the possibility of development of complex conjugated fault patterns and simultaneous faulting in the oceanic rift domain and continental passive margin area in case of multi-directional stress field. The predicted surface deformation patterns resemble the observed topography and Late Eocene to recent faulting from the submerged Arctic continental ridges. These findings are of major importance for assessment of the mechanisms of evolution of ultra-slow spreading centers, lithosphere rheology and better understanding of the Arctic region.

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Mantle Lithosphere Interactions

Relationship between slab dip and topography segmentation in an oblique subduction zone : insights from numerical modeling

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Abstract:

Slab dip controls the state of stress in an overriding plate and affects mountain building. Analog and numerical models have shown variations in tectonic regime induced by slab folding over the 660 km depth discontinuity zone in orthogonal convergence. Here, we use a three-dimensional model of oblique subduction (30°) accounting for free top surfaces, and applied far field convergence over about 100 Myr. This model couples solid visco-elastic plates with a simple Stokes fluid solver via the Fictitious Domain Method. We show how slab folding generates along-strike slab dip segmentations and induces temporal variations in topography of the overriding plate, in addition to the spatial variations only due to subduction obliquity. When the subducting plate begins to curve forward, the elevation height rises inland and varies by 3 km along the 1000 km long trench, displaying stress rotation and strain partitionning about 300 km inland in the arc area. These results may be compared with the Chilean Andes because of its linear margin and well-constrained plates kinematics. Thus, we propose a new explanation to the general decrease in elevation from the Central to Southern Andes, which still remains to be combined with other 3D mechanisms to explain the actual Andean topography (eg. Ridge subduction, surface processes gradients, etc.).

Towards dynamically constraining subduction zone parameters from surface-topography characteristics

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Abstract:

The sticky-air method allows global models of mantle convection calculated on an Eulerian grid to realistically reproduce a free surface that is both physically accurate and computationally sensible (Matsumoto and Tomoda, 19983; Schmeling et al., 2008; Crameri et al., 2012a). The importance of a free surface for plate tectonics modelling is, for example, dramatically highlighted by the crucial change in system behaviour: A freely evolving surface topography enables realistic single-sided subduction (Crameri et al., 2012b). This allows for a more extensive study of realistic subduction that is, in contrast to the numerous other models, dynamically fully self-consistent.

Being able to model both accurate surface topography and realistic subduction we are able then to thoroughly investigate the link between individual topographic signals and subduction parameters. In fact, we try to dynamically constrain a subduction zone only by the topographic signal observed at the planet's surface.

For this, we use global models with a free surface that are calculated by the finite-volume code StagYY (e.g., Tackley 2008) using a multi-grid method on a fully staggered grid. We apply the sticky-air method with carefully chosen parameters (Crameri et al., 2012b) to approximate the free surface. A weak hydrated crustal layer that is subducted fully self-consistent on top of the sinking plate produces lubrication between the two colliding plates for stable, on-going subduction (Crameri and Tackley, 2015). The dynamically fully self-consistent model is calculated in either a 2-D or 3-D Cartesian geometry and has an initial subduction zone to produce plate convergence.

We systematically test the topography signal depending on (i) shallow slab-dip, (ii) slab buoyancy (iii) radial mantle viscosity, (iv) plate strength, and (v) 3-D mantle flow. Results

include detailed systematics and highlight slab dip and mantle viscosity as major agents for upper plate deflection and the slab buoyancy for lower plate deflection.

Overall, this study quantifies the ability of various subduction parameters to influence surface topography and, in reverse, constrains subduction zones from the surface to depth and through time.

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SUBDUCTION-INDUCED BREAK-UP AND DRIFTING OF CONTINENTAL PLATES

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ABSTRACT:

The break-up of continents is a crucial stage of the episodic aggregation and dispersal of tectonic plates on Earth, the Wilson cycle. Physical modeling and plate tectonic reconstructions suggest that rifting and break-up of plates, followed by the formation of an oceanic basin, are sustained by tensional stresses within continent interiors. However, why break-up and oceanic spreading occur in the core of large plates, far from plate boundaries, remains unclear.

Here we use two-dimensional numerical simulations to show that the dynamics of break-up and continental drifting can be coupled to, and strongly controlled by, the large-scale mantle flow pattern developing during lithospheric subduction. Different subduction styles are found, with lithospheric slabs either stagnating above the 660 km discontinuity or penetrating deeper into the lower mantle.

The upward return mantle flow induced by subduction, in turn, exerts basal tractions to the upper plate. This divergent asthenospheric flow beneath continents leads to extension and break-up at 250-350 km from the trench in stagnating slab models. However, when the slab penetrates deeper, the subduction-induced mantle flow cell enlarges and break-up switches to 2800-3500 km from the margin, driving the drifting of large continental plates. While the upper mantle-confined dynamics is comparable to the evolution of the Japan arc and of the Western Mediterranean and the underlying mantle structures, the coupled deeper subduction-mantle flow dynamics illustrates an alternative mechanism for the opening of the Atlantic Ocean and drifting of the large South and North American Plates during the Farallon plate subduction.

THE EFFECTS OF FAR-FIELD BOUNDARY CONDITIONS ON 2D NUMERICAL SOLUTIONS FOR CONTINENTAL RIFTING: TESTS AND RECIPES FOR IMPROVED TREATMENT OF ASTHENOSPHERE FLOW AND MELTING

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ABSTRACT:

Recent geodynamic models (e.g. Huismans et al., Buiter et al., Brune et al., Lavier et al., Martinez et al., Armitage et al.) primarily use extremely simplified and incompatible far-field boundary conditions that have been used for decades with little assessment of their effects on asthenospheric flow beneath the rifting region. Huismans and Buiter assume there is no vertical flow into the rifting region, with the asthenosphere flowing uniformly into the rifting region from the sides beneath lithosphere moving in the opposing direction, Armitage et al. uses divergent velocities on the upper boundary to impose break-up within a Cartesian box, while the other studies generally assume there is uniform horizontal flow away from the center of rifting, with uniform vertical flow replenishing the material pulled out of the sides of the computational region. Except for extremely large closed-box calculations, none of these far-field flow BCs is consistent with the predicted solution for flow driven by two diverging tectonic plates. All are likely to significantly shape the pattern of asthenospheric flow beneath the stretching lithosphere that is associated with pressure-release melting and rift volcanism. Thus while all may lead to similar predictions of the effects of crustal stretching and thinning, none may lead to accurate determination of the asthenospheric flow and melting associated with lithospheric stretching and breakup.

Here we will show the results of a suite of numerical experiments that explores the asthenosphere flow and melting effects of the commonly used far-field BC choices in addition to their predictions for crustal flow and faulting for the same initial crustal and lithospheric structures. We compare these to likely more realistic boundary condition choices, like the low-cost analytical solution for flow associated with two diverging plates that stretch over a finite-width region.

Influence of subduction history and surface processes on continental-scale topography

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Abstract:

Flow within the deep Earth shapes its surface over tens of million years and thousands of kilometers, with consequences for the evolution of continental-scale topography, drainage patterns and sediment deposition. We investigate the interaction of solid-Earth and surface processes by coupling global tectonic reconstructions and computations of mantle flow with models of erosion, sediment transport and deposition.

We first consider the Miocene evolution of South American topography that is marked by the drying up of an inland sea in western Brazil (the Pebas system) and the drainage reversal of the Amazon River between 20 and 10 Ma. We build a simple model of paleogeography that accounts for fluctuations in long-term sea level and dynamic topography. Testing alternative subduction scenarios, we find that the flattening of the Peruvian subduction can reproduce Miocene Pebas flooding, and that continental-scale tilting also contributed to the drainage reversal of the Amazon River.

We next consider the evolution of eastern Australia since the Late Cretaceous, which is characterised by two phases of modelled uplift (~ 200 m each) between 120 Ma and 80 Ma and between 60 Ma and 20 Ma, respectively due to the cessation of long-lived subduction to the east of Australia at around 100 Ma, and to the Cenozoic motion of Australia towards the Pacific superswell. These results are consistent with the uplift history deduced from the analysis of river profiles (Czarnota et al., 2014). We couple these dynamic topography predictions with a continental-scale surface process model that we use to compute 100 Myr of landscape evolution from a history of varying climate, sea level and mantle flow. The model predicts the time dependence of erosion and drainage patterns that we compare to the sedimentary record in key basins, paleo-drainage from paleogeography and denudation rates. In particular, over 5 km of post-rift sediments were deposited in the Ceduna Basin (the southern margin of Australia) in two main phases starting at ~ 80 Ma and ~ 55 Ma. In order to match the Ceduna Basin sedimentation history, we vary the coefficient of erosion by an order of magnitude and the amplitude (between 200 m and 1,000 m) of an uplift event that affected eastern Australia at 95 Ma and that is not fully captured by the mantle flow model.

Czarnota, K., Roberts, G. G., White, N. J., & Fishwick, S. (2014). Spatial and temporal patterns of Australian dynamic topography from River Profile Modeling. Journal of Geophysical Research: Solid Earth, 119(2), 1384-1424.

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Mantle Lithosphere Interactions

TWO APLICATIONS OF THE MANTLE CONVECTION CODE "ASPECT" FOR GEODYNAMICS

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ABSTRACT:

Here we present two applications of the mantle convection code ASPECT for geodynamics and specifically subduction modeling. The first applications shows the modeling of fully thermo-mechanically coupled subduction and the second the modeling of complex 3d geological settings.

ASPECT (Kronbichler et al., 2012), short for Advanced Solver for Problems in Earth's ConvecTion, is a new Finite Element code which was originally designed for thermally driven (mantle) convection and is built on state of the art numerical methods (adaptive mesh refinement, linear and non-linear solver, stabilization of transport dominated processes and a high scalability on multiple processors).

The first application model contains three different compositions: two different crustal compositions on top of both the subducting and the overriding plates and a mantle composition. We implemented a viscoplastic rheology using frictional plasticity and a composite viscosity defined by diffusion and dislocation creep. The lithospheric part of the mantle has the same composition as the rest of the mantle but has a higher viscosity because of a lower temperature. The temperature field is implemented in ASPECT as follows: a linear temperature gradient for the lithosphere and an adiabatic geotherm for the sublithospheric mantle. The Initial slab temperature is defined using the analytical solution of McKenzie (1970). The plates can be pushed from the sides of the model, and correspondingly it is possible to define an additional independent mantle in/out flow through the boundaries.

We will show a preliminary set of models, highlighting the current codes capabilities, such as the fine tuned use of Adaptive Mesh Refinement in combination with topography development both through a true free surface and sticky air and solving for strongly non-linear rheologies.

The second application shows our efforts to increase the complexity our 3d numerical models can handle. This includes the use of spherical geometries and more complex initial conditions for these geometries to be able to model more realistic geological settings.

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CONSTRAINING SLAB BREAKOFF INDUCED MAGMATISM THROUGH NUMERICAL MODELLING

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ABSTRACT:

Post-collisional magmatism is markedly different in nature and composition than pre-collisional magmas. This is widely interpreted to mark a change in the thermal structure of the system due to the loss of the oceanic slab (slab breakoff), allowing a different source to melt. Early modelling studies suggest that when breakoff takes place at depths shallower than the overriding lithosphere, magmatism occurs through both the decompression of upwelling asthenopshere into the slab window and the thermal perturbation of the overriding lithosphere (Davies & von Blanckenburg, 1995; van de Zedde & Wortel, 2001). Interpretations of geochemical data which invoke slab breakoff as a means of generating magmatism mostly assume these shallow depths. However more recent modelling results suggest that slab breakoff is likely to occur deeper (e.g. Andrews & Billen, 2009; Duretz et al., 2011; van Hunen & Allen, 2011).

Here we test the extent to which slab breakoff is a viable mechanism for generating melting in post-collisional settings. Using 2-D numerical models we conduct a parametric study, producing models displaying a range of dynamics with breakoff depths ranging from 150 - 300 km. Key models are further analysed to assess the extent of melting. We consider the mantle wedge above the slab to be hydrated, and compute the melt fraction by using a simple parameterised solidus. Our models show that breakoff at shallow depths can generate a short-lived (< 3 Myr) pulse of mantle melting, through the hydration of hotter, undepleted asthenosphere flowing in from behind the detached slab. However, our results do not display the widespread, prolonged style of magmatism observed in many post-collisional areas, suggesting that this magmatism may be generated via alternative mechanisms. This further implies that using magmatic observations to constrain slab breakoff is not straightforward.

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Mantle Lithosphere Interactions

Thermo-mechanical modelling of progressive deformation and seismic anisotropy at the lithosphere-asthenosphere boundary: the effect of a horizontal pressure gradient

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Abstract:

Understanding the interaction between the oceanic plate and the upper mantle, especially along the lithosphere-asthenosphere boundary (LAB), is crucial in understanding plate tectonics. In this study, we analyzed the accumulated shear strain within the upper 400 km of an oceanic plate. Therefore, we numerically calculated the velocity field within a two-dimensional channel of certain depth and length with a constant plate velocity on top, no slip at the bottom, and open boundaries at the side. We assume a composite rheology (dislocation and diffusion creep) in combination with a half space cooling model temperature field with variable thermal parameters for an oceanic plate of a certain age (120 Ma). Additionally, we applied a constant pressure at the left or right boundary of the channel to obtain either a driving or resisting asthenosphere flow. Due to the applied kinematic boundary conditions for a Couette-flow model and the lateral viscosity variations within the channel one obtains a minor induced Poiseuille-flow component within the model. Thus, the stresses vary significantly in comparison to the 1D solution of a Couette-flow.

Our model results show, that deformation along the LAB is strongly governed by temperature and relative motion between the lithosphere and asthenosphere. In case of Couette-flow boundary conditions, one obtains a standard high shear zone within the asthenosphere, with decreasing strain towards the upper and lower boundary of the model. In case of Couette-Poiseuille-flow boundary conditions, deformation pattern change significantly. Due to the plug flow component, one obtains two high shear zones within the upper mantle: 1) at the base of the lithosphere and 2) at the lower boundary of the channel. Thereby, maximum shear strain at the LAB depends strongly on the intensity of the additional pressure and on its direction (i.e., either driving or resisting). In case of a driving asthenosphere flow, shear strain along the LAB is decreased significantly, in comparison to

a Couette flow, for relatively small pressure; with increasing pressure, shear strain along the LAB increases and exceeds the shear strain observed within the Couette-flow model. In case of a resisting asthenosphere flow, however, shear strain along the LAB is always higher in comparison to the Couette flow model, already for relatively small pressures. Due to the additional pressure and the corresponding shear zones with opposite shear senses (i.e., a transition from sinistral to dextral with depth), anisotropy within the upper mantle varies significantly.

SUBDUCTION HISTORY AND SLAB MORPHOLOGY

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ABSTRACT:

Subduction of oceanic lithosphere into the Earth's mantle is thought to be the main driving force for global plate tectonics. It is generally thought that subduction initiates when a plate is old hence thick and globally denser than the asthenosphere below. However the age of the subducting plate at the trench ("slab age") spans a wide range, from less than 30 Myr in Central and South America to 150 Myr in the Marianas. The morphology of subducting slab in the upper mantle is also very variable, from slabs stagnating at the top of the lower mantle to slabs penetrating well beyond 1000 km depth.

People have looked (rather unsucessfully) for correlations between slab morphology and subduction parameters, including age at the trench, on the basic assumption that old (thick) plates are likely to generate a large slab pull force that would influence slab dip. Thermo-mechanical models reveal complex feedbacks between temperature, strain rate and rheology, which explains why slab morphology is dependent on subduction history. We illustrate some of these cases for which instantaneous slab age cannot be linked to morphology.

We acknowledge INSU (SYSTER program) and NERC for founding.

MODELS AND OBSERVATIONS OF PLUME-RIDGE INTERACTION IN THE SOUTH ATLANTIC AND THEIR IMPLICATIONS FOR CRUSTAL THICKNESS VARIATIONS

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ABSTRACT:

Mantle plumes are thought to originate at thermal or thermo-chemical boundary layers, and since their origin is relatively fixed compared to plate motion they produce hotspot tracks at the position of their impingement. When plumes reach the surface close to mid-ocean ridges, they generate thicker oceanic crust due to their increased temperature and hence higher degree of melting. Observations of these thickness variations allow estimates about the buoyancy flux and excess temperature of the plume. One example is the interaction of the Tristan plume with the South Atlantic Mid-Ocean Ridge, however, conclusions about the plume properties are complicated by the fact that the Tristan plume track has both on- and off-ridge segments. In these cases, where a plume is overridden by a ridge, it is assumed that the plume flux has a lateral component towards the ridge (the plume is ``captured'' by the ridge). Additionally, sea floor spreading north of the Florianopolis Fracture Zone did not start until 112 Ma -- at least 15 Ma after the plume head arrival -- while the Atlantic had already opened south of it. Therefore, the plume is influenced by the jump in lithosphere thickness across the Florianopolis Fracture zone.

We present crustal thickness and plume tracks of a three-dimensional regional convection model of the upper mantle for the Tristan-South Atlantic ridge interaction. The model is created with the convection code ASPECT, which allows for adaptive finite-element meshes to resolve the fine-scale structures within a rising plume head in the presence of large viscosity variations. The boundary conditions of the model are prescribed from a coarser global mantle convection model and the results are compared against recently published models of crustal thickness in the South Atlantic and hotspot tracks in global moving hotspot reference frames. In particular, we investigate the influence of the overriding ridge on the plume head.

Thus, our comparison between models of plume-ridge interaction and observations of crustal thickness in the South Atlantic can improve the estimate about the buoyancy flux and excess temperature of the Tristan plume over time. Moreover, it provides an estimate about the quality of the employed global plate reconstructions and hotspot track models.

This project was funded by the Deutsche Forschungsgemeinschaft (DFG) under grant STE 907/8-2 to BS as part of the DFG Priority Program SPP 1375 "South Atlantic Margin Processes and Links with onshore Evolution".

The computational resources were provided to JD and RG by the North-German Supercomputing Alliance (HLRN) as part of the project "Plume-Plate interaction in 3D mantle flow -- Revealing the role of internal plume dynamics on global hot spot volcanism".

FLAT-SLAB SUBDUCTION, TOPOGRAPHY, AND MANTLE DYNAMICS IN SOUTHWESTERN MEXICO

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ABSTRACT:

Topography above subduction zones arises from the isostatic contribution of crustal and lithospheric buoyancy, as well as the dynamic contribution from slab-driven mantle flow. We evaluate those effects in southwestern Mexico, where a segment of the Cocos slab subducts horizontally. The eastern part of the volcanic arc --- the Trans-Mexican Volcanic Belt --- stands at an average elevation of 2.3 km, nearly 1.3 km above the forearc. Lateral changes in bulk crustal density are relatively small, and seismic imaging shows that there is little variation in crustal thickness between these two regions. Thus, the elevation difference between the arc and the forearc should arise from differences in mantle properties. We present finite-element models of flat-slab subduction that provide a simultaneous match to topography, plate velocities, and stress state in the overriding plate. We find that the dynamic effects are primarily controlled by the amount of coupling at the subduction interface and in the mantle wedge, the lack of slab anchoring into the lower mantle, and the absence of continental mantle lithosphere. With a mantle wedge and a subduction interface that are respectively 2 and 4 orders of magnitude weaker than the asthenosphere, the flat slab exerts a downward pull that can explain most of the elevation difference between the forearc and the arc. We infer that lateral viscosity variations play a significant role in shaping dynamic topography in complex tectonic settings, and that sublithospheric dynamics can influence the topography at wavelengths that are significantly shorter than previously recognized.

UPSTREAM OFFSET OF SURFACE VOLCANISM WITH RESPECT TO THE PLUME AXIS EXPLAINED WITH ELASTIC PLATE FLEXURE

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ABSTRACT:

La Reunion and Hawaii result from the arrival of a plume below a translating oceanic lithosphere, and in both cases surface volcanism develops offset by ~150 km upstream from the axis of the plume with respect to plates' motion. Modelling studies have already intensively explored plume-lithosphere interaction since the 1970s. However they either 1) stretch the overriding plate, generating a variety of failure structures, or 2) they do not resolve the elastic behaviour at the top ~50-100 km of the Earth but only account for viscous behaviour. Here we propose a numerical approach in which 1) elasto-visco-plastic behaviour is handled at kilometric resolution, and 2) the overriding lithosphere drifts above the rising hot-spot. We observe the development of compressional flexural stresses above the upward load exerted by the plume head, equivalent but in opposite direction to the downward loading of seamounts, studied with visco-elasticity in the 1980s. This horizontal compression covers a relatively thin layer 10-30 km thick at 50-100 km depth, over a lateral extent of about 150 km, and is consistent with analytical predictions of elastic plate bending calculated by Hafner (1951). Such elastic flexure phenomena is transient that is progressively erased by viscous response to plume loading, and thus it depends on 1) the thermal erosion and viscous loading exerted by the plume, 2) the speed of plate drift and 3) the rheology of the lithosphere controling its elastic thickness.

Although melt production and migration is not included in our model, it obviously evolves according to the lithospheric stress pattern. First, horizontal elastic compression at the base of the lithosphere forces ponding of buoyant melts issued from the plume axis. Then, as the stress field rotates away from the plume head, these melts resume their ascension and open dikes via propagating “porosity waves”. Our model explains: i) The ~150 km 'upstream' shift between the axis of the plume and the active volcanoes of both theHawaii and Réunion swells, ii) synchronous activity of the 3 main volcanoes at Reunion over kyears, iii) this offset can persist millions of years if the speed of plate drift is greater than the ratio of the plume head width over the plates' Maxwell relaxation time, which opens questions on the appropriate rheology for describing strong variations in viscosity and strain-rate at critical depths corresponding to isotherms 500°-700°C. This study advocates for the necessity of accounting for elasticity in transient problems even when dominated by viscous flow.

Mantle Lithosphere Interactions

THE ROLE OF PLATEAU COLLISION-SUBDUCTION ON OVERRIDING PLATE DEFORMATION IN ALASKA

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ABSTRACT:

Properties of subducting slabs can have a first order control on the surface deformation of overriding plates. The Pacific-North American plate boundary in south-central Alaska is characterized by flat slab subduction. Previous 3D geodynamic models have shown that flat slab subduction can explain the major basins and several of the major mountain ranges in south-central Alaska. However, the models over-predict subsidence in the Talkneetna Mountains region and only predict a limited amount of deformation in the interior. The relative contribution of the flat slab geometry and thermal buoyancy have not yet been tested against the contribution of the buoyancy due to the thickened crust of the subducting Yakutat plateau. As a first step in understanding this process, we present a 3D characterization of the Yakutat Plateau and a set of 2D models representative of the region investigating the contribution from the slab geometry versus the plateau buoyancy. By modeling a subduction zone using a realistic, modern slab configuration, an understanding of the mechanisms that are involved in, and that drive, upper plate deformation can be better understood.

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Perennial plate tectonics with lasting mantle lithosphere scars

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Abstract:

Although the conventional theory of plate tectonics can explain non-rigid behaviour at plate boundaries, it cannot adequately explain the processes involved in deformation and seismicity within plate interiors.

Here, we consider that the pre-existing deformation or "scarring" within the mantle lithosphere may have a very long lived presence that could incorporate deformation of the plate interior and plate boundary. Mantle lithosphere scars from continent-continent collisions could generate virtual plate boundaries that remain over long timescales, producing "perennial" plate tectonics. Local geophysical studies can map the crustal environment well, and global whole mantle tomography models are rapidly improving, yet high-resolution images of the mantle lithosphere are often not available in regions where scarring may be present. Where mantle lithosphere heterogeneities have been observed (usually interpreted simply as subduction scars), the same attention has not been afforded to them as, for example, re-activation of faults within the Earth's crust. In idealized numerical simulations, we compare how relic scarring at varying depths in the lithosphere affects patterns of deformation. High-resolution thermal-mechanical numerical experiments explore continental lithospheric deformation featuring a weakened crust and mantle lithosphere scars. Our simplified models show that deep lithospheric scars can control the tectonic evolution of a region over shallow geological features, indicating the importance of mantle lithosphere heterogeneities. The Altyn Tagh Fault (ATF) in central China is an example of an ancient continental collision zone that undergoes periodic deformation during times of regional compression. We suggest that the ATF may be a locale where a long-lasting mantle lithosphere scar can control the subsequent crustal evolution and deformation, with ancient plate boundaries having a "perennial" plate tectonic presence.

THE DYNAMICS OF DOUBLE SLAB SUBDUCTION

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ABSTRACT:

Regional interactions between multiple subducting slabs have been proposed to significantly modify slab dynamics relative to that expected for a single slab. Here we use 3-D, time-dependent subduction models to explore how the kinematic evolution of a subducting slab, particularly trench and plate motions, can be affected by the presence of an additional slab, with all of the possible slab dip direction permutations. A second slab results in additional slab pull, and a more complex 3-D mantle flow field due to the interaction of multiple mantle return flow cells. Such additional complexities can give rise to the trench advance and rapid subducting plate motion observed to occur, or have occurred, at a number of subduction zones on Earth.

LITHOSPHERE-ASTHENOSPHERE INTERACTIONS NEAR THE SAN ANDREAS FAULT

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ABSTRACT:

We decipher the strain history of the upper mantle in California through the comparison of the long-term finite strain field in the mantle and the surface strain-rate field, respectively inferred from fast polarization directions of seismic phases (SKS and SKKS), and Global Positioning System (GPS) surface velocity fields. We show that mantle strain and surface strain-rate fields are consistent in the vicinity of San Andreas Fault (SAF) in California. Such an agreement suggests that the lithosphere and strong asthenosphere have been deformed coherently and steadily since >1 Ma. We find that the crustal stress field rotates (up to 40 degrees of rotation across a 50 km distance from 50 degrees relative to the strike of the SAF, in the near-field of SAF) from San Francisco to the Central Valley. Both observations suggest that the SAF extends to depth, likely through the entire lithosphere. From Central Valley towards the Basin and Range, the orientations of GPS strain-rates, shear wave splitting measurements and seismic stress fields diverge indicating reduced coupling or/and shallow crustal extension and/or presence of frozen anisotropy.

Chamberlain, C., Houlié, N., Bentham, H.L.M. and T. Stern (2014), Lithosphere-Asthenosphere interactions near the San Andreas fault, EPSL, 399, 14-20. 10.1016/j.epsl.2014.04.048.

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THERMO-MECHANICAL INVESTIGATION OF ONSET AND STABILITY OF FLAT SUBDUCTION

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ABSTRACT:

Flat slab subduction comprises only ~10% of the present-day subduction systems. Numerical and analog models have explored potential mechanisms for slab flattening that include: (a) mantle wedge suction; (b) thermal/compositional buoyancy of the oceanic plate; and (c) trench retreat and overriding plate velocity. However, previous modeling studies have one or more of the following limitations: they (a) consider only temperature-dependent Newtonian viscosity; (b) do not have a competent lithosphere at the surface; (c) do not consider a free upper surface; (d) fix the plate interface geometry; (e) prescribe non-zero velocities at all upper mantle boundaries, including at the bottom; or (f) focus on a single cause for flat-slabs (e.g., plateau subduction), or only a specific subduction zone (e.g, Peru). To our knowledge, there has been no systematic study that considered all of the key factors (or combinations thereof) affecting flat-slab subduction.

Here, we compare the effects of all previously recognized factors along with two not previously examined: temporary plate-velocity variations, and the presence of older slab material stagnated at the mantle transition zone. We use the visco-elasto-plastic ALE code, SULEC (Buiter & Ellis 2012) for modeling large finite-strain deformation. We restrict ourselves to 2D models, and ignore shallow mantle phase transformations (e.g., basalt-eclogite) that mainly affect the timing and/or duration of flat slab subduction. However, our models include several other realistic features such as: (a) lateral/vertical structure of the crust and lithosphere (e.g., continental lithosphere with/without a craton; oceanic lithosphere with tapered thickness governed by plate cooling and a harzburgite layer within); (b) a true free upper-surface for predicting surface topographic evolution; (c) plate velocity boundary conditions imposed in the far-field, with trench-velocity depending on over-riding plate deformation and slab pull; (d) latest laboratory-based constitutive relations, with deformation dominated by plastic yielding & dislocation creep at depths shallower than

~250 km depth and by diffusion creep at greater depths. Our model domain is 6000 km by 1500 km with grid spacing varying from 1 km near the surface and central portions of the model domain to 10 km near the edges. In that modeling context, we examine individually, and in combination, effects on flat subduction of factors that include: a weak mantle wedge, a subducting oceanic plateau/ridge, slab-age, presence of thick craton in the overriding plate, short-term changes in plate velocities, and transition zone slabs.

As in previous studies, we find that positive trench-retreat velocity and integrated slab-strength (as measured by differential stress) are necessary, but not sufficient, conditions for flat-slabs. While the additional suction in the mantle-wedge available in the presence of a craton does promote flat slab subduction, models without a craton also produce flat-slabs. In the absence of a craton, flat-slabs are promoted by large trench-retreat velocities, when either the slab is positively buoyant (structurally, or thermally), or in the presence of an underlying transition zone slab. Slabs at the transition zone promote near-surface flat-slabs due to inter-slab stress transmission. In our models (as in Earth observations), flat-slabs are transient with their duration dependent on the flat-slab buoyancy (and of course phase changes that we ignore here). Younger oceanic lithosphere, esp. one containing a plateau/ridge provides a longer lasting flat-slab (~ 10 Myr or longer, e.g., central Mexico), while older lithosphere flattens for only a few Myr unless dynamic support from transition zone slabs is present. Future goals for this project include comparisons of present-day stress-orientations inferred from focal mechanisms at present-day flat slabs to those predicted by our models. Longer-term goals include considering the effects of shallow mantle phase changes, as well as regional 3D studies that include first-order plate geometry and their historic motions.

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Integrating predictions from 3D numerical flow models with observations of seismic anisotropy from the Nazca-South America boundary

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Abstract:

Mantle convection drives the tectonic motions of Earth's lithospheric plates and the viscous deformation of the mantle rocks underneath them. Observations of seismic anisotropy yield some of the most direct constraints available on both past and present-day deformation in the Earth's mantle. To first order, predictions of upper mantle anisotropy made by global mantle flow models match seismological observations well beneath ocean basins, but the fit is poorer in continental regions and in regions of greater tectonic complexity such as subduction zones.

The Andean margin can be subdivided into five tectonic segments. These segments comprise of regions of normal subduction, where there is active volcanism such as Ecuador, and flat subduction where there is cessation of volcanism such as in northern-central Peru. Presently, 10% of subduction zones worldwide show shallow or flat subduction however extending over 1500km along strike (3oS to 15oS), the Peruvian flat slab segment is by far the most extensive present-day region of flat subduction in the world. Peru is therefore an ideal study location for this research of deformation-induced lattice preferred orientation (LPO) of intrinsically anisotropic minerals.

This study uses a 3D petrological-thermo-mechanical subduction model, I3MG (Gerya, 2010), alongside two additional codes, D-Rex (http://www.ipgp.fr/~kaminski/; Kaminski et al., 2004) and FSTRACK (http://earth.usc.edu/~becker/data.html; Becker et al., 2006) to replicate the Peruvian flat slab subduction system and to predict the seismic anisotropy of the region. The results will hopefully provide a clearer insight into the upper mantle flow around the flat slab subduction at the Nazca-South America boundary.

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DOUBLE-SIDED SUBDUCTION SYSTEMS: INSIGHTS FROM ANALOGUE MODELS

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ABSTRACT:

Following the breakup of Pangea supercontinent, the creation and consumption of the Tethys ocean has created a complex tectonic environment in the Alpine-Mediterranean area, with several smaller continental and oceanic fragments. The present geology of the region was established during the late Cenozoic by subduction and suturing of remaining oceanic fragments and collision of continental blocks. This study specifically focused on the Adria plate, which had ongoing subduction since the Miocene beneath the Apennines and Calabrian-arc as well as the Dinarides-Hellenic arc. Tectonic reconstructions of these subduction systems show asymmetric evolution of the two sides. The aim of this study was to investigate the scenarios characterizing the two counter subductions, and to understand if their likely interactions have happened through the mantle or the partly continental Adria plate. For this purpose, we designed and performed a set of 24 analogue models of single and double-sided subductions with progressively increasing degrees of complexity.

The modeling results show that the double-sided subduction of a homogeneous oceanic plate most likely evolves symmetrically, but even a small change in plate buoyancy can have a huge influence on the subduction history. The tectonic complexity (i.e. interacting slabs in double-sided subduction) can intensify this effect leading to an un-expected cessation of one of the subductions. These results give insights to unravel the asymmetric evolution of the Eastern and Western sides of Adria.

A COMPLEX MELT-NETWORK AND THE EFFECT OF HIS GEOMETRICAL PROPERTIES ON THE SHEAR VISCOSITY OF THE MATRIX IN A PARTIALLY MOLTEN MEDIUM

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ABSTRACT:

The shear viscosity of a solid matrix in a partially molten medium, especially in the olivine-basalt-system, is a commonly discussed topic in geodynamics because it is an important property for the process of melt migration and matrix compaction. Different deformation mechanisms need to be included because the molten phase affects the physical behaviour of the matrix in different ways. The model presented here combines a mechanical weaking process after Schmeling et al (2012) and a short-circuit-diffusion process described by Cooper & Kohlstedt (1986). For both processes a detailed knowledge about the geometrical distribution of the molten phase is needed. Therefore a three-dimensional, interconnected and geometrically self-consistant melt-network was designed. This network combines melt-pockets, melt-tubes and melt-films and includes curved and flat interfaces between the melt and the solid. The mathematical formulation for the important geometrical properties of the network, that affect the physical properties of the matrix, is semi-analytical and contains four unknown free parameters, that describe the shape of the network. Experimental observations on the wetness of an olivine-basalt-system with melt fractions up to 47% were used to fit the free parameters by a grid-search-algorithm. To implement the network into the model of Schmeling et al (2012) parts of the network (melt-pockets and melt-films) were approximated by oblate ellipsoids. The aspect ratio (ratio between short and long half axis) describing these ellipsoids and the ratio of the melt fractions identified with the different melt geometries will change with total melt fraction. To consider the short-circuit-diffusion process a mean characteristic diffusion distance analog to that of Cooper & Kohlstedt (1986) was defined, depending on the free parameters and the melt fraction. Assuming that the intrinsic viscosity of the matrix is affected by the short-circuit-diffusion process, we find a melt-fraction-dependent matrix viscosity that is in good agreement with experimental results from Hirth & Kohlstedt (1995). Because of the

mechanical weakening process the matrix shear viscosity drops to zero at about 33% melt-fraction. At this point the network-model predicts that grains should still be in contact (wetness < 1), implying that mechanical disaggregation may occur even if still some grains are in contact with each other.

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COUPLING STOKES AND DARCY FLOW IN MELT MIGRATION MODELLING

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ABSTRACT:

Melt migration can be modelled by coupling variable-viscosity Stokes flow and Darcy flow. Stokes Flow, generally, captures the long-term behavior of the mantle and lithosphere while Darcy flow models the two-phase regime.

The major unknowns of the coupled system are solid velocity, fluid pressure and compaction pressure. The fluid velocity can be computed in a post-processing step.

We present benchmarks and first small-scale results of the fully-coupled system with visco-elasto-plastic rheologies. This comprises elasto-plastic effects from shearing (Mode II) as well as poro-elastic effects and “opening mode” (Mode I) tensile plasticity. The system is solved using the Finite Element Method on triangular or quadrilateral grids in the Matlab-based code Mvep.

This work was supported by the Max Planck Graduate Center with the Johannes Gutenberg-Universität Mainz (MPGC).

Strain partitioning in the crust during continental collision: insight from 2D numerical modeling

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ABSTRACT:

Crustal shortening variation along strike during continental collision is addressed in the central Alps (Rosenberg and Kissling, 2013). Shortening pattern is gradually changed from upper plate crustal shortening (UPCS) in the east (e.g. Engadine profile in Rosenberg and Kissling, 2013) to lower plate crustal shortening (LPCS) in the west (e.g. Simplon profile in Rosenberg and Kissling, 2013). We address a question that what controls UPCS or LPCS to the first order? Does UPCS or LPCS pattern develop in a way more depending on geological structures (i.e. the inheritance from previous subduction) or lithospheric properties (e.g. rheological layering)?

We use a 2D thermo-mechanical coupled numerical model (Gerya and Yuen, 2003) to investigate the crustal strain partitioning during continental collision. Our numerical model directly starts from continental collision, and subduction inheritance is considered in a simple way by using an prescribed oblique weak zone, which decouples two continental plates in an asymmetric way. Several important model parameters are tested, such as the lithospheric rheological structure, the lithospheric thermal structure, the convergence rate and the weak zone geometry. Particular attention is paid on the influence of crustal strength (i.e. strength contrast of crust between two continental plates) on shortening partitioning.

Our preliminary results show that LPCS is generated in most numerical experiments, since the upper plate plays a role as a strong backstop. Systematically increasing the crustal strength of the lower plate (while keeping other parameters unchanged), results in the transition from LPCS to UPCS. The key of the LPCS to UPCS transition is the break-off of the backstop, which may largely shaped by the initial weak zone and lithospheric structure. Influence of rheological structures and weak zone geometries are also tested.

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Numerical modeling of the destruction of North China craton in terms of thermal erosion

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ABSTRACT:

Unlike other Archaen cratons, the lithosphere beneath the eastern part of North China Craton (NCC) may well have been thinned to lower-crustal depths in recent times. The thinning process is estimated to have started as early as the late Triassic (~210Ma c.a.) and lasted to the early Cretaceous (~115Ma c.a.). During this time the NCC was surrounded by three active margins with subduction occurring in northern, southern and eastern directions. According to seismic images of some recent and modern subduction zones (e.g. Indo-Eurasia), subduction-related processes can potentially thin the lithospheric mantle to ~80km very quickly by ‘lithosphere delamination’, and create a disequilibrium temperature field. Following this event, the nearly instantaneous interaction between hot asthenospheric materials and the cold relics of the lithospheric mantle could lead to a large density contrast which may trigger ‘thermal erosion’ of the remaining Archaean lithospheric mantle.

Based on this conceptual model, we are investigating the possible thinning of the lithospheric mantle to lower crustal depths by ‘thermal erosion’ following a deeper delamination event. We have tested more than eighty numerical experiments, exploring the effects of variables such as viscosity, thermal expansion, the initial temperature of the lithospheric mantle and the temperature of the asthenosphere following a delamination event. With these mechanical assumptions, for many initial variables it takes 10s of millions of years to thermally erode the Archean lithosphere from ~80 to Moho depths. We are still testing the robustness of this numerical result.

UNDERSTANDING LITHOSPHERIC STRESSES: SYSTEMATIC ANALYSIS OF CONTROLLING MECHANISMS WITH APPLICATIONS TO THE AFRICAN PLATE

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ABSTRACT:

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 stresses invoked by lateral variations of lithospheric density structure, sublithospheric tractions, ridge push, and subduction processes. In this study, we attempt to quantify the influence of these mechanisms and understand stresses within the lithosphere using the African plate (TAP) as an example. To do so we start with the simplest possible model and perform step-by-step building of a more physically realistic model discussing the influence of each step of increasing complexity. The finite-element based suite ProShell was developed to combine several data sets, estimate the gravitational potential energy (GPE) of the lithosphere, and calculate stresses on the real (non-planar) geometry of TAP. We introduce several quantitative parameters to measure how the modeling results fit observations and iterate these model parameters to match the observed stresses as accurately as possible. The starting model is based on the CRUST2 data set for the crust, and a half-space-cooling model to approximate the lithospheric mantle. Even though the results of this oversimplified model do not fit the observations satisfactorily, the model shows how ridge push can create compressive stresses within the lithosphere. More complex models show the importance of density structure of the lithosphere, especially within mantle. Our models show that the stress regime within TAP is mainly set up by a global balance of masses and mass moments between continental and oceanic parts of the plate. The orientation of stresses, in contrast, is more influenced by local features expressed by topographic and density structure variations, although influence of density variations within the subcrustal lithosphere is smoothed by the crust above. The series of experiments based on the iteration of controlling parameters achieves the best fit between modelled and observed stresses when physically feasible values were used. This gives us confidence that the methodology appropriately models the rheological structure alongside coupling the lithosphere with the convecting underlying mantle. The experiments also show that the bending stresses within the lithosphere may contribute to the stress pattern.

Reconciling numerical models of the mantle wedge with lava thermobarometry in Tonga

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Abstract:

The mantle wedge is the main stage for the generation of magma in subduction zones and, thus, plays a major role in the geochemical cycling of elements into and out of the deep Earth. Numerical models of the mantle wedge have advanced significantly in the last 40 years and predict a range of possible pressure-temperature conditions for different model parameters. Here we examine the Tongan subduction zone, from both a petrologic and numerical perspective, to reconcile thermal structures and investigate the likely conditions of melt generation and equilibration. Lava samples were compiled from GEOROC, and filtered to include only samples with MgO contents between 6 and 10wt% to minimize the effects of extensive fractionation or accumulation of crystal phases. The pressures and temperatures of melt equilibration were calculated using a thermobarometer based on silica activity in the melt (Lee, 2009) for a range of melt water contents and Mg# of the residue. To ascertain which numerically predicted (Davies, 2011) pressure-temperature conditions best match thermobarometric calculations, we vary model decoupling depth, upper plate thickness, mantle potential temperature and rheology. Where petrological P,T estimates overlap with model conditions, they plot near the base of a relatively thin upper plate lithosphere. In the most successful models, the points are approximately sub-arc, near the boundary with the stagnant fore-arc corner. Two end-member scenarios are possible: (i) melts are generated deep in the wedge, near the slab surface, and subsequently rise and re-equilibrate when reaching the higher viscosity lithosphere; or (ii) the base of the lithosphere is the initial position of melt generation. Whilst the most likely scenario is intermediate between these extremes, the latter would imply high degrees of melting (20-30%). Melt inclusion data from Tonga suggest that the magmas have original water contents of 3-5% wt% H2O (Plank, 2013). When assuming these pre-eruptive water contents, a relatively high mantle potential temperature is needed to reconcile the numerical models with the thermobarometry. This agrees with previous studies that suggest that relatively hot mantle from the Samoan plume has flowed into the Tongan wedge (Kelley, 2006).

Alternatively, higher water contents are needed. Short length-scale variations in the

calculated pressure of melt equilibration may indicate a mineralogically heterogeneous mantle and/or variable pathways of melt transport.

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Mantle Lithosphere Interactions

STRONG PLATES & WEAK SLABS

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ABSTRACT:

Plate Tectonics on Earth is characterized by a single down-going plate descending into the Earth's mantle below an overriding plate. At convergent zones with one oceanic plate and one continental plate the continental plate is too buoyant to subduct. At convergent zones with two oceanic plates both plates are composed of the same material and the asymmetry introduced by differing plate materials can not be used to explain single-sided subduction. Such oceanic/oceanic convergent zones comprise some 40% of convergent margins on Earth.

In models however the de facto mode of such convective systems is characterized by convergent zones with two-sided downwellings. In previous work we have found that the balance of stresses requires the down-going plate to be weak enough to bend and the overriding plate to be strong enough to resist the stresses created by the viscous coupling to the down-going plate. The strong down-going plates of that study retained sufficient strength such that the stresses at the slab tip as it approached the top of the lower mantle are transmitted to the surface. The transmission of these stresses to the surface changes the state of stress at the convergent zone and therefore the state of viscous coupling between the two plates.

We present 2D models in which the subducting plate is weakened by virtue of having been bent. The results presented here show the change to the system in the case where the surface plate has physical properties that make it sufficiently strong to resist viscous coupling at the plate interface yet is weakened and the stresses generated by the slab interaction with the lower mantle are muted.

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Thermal evolution and heat-pipe melt transport: implications for one-plate planets

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Abstract:

During the early evolution of terrestrial bodies, a large amount of mantle melting is expected to significantly affect the energy budget of the interior through heat transport by volcanism. Partial melt, generated when the mantle temperature exceeds the solidus, can propagate to the surface through dikes, thereby advecting upwards a large amount of heat. This so-called heat-pipe mechanism is an effective way to transport thermal energy from the melt region to the planetary surface. Indeed, recent studies suggest that this mechanism may have shaped the Earth's earliest evolution by controlling interior heat loss until the onset of plate tectonics (Moore & Webb, 2013). Furthermore, heat-piping is likely the primary mechanism through which Jupiter's moon Io loses its tidally generated heat, leading to massive volcanism able to cause a present-day heat-flux about 40 times higher than the Earth's average heat-flux (O'Reilly & Davies, 1981). However, despite its obvious importance, heat-piping is often neglected in mantle convection models of terrestrial planets because of its additional complexity and vaguely defined parameterization.

In this work, we have included the heat-pipe mechanism in the mantle convection code Gaia-v2 (Hüttig et al., 2013) and systematically studied its influence on the heat transport using both steady-state and thermal evolution models.

The first approach modelled here is based on (Moore & Webb, 2013). Whenever melt is generated, it is completely extracted from the melt region and placed at the surface, where it instantaneously cools to the surface temperature. To conserve mass, material is advected downwards to refill the region from which melt has been extracted. This downward advection results in cooling of the mantle. In the second heat-pipe scenario, we take into account the possibility of intrusive volcanism. Following (White et al., 2006), we consider an extrusive-to-intrusive ratio of 0.2, i.e. 20% of the melt is extracted to the surface while 80% is emplaced at a fixed depth in the stagnant-lid, where it cools by conduction.

Our steady-state results are consistent with (Moore & Webb, 2013) and show that in systems with strongly temperature-dependent viscosity the heat-pipe mechanism sets in at a Rayleigh number Ra ~ 2 × 107 . Upon increasing Ra up to ~ 6 × 107 , we observe a systematic decrease of the average mantle temperature accompanied by an increase of the

lid thickness compared to cases where heat-piping effects are neglected. By increasing further the Rayleigh number, the effect levels off, eventually leading to an average mantle temperature ~ 10% smaller and a stagnant lid almost twice as thick.

Further, we run a series of thermal evolution models in a 2D cylindrical geometry. Using Mercury-, Moon- and Mars-like parameters, we consider a mixed-heated system with a cooling boundary condition at the CMB and radioactive decay. By comparing the evolution of the mean mantle temperature for the two heat-pipe models to a case where heat-pipe is neglected, our results show a maximum peak-to-peak difference of several hundreds degrees in the early stages of the planetary evolution, when a large amount of melt is produced. Over time, the difference between cases with and without heat piping decreases and tends to vanish toward present day. Nevertheless, the amount of produced crust varies significantly between the models with the thinnest and thickest crusts obtained for the 100% extrusive heat-pipe model and the model in which heat-piping is neglected, respectively.

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THE EFFECT OF NON-LINEAR RHEOLOGY ON THE DYNAMICS AND TOPOGRAPHY OF 3D SUBDUCTION-COLLISION MODELS

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ABSTRACT:

Most of the major mountain belts and orogenic plateaus are found within the overlying plate of active or fossil subduction and/or collision zones. It is well known that they evolve differently from one another as the result of specific combinations of surface and mantle processes. These differences arise for several reasons, such as different strengths of materials, different amounts of regional isostatic compensation, and different mechanisms by which forces are applied to the convergent plates. All these possible controlling factors can change with space and time.

Here, we employ the code LaMEM to perform new high-resolution long-term 3D simulations of subduction/continental collision in an integrated lithospheric and upper-mantle scale model. We test the effect of visco-elasto-plastic rheology on mantle and lithosphere dynamics in a model setup that resembles a simplified tectonic map of the India-Asia collision zone. We use the “sticky-air” approach to allow for the development of topography and the dynamics of subduction and collision is entirely driven by slab-pull (i.e. “free subduction”). The models exhibit a wide range of behaviours depending on the rheological law employed: from linear to (passive-)temperature-dependent visco-elasto-plastic rheology that takes into account both diffusion and dislocation creep. Finally, we discuss the implications on lithosphere dynamics at convergent margins.

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TIME-DEPENDENT EVOLUTION OF SUBDUCTION BENEATH NON-UNIFORM OVERRIDING PLATE: SLAB DIP, TRENCH PARALLEL FLOW AND SUBDUCTION VELOCITY

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ABSTRACT:

Subduction in Middle and South America shows significant along-strike variations of different subduction features. In particular there is a good correlation between variations of the overriding plate thickness and variations of the slab dip, seismic anisotropy and subduction velocity. Previous numerical models have shown that overriding plate thermal state influences the slab dip and variations in slab dip can cause trench-parallel flow above the slab. This suggests a causal link between overriding plate structure, slab geometry and mantle flow in subduction zones. Models also show that interplate coupling is stronger for colder overriding plates, which might lead to lower subduction velocities.

We implement generic numerical models to study the effect of the overriding plate structure on the evolution of slab geometry, induced mantle flow and subduction velocity. We solve the 3D, time dependent thermo-mechanical equations with a non-linear rheology to simulate buoyancy driven subduction processes. We find that along-strike variations in thermal thickness of the overriding plate cause increased hydrodynamic suction and shallower slab dip beneath the colder portion of the overriding plate; the variation in slab geometry drives strong trench-parallel flow beneath the slab and a complex flow pattern above the slab. The location and strength of trench-parallel flow vary with the time-dependent evolution of the slab, suggesting that the global variability in seismic anisotropy observations in subduction zones is in part due to the non-steady-state behavior of these systems. This new mechanism for driving trench-parallel flow provides a good explanation for seismic anisotropy observations from the Middle and South America subduction zones, where both slab dip and overriding plate thermal state are strongly variable. Our results also show that increased interplate coupling beneath a colder portion of the overriding plate leads to a reduction of the subduction velocity in the region, leading to along-strike variations subduction velocity. These results provide a good explanation of the observed present-day variations in subduction velocity in Middle and South America, as well as the Phillipine Sea Plate.

Therefore, in addition to mechanisms such as variations in subduction plate age or slab length in the upper mantle, the possible role of overriding plate structure should be taken into account in interpreting causal mechanisms for variation subduction velocity in plate reconstructions.

CHARACTERISTICS OF CONTINENTAL DRIFT THROUGH DEEP GEOLOGICAL TIME

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ABSTRACT:

A century ago, Alfred Wegener introduced his ideas about continental drift and his concepts paved the way for several geodynamic breakthroughs: mantle convection, plate tectonics and their dynamic link. In contrast, to the efficiently recycled oceanic plates, which are hard to reconstruct far back in time, continents strongly resist recycling and thus provide a geological inventory for Earth's mantle and plate dynamics at pre-Pangean times.

Paleomagnetic data provides constraints on paleogeographic locations of various continental blocks over time and thus allowing for their drifting rates. However, it does not reveal the dynamic causes behind continental drift. What causes continents to accelerate or decelerate or change their drifting direction? An understanding of these questions is required to gain insight into the coupling between continental drift, plate tectonics and internal dynamics, which is e.g. essential for reconstructing Earth's tectonic history prior to Pangea's dispersal.

Taking this as a motivation, we use a set of global mantle convection simulations including self-consistent plate tectonics and continents to investigate the evolution of continental drift over long time scales. These cases of synthetic plate motions are designed to match modern plate reconstructions since 200 Ma, but additionally include periods of both continental assembly and dispersal.

The drift of continents is strongly time-dependent and may vary by up to an order of magnitude globally (and even more regionally). The average drifting speed appears to depend on the background level of global plate motion, but also on the evolution of continental configuration. Both are sensitive to the generation, distribution and destruction of plate boundaries in the oceanic domain, since this controls the forces acting on the plates as well as convective planform.

Continental configuration evolves depending on the global wavelength characteristics of mantle flow: shorter wavelength flow favors more dispersed continents, very long wavelength may cause very compact continental assemblies that are difficult to disperse, and only cases with intermediate(-long) wavelength may be prone to episodic assembly and dispersal of continental clusters.

Since these characteristics are dependent on the rheological properties of mantle and lithosphere, we also discuss the role of lithospheric yield strength, activation energy, and lower/upper mantle stratification in order to identify conditions for extreme events like very fast motion of single continents (like India, for instance).

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COUPLING GEODYNAMIC WITH THERMODYNAMIC MODELLING - APPLICATION TO THE EIFEL PLUME

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ABSTRACT:

Coupling geodynamic with petrological models is fundamental for understanding magmatic systems from the depth of the melting source to the point of magma crystallisation. Most of the current geodynamic codes use a simplified magma extraction algorithm and/or a simple parameterized petrological model to simulate melt formation and migration.

Here, we develop a method to better track the petrological evolution of the source rock, and predict the compositions of the extracted melts. We combine a geodynamic code with a thermodynamic model for magma generation and evolution. For the geodynamic modelling a finite element code (MVEP2) solves the equations for conservation of mass, momentum and energy. The thermodynamic modelling of phase equilibria in magmatic systems is performed with pMELTS for mantle-like bulk compositions.

The thermodynamic information includes density, melt fraction and the liquid and solid compositions, and is carried by each particle in the code (using marker-in-cell method), so that the physical and chemical properties can change locally as a function of previous melt extraction events and pressure and temperature conditions.

Calculating the phase diagrams is performed in three steps.

1. The initial rock composition is computed over the full upper mantle P-T range with pMELTS.
2. Once the melt fraction on the diagram exceeds a critical melt fraction melt is extracted. Because the extracted melts and residue have different chemical compositions, the solidus/liquidus of the remaining solid will change and future melting and melt extraction must take this new chemistry into account. We implement several melt extraction events and take the change in chemistry into account until the remaining melt fraction is below the critical melt fraction.
3. We use the residual rock compositions, produced by melt extraction, for the next calculations with pMELTS. The volume of extracted melt is tracked, as is the ultimate compositions of the remaining source.

We repeated step 2 and 3 for a second depletion event.

With each depletion event (step 2) it becomes more difficult to reach the solidus temperature and create a melt fraction in the P-T field. The reason for this is the depletion of incompatible

elements in the source rock that prefer to go into melt phases.

While computing such petrological phase diagrams on the fly is computationally unfeasible, existing melt parameterizations are only valid for limited compositional ranges. Therefore, we employed a different strategy and pre-computed a large number of phase diagrams and tracked the full chemistry of the solid rocks and extracted melts. The chemistry information is added to the particles in the thermo-mechanical code, which allows tracking the different types of rocks that form at different stages of the model evolution. Our method is general as long as sufficient thermodynamic data exist to predict the solidus and liquidus and the melt and depleted rock chemistry.

We will also show preliminary results of a model application to the Eifel plume, where melting is thought to be caused by either hot melting or as a result of a “wet” plume. We present model results with different initial rock compositions (primitive vs. water rich metasomatized mantle) and analyze how the source rock chemistry and melt chemistry evolve as a function of melt extraction.

Mantle Lithosphere Interactions

Influence of Edge-Driven 3D Convection on Mantle-Lithosphere Interactions in East Africa

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ABSTRACT:

The dynamics of lithospheric coupling to convecting mantle remains an outstanding challenge in geodynamics. Forcing from horizontal basal shear is thought to play an important role in the evolution of surface features – a hypothesis that is supported by correlations in absolute plate motion, mantle flow directions, and aligned SKS splitting observations. In this work we investigate mantle-lithosphere interactions in the Western Branch (WB) of the East African Rift where extension is isolated from broad upper mantle thermal anomalies related to plumes. Here, GNSS observations within the WB indicate along-rift motions that align with the fast direction of SKS splitting observations.

We employ the finite element open-source code ASPECT (Advanced Solver for Problems in Earth's Convection) to solve for instantaneous Stokes flow of the mantle-lithosphere system and calculate basal shear tractions at the lithosphere-asthenosphere boundary in 3D. Our model domain is limited to the WB in the East African Rift where we impose Earth's ellipsoidal shape by mapping topography relative to WGS84 to a regional mesh. Lithospheric structure is laterally varying, which we define with a linear geothermal gradient from the surface to a 1673 K isotherm that contours the LITHO1.0 global lithospheric thickness model. Below this isotherm temperature increases adiabatically to a depth of 500 km. The model domain is sub-divided into laterally varying CRUST1.0-defined crust, mantle-lithosphere, and sub-lithospheric mantle. We use steady state flow laws for the mantle-lithosphere and sub-lithospheric mantle regimes and tangential flow boundary conditions.

Our edge-driven flow calculations in the upper mantle show an upwelling flow pattern west of the central WB that directs northward, along-rift flow in the northern WB and southward rift-parallel flow along the southern WB. The magnitude of basal shear stress at the lithosphere-asthenosphere boundary ranges from 1-3 MPa beneath the rift. An independent estimate of vertically averaged lithospheric stress suggests volcanically active regions in the WB are sufficiently weak to be deformed by basal shear tractions.

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TOPOGRAPHY CAUSED BY MANTLE DENSITY VARIATIONS: OBSERVATION-BASED ESTIMATES AND MODELS DERIVED FROM TOPOGRAPHY AND LITHOSPHERE THICKNESS

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ABSTRACT:

Mantle convection can cause uplift and subsidence of the lithosphere. Because many continental areas are close to sea level, it is important to understand how these vertical displacements occurred through time causing continental inundations. Towards this goal, this paper aims at distinguishing between topography due to (1) crustal thickness variations, (2) the age of oceanic lithosphere, (3) other lithospheric density variations and (4) mantle convection. Residual topography (after subtracting contributions (1) and (2) from actual topography) is compared to a ``model'' topography derived from seismic tomography, and the fit is optimized by varying a number of parameters and assumptions. Both residual and model topography are corrected for contribution (2), but contain both (3) and (4). Distinction between the latter two becomes important for time-dependent computations, as anomalies within the lithosphere move with the plates and do not cause uplift or subsidence, but is not so crucial for present-day because topography amplitude is very similar regardless of whether density anomalies are within or beneath the lithosphere

Lithospheric density anomalies are uncertain, because they are probably due to variations in composition and temperature; a simple scaling from seismic to density anomalies is likely inappropriate in the lithosphere. Therefore, a lithosphere thickness model is derived: It is also based on tomography, and calibrated such that average thickness as a function of sea floor age visually matches the theoretical curve for half-space cooling. Using several recent tomography models, predicted thickness agrees quite well with what is expected from half-space cooling in many oceanic areas younger than 110 Myr, it increases less strongly with age for older oceanic lithosphere, and is quite variable on continents, with thick lithosphere up to ~ 250 km inferred for many cratons.

Best-fitting models feature a small positive density anomaly ~ 0.2% in the continental lithosphere - far less than inferred from thermal anomalies, a viscosity ~1e20 Pas in the asthenosphere, increasing to ~1e23 Pas in the lower mantle above D''. The resulting

viscosity structure yields a good fit to the geoid. With recent tomography models, computed root mean square (rms) amplitudes of model topography (corrected for ocean floor cooling) are slightly (<~ 30 %) larger than residual topography, and correlation is ~0.6, whereby many smaller scale features can now also be matched better than previously. Correlation becomes lower for degrees 15 and higher, where a large fraction of the density anomalies causing topography other than due to crustal isostasy is probably located within the lithosphere. Comparison of results with different viscosity structures indicates that lateral viscosity variations lead to moderate variations in modelled topography amplitude of a factor probably <2. Such variations can at least partly explain that model topography amplitudes are somewhat too low on continents, particularly for large cratons such as in Eurasia, and somewhat too high in oceans, particularly under the fast-spreading East Pacific Rise.

USING GLOBAL PLATE VELOCITY BOUNDARY CONDITIONS FOR EMBEDDED REGIONAL GEODYNAMIC MODELS

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ABSTRACT:

The treatment of far-field boundary conditions is one of the most poorly resolved issues for regional modeling of geodynamic processes. In viscous flow, the choice of far-field boundary conditions often strongly shapes the large-scale structure of a geosimulation. The mantle velocity field along the sidewalls and base of a modeling region is typically much more poorly known than the geometry of past global motions of the surface plates as constrained by global plate motion reconstructions. For regional rifting models it has become routine to apply highly simplified ‘plate spreading’ or ‘uniform rifting’ boundary conditions to a 3-D model that limits its ability to simulate the geodynamic evolution of a specific rifted margin. One way researchers are exploring the sensitivity of regional models to uncertain boundary conditions is to use a nested modeling approach in which a global model is used to determine a large-scale flow pattern that is imposed as a constraint along the boundaries of the region to be modeled. Here we explore the utility of a different approach that takes advantage of the ability of finite element models to use unstructured meshes than can embed much higher resolution sub-regions. In our initial project to validate this approach, we create a global spherical shell mesh in which a higher resolution sub-region is created around the nascent South Atlantic Rifting Margin. Global Plate motion BCs and plate boundaries are applied for the time of the onset of rifting, continuing through several 10s of Ma of rifting. Thermal, compositional, and melt-related buoyancy forces are only non-zero within the high-resolution sub-region, elsewhere, motions are constrained by surface plate-motion constraints. The total number of unknowns needed to solve an embedded regional model with this approach is less than 1/3 larger than that needed for a structured-mesh solution on a Cartesian or spherical cap sub-regional mesh. Here we illustrate the initial steps within this workflow for creating time-varying surface boundary conditions (using GPlates), and a time-variable unstructured 3-D spherical shell mesh.

THE INTERACTION BETWEEN SUPERCONTINENT CYCLES AND COMPOSITIONAL VARIATIONS IN THE DEEP MANTLE

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ABSTRACT:

Earth is the only planet known to currently feature active plate tectonics. Two features that may play a role in the Earth's ability to sustain plate-like surface motion are the presence of continents and the inferred chemical piles lying on the core mantle boundary. In a previous study that modelled thermochemical convection in the mantle (with evolving plates) it was shown that upwellings that form on top of chemical piles are relatively weak [Trim et al., 2014]. Consequently an intrinsically dense layer enveloping the entire core decreases the vigour of convection and the likelihood of surface failure. Surface yielding is required in order to maintain plate tectonics and form new plate boundaries. In contrast to the mantle upwellings that form above the chemically dense provinces in our models, particularly vigorous plumes form where the ambient mantle lies adjacent to the core mantle boundary and at the edges of the chemically dense piles. Continents also affect surface mobility due to their inherent buoyancy and their distinct yield strength. In this study we employ numerical models of mantle convection featuring both tectonic plates and compositional variation in the mantle and lithosphere. Plates and continents evolve dynamically with velocities determined by a force-balance method. Compositional variations in the deep mantle are tracked using the tracer ratio method. We examine the effect of continents on planetary surface mobility, the impact of compositional variation on plate evolution and the frequency of supercontinent assembly, including how temporal evolution is affected by the density of the chemical piles.

Trim, S. J., Heron, P. J., Stein, C., & Lowman, J. P. (2014). The feedback between surface mobility and mantle compositional heterogeneity: Implications for the Earth and other terrestrial planets. Earth and Planetary Science Letters, 405, 1-14.

ROLE OF VISCOELASTICITY IN MANTLE CONVECTION MODELS

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ABSTRACT:

A present limitation of global thermo-chemical convection models is that they assume a purely viscous or visco-plastic flow law for solid rock, i.e. elasticity is ignored. This may not be a good assumption in the cold, outer boundary layer known as the lithosphere, where elastic deformation may be important.

A method for adding elasticity to a viscous flow solver to make a visco-elastic flow solver, which involves adding advected elastic stress to the momentum equation and introducing an "effective" viscosity has been proposed (e.g. Moresi, 2002). In this study we test a grid-based version of the method in context of thermal convection in the Boussinesq approximation.

The main obstacle is that Maxwell viscoelastic rheology produces instantaneous deformation if instantaneous change of the driving forces occurs. It is not possible to model such deformation in a velocity formulated convection model, as velocity undergoes a singularity for an instantaneous deformation. For a given Rayleigh number there exists a certain critical value of the Deborah number above which it is necessary to use a thermal time step different from the one used in viscoelastic constitutive equation to avoid this numerical instability from happening. Critical Deborah numbers for various Rayleigh numbers are computed. We then propose a method to decouple the thermal and constitutive equations in a way more suitable for global studies, which is different from the method refered to earlier. The computational domain is expected to be composed of two parts: One in which elastic effects are important and where material does not move significantly within one elastic time step and one where elastic effects are not important, where material is allowed to move across many cells within one elastic time step.

Local accumulation of stress in viscoelastic simulations is observed, suggesting elasticity could e.g. trigger plasticity in realistic cases.

Stress in high viscous lithosphere by melt emplacement

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Abstract:

Transport of melt through and into the lithosphere has an essential influence on it's state, properties and evolution. Mantle circulation, physically often seen as viscous flow, acts on a long time scale compared with the rapid ascent of melt originating in the asthenosphere. Due to this large scaling contrast the short time scale transfer of melt is replaced by melt extraction and emplacement at a given depth zone above the source region in our numerical approach. Applying a full compaction formulation new findings reveal probably consequential stresses in the high viscous lithosphere.

Thermo-mechanical physics of visco-plastic flow is approximated by Finite Difference Method with markers in an Eulerian formulation in two dimensions. The equations of conservation of mass, momentum and energy are solved for a multi component and two phase system: melt and solid matrix in a full compaction formulation. The high Prandtl number approximation is applied, elasticity is neglected, and viscosity is temperature-, stress- and depth-dependent. Taking in account depletion and enrichment melting and solidification are controlled by a simplified linear binary solid solution model under consideration of extraction and emplacement of melt.

A continental rift scenario serves to define a model comprising asthenosphere and lithosphere under extensional conditions. A temperature anomaly generates deep melt intruding the lithosphere on its way up. Above a fraction limit melt extraction induces underpressure at its origin region attracting ambient melt and contracting the matrix. A melt fraction minimum develops in the initial batch. In the emplacement zone above sudden dilatation, immediate freezing, increase of enrichment and heating takes place. The dilatation of the rock matrix generates relative high stresses if it's viscosity is high. The behaviour is not intuitively comprehensible.

NUMERICAL MODELING OF DESTRUCTION OF THE NORTH CHINA CRATON BY SUBDUCTION OF THE WESTERN PACIFIC

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ABSTRACT:

The reasons for the longevity of cratons, which exists for bilions of years, are usually attributed to their water-poor chemistry, which results in a sufficiently large viscosity contrast with underlying asthenosphere to isolate craton from mantle convection. The reactivation and destruction of the North China Craton has attracted attention in recent years and is a natural laboratory to investigate the evolution of Cratons, including their lithospheric modification, and mantle recycling. The mechanisms of geodynamic processes underlying these tectonic events are still under debate though. Long-term subduction of western Pacific Plate underneath North China Craton is perhaps a potential mechanisms, which might be crucial to understand craton rejuvenation and lithosphere-asthenosphere interaction. Recent high-pressure and high-temperature experiments show that subducted oceanic crust could bring water into the lower mantle. Therefore, we here implement a 2-D petrological-thermomechanical model to investigate subduction dynamics with (de)hydration processes. A simplified water migration scheme is introduced to test the effect of water on mantle dynamics and partial melting. We find that subducting slab can weaken and thin cratonic lithosphere in two ways: (1) Large amounts of water concentrate at the subduction corner in the transition zone and form hydrated melt impinging into mantle wedge due to positive buoyancy and low viscosity. (2) Hydrated melt spreads out laterally and interacts with the craton margin, which results in lateral erosion of the cratonic lithosphere by small-scale convection and ultimately in delamination of a large block of lithosphere. Systematic simulations will be presented that give first hints at the underlying physics of these processes.