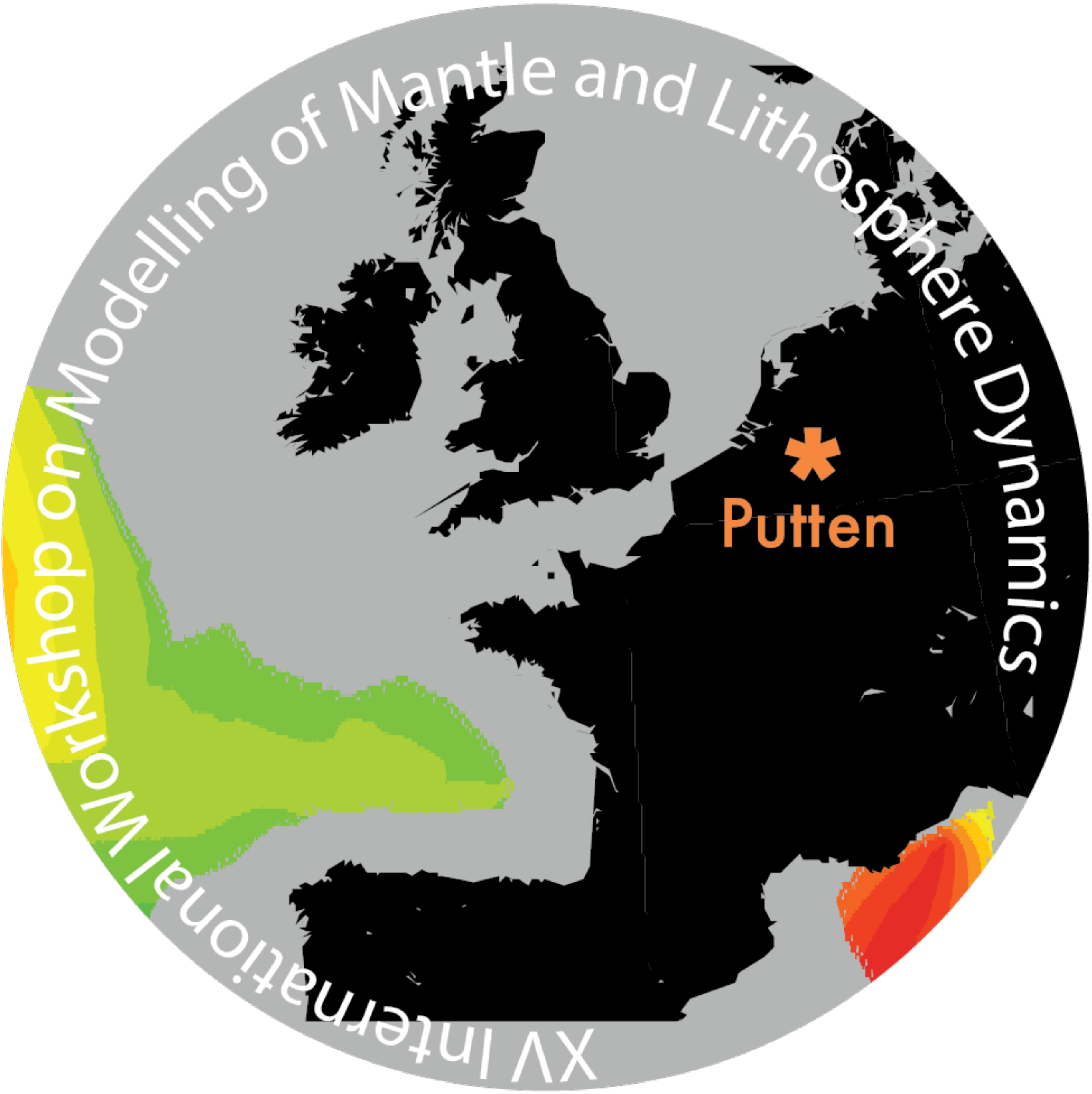

CIG COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

CEED

EGU European Geosciences Union

Universiteit Utrecht

Contents

The workshop was initiated in 1987 in Neustadt an der Weinstrasse, Germany, and has been followed by meetings every two years in various European countries. The last workshops were held in Oleron, France (2015), in Hønefoss, Norway (2013) and in Gross Doelln, Germany (2011).

The 2017 workshop will be held at a lakeside hotel near Putten, The Netherlands. The meeting is (so far) co-sponsored by the Utrecht University, the Oslo University Centre for Earth Evolution and Dynamics (CEED), and the Computational Infrastructure for Geodynamics (CIG).

This workshop is part of the EGU conference series.

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The scientific committee consists of:

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Sessions and invited speakers

Session 1: Crust/lithosphere modelling

- T. Duretz (Géosciences Rennes, France)
- C. Currie (University of Alberta, Canada)
- S. Brune (GFZ Potsdam, Germany)

Session 2: Global modelling of early and recent Earth

- P. Tackley (ETH Zurich, Switzerland)
- C. Lithgow-Bertelloni (University College London, UK)
- C. Conrad (CEED, University of Oslo, Norway)
- D. Stegman (UC San Diego, USA)

Session 3: Subduction & mantle flow modelling

- T. Becker (The University of Texas at Austin, USA)
- F. Garel (Geosciences Montpellier, France)
- M. Faccenda (University of Padua, Italy)

Session 4: Rheology

- J. Hernlund (Tokyo Institute of Technology, Japan)
- R. de Borst (The University of Sheffield, UK)

Session 5: Methodological advances

- D. May (University of Oxford, UK)
- Y. Podladchikov (University of Lausanne, Switzerland)
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Keynote abstracts

What complexity is required to understand subduction dynamics? Effects of the overriding plate, slab-slab interactions, rheology, and the subduction interface.

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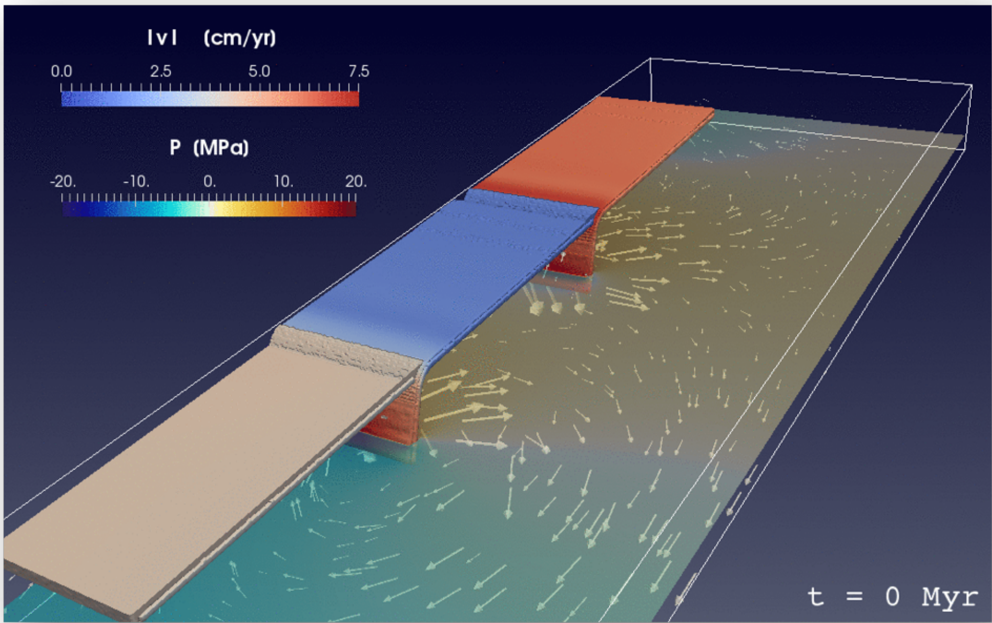
Slab pull reigns supreme in controlling plate motions, and subduction dynamics are at the root of much of intraplate deformation as well. This has motivated a huge number of studies that explore slab dynamics including trench motions, often with simplified rheologies and treating slabs in isolation. Here, I review some of the recent efforts to move beyond those simplifications. Rock rheology is a usual suspect for uncertainty. Indeed, if a power-law rheology is considered for the mantle, slab motions are lubricated by a shear layer, and trench rollback is dramatically reduced compared to the more often considered Newtonian case. Considering the rheological behavior of the lithosphere, slab dips appear controlled by overriding plate thickness. This indicates effectively plastic behavior and a minor role for slab bending. As a consequence, the balance of viscous dissipation may be shifted such that the viscosity of the deep plate boundary shear zone matters. Regardless of slabs' resistance to shear and interface effects, pressure differences in the mantle will also modify slab morphologies and trajectories, and double slab configurations can be used to explore the range of interactions and elucidate regional tectonics [1]. All of these effects may be relevant for understanding changes in plate tectonic configurations throughout the Cenozoic, where a consistent forward model remains elusive.

[1] Holt et al., Geophys. J. Int., 209, 250-265, 2017.



An example of double slab subduction [1]

Continental rifting: from plate boundary processes to global geodynamics

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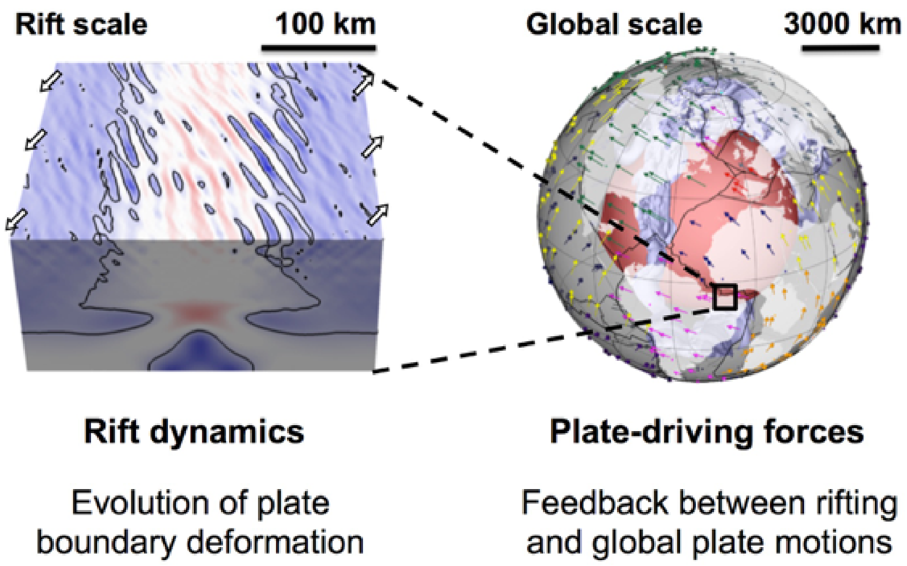
The processes that affect continental rifting involve a large range of scales: from individual faults and shear zones over plate boundary dynamics to global-scale plate motions. Combining numerical modeling with observations from presently active rifts and passive margins, we investigate the structural evolution of continental rifts, their feedback on plate movements and the role of rifting for paleoclimate.

Crustal rheology plays a key role in shaping continental rifts: if crust and mantle are strongly coupled, continental extension produces large faults that border a narrow rift, while crust-mantle decoupling produces wide rifts. Here we first focus on a >300 km wide rift segment in the Turkana depression of the East African Rift, which locates in-between the narrow Ethiopian and Kenyan Rifts. 3D numerical and analog rift models reveal that the seemingly wide rift characteristics of the Turkana depression are controlled by lithospheric heterogeneities inherited from a Mesozoic phase of rifting instead of crust-mantle decoupling.

In order to connect the plate boundary scale to the global scale processes we conduct a global analysis of rift velocity and rift length history for the last 200 million years that combines plate tectonic reconstructions with data from the geological rift record. Analysing regional rift kinematics we find that many successful rifts start with a slow phase of extension followed by rapid acceleration that introduces a fast rift phase prior to continental breakup. We reproduce the rapid transition from slow to fast extension using analytical and numerical modelling with constant force boundary conditions. Our results demonstrate that abrupt accelerations of entire plates during continental rifting are controlled by a rift-intrinsic strength-velocity feedback.

Finally, we connect the global length of rift systems to paleo-atmospheric CO_2 concentrations, which is motivated by a recently documented link between rift-related faulting and CO_2 degassing. We deduce the history of global rift length for the last 200 Myr and estimate global rift-related CO_2 degassing rates assuming that the release of CO_2 scales with the faulted surface extent of rifts and therefore rift length. We find that the timing of enhanced CO_2 degassing from continental rifts correlates with two well-known periods of elevated atmospheric CO_2 in the Mesozoic and Cenozoic as evidenced by multiple independent proxy indicators. We therefore suggest that rift-related degassing constitutes a key component of the deep carbon cycle.



Conceptual figure illustrating the relevant range of scales for plate boundary processes and global geodynamics during continental rifting.

Misshapen Earth: inferring dynamic topography from bathymetry and plate motions

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Earths surface is deflected vertically by stresses associated with convective mantle flow, across wavelengths ranging from hundreds to tens of thousands of km. Although dynamic topography is important for both sea level change and continental uplift and subsidence, it cannot be easily observed because it is obscured by isostatic topography that is several times larger. As a result, both the amplitude and the time-dependence of long-wavelength dynamic topography remain controversial. Here we develop new constraints on the longest wavelength components of dynamic topography (tens of thousands of km) using two observations that have not been previously utilized as constraints. First, we examine asymmetries in seafloor bathymetry across the Mid-Atlantic Ridge (MAR) and the East Pacific Rise (EPR) and we find that both ridges are tilted toward South America, as predicted by global mantle flow models. However, we find that this asymmetry is best explained by long-wavelength dynamic topography of only ∼500 m amplitude, or about half of what is predicted by global mantle flow models. Second, we demonstrate a tight relationship between the spatial pattern of long-wavelength dynamic topography and plate motions. This coupling allows us to develop a model of long-wavelength dynamic topography back through the Mesozoic using plate tectonic reconstructions. Continental motions over this modeled dynamic topography predict patterns of continental uplift and subsidence that we can relate to specific geological observations. Furthermore, we show that dispersal of the Pangean supercontinent away from stable upwelling beneath Africa may have exposed the seafloor to an increasingly larger area of growing positive dynamic topography during the Mesozoic. This net uplift of the seafloor caused ∼60 m of sea level rise during the Triassic and Jurassic, which is a significant component of the estimated ∼200 m of sea level change during the Phanerozoic. Although our new model of time-dependent dynamic topography helps to explain several geologic observations, its link to time-dependent global mantle flow models raises new questions that may require a re-evaluation of such models.

Numerical models of flat-slab subduction: Farallon plate dynamics and the Laramide orogeny

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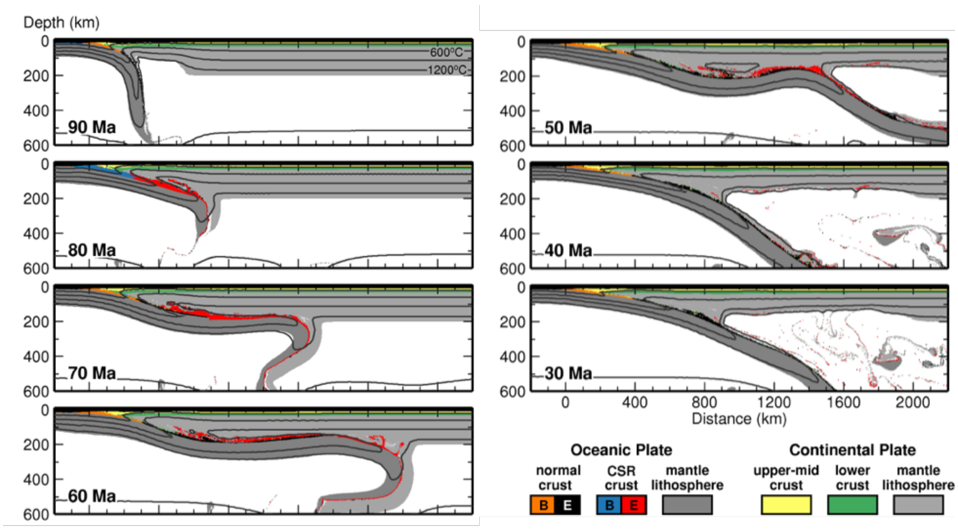
The Laramide orogeny is an enigmatic event that affected the western United States (US) from the Late Cretaceous to early Oligocene. It is marked by a migration of crustal deformation and volcanism that swept ∼1500 km northeastward from ∼90 to ∼55 Ma and then southwestward from ∼55 to ∼30 Ma [1]. This pattern is interpreted to reflect a change in the Farallon Plate subduction trajectory, from a relatively steep angle to subhorizontal (i.e., flat-slab), followed by resteepening.

In this study, geodynamic models are used to assess the development and demise of flat-slab subduction. Models use the two-dimensional thermal-mechanical code SOPALE [2] and include lithosphere properties and horizontal plate velocities consistent with those of the western US from 90 to 30 Ma. Within the model domain, the oceanic plate evolves dynamically in response to imposed plate convergence and internal buoyancy forces. Models examine how the subduction geometry is affected by (1) oceanic plate density, (2) upper plate motion, and (3) upper plate structure.

The onset of the Laramide orogeny coincided with westward acceleration of North America and subduction of the Conjugate Shatsky Rise (CSR) oceanic plateau. Models show that both factors are required to generate flat-slab subduction, as the Farallon plate was old, and therefore cold and dense [3]. To deflect the slab to a subhorizontal trajectory, the CSR crust must have remained metastable (i.e., eclogitization was either delayed or proceeded slowly), such that it was buoyant for 20-30 Ma after subduction. The upper plate thickness and rheology primarily control the depth of the flat slab, with a deeper slab below a thick, strong (dry) upper plate.

Once established, the flat-slab underplates the continent at ∼60 km/Ma, even after the CSR has passed through the trench (Figure). The main control on termination of flat-slab subduction is metamorphic densification of the CSR crust, with slab roll-back initiated when the CSR becomes more dense than mantle (55 Ma in our preferred model); the rate of densification has only a minor effect on the timing. Slab steepening is aided by (1) a decrease in plate convergence and continental westward motion at 50 Ma, and (2) rheological weakening of the upper plate, perhaps due to hydration from the underlying flat slab. These allow the flat-slab to decouple from the continent, resulting in continental heating (magmatism?) and surface uplift as the slab rolls back (Figure).

[1] Copeland et al., Geology, 45, p223-226, 2017.
[2] Fullsack, Geophysical Journal International, 120, p1-23, 1995.
[3] Liu & Currie, Tectonophysics, 666, p33-47, 2016.



Evolution of a numerical model showing the development and removal of flat-slab subduction below the western United States from the Late Cretaceous to early Oligocene [1].

Plasticity and fracture in porous media: uniqueness, mesh dependency, and fluid transport

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Abstract

The mechanical behaviour of geomaterials (soils, rocks) is enormously complex. It involves a strong pressure dependence, a coupling between shear loadings and the volumtric response, non-linearity from almost the onset of loading, as well as time dependence, to mention just a few observations that severely complicate the accurate and robust modelling of this class of materials. And these are just some complexities from the mechanical side. Soils and rocks nearly always contain fluids, and the interaction between fluids and the solid material gives rise to additional complications, and sometimes unexpected physical phenomena. But also other diffusion phenomena can play a role, such as thermal heating, for instance during earthquake loadings.

The constitutive modelling of the mechanical behaviour is therefore a task that is far from trivial. Often, the framework of plasticity theory is used. However, the characteristics of soils and rocks almost inevitably make it necessary to include strain softening and non-associated plastic flow, which typically render the initial value problem non-unique at a generic stage in the loading process. While techniques have been developed in the literature to deal with such bifurcation points, practice may be difficult, since the discretisation, e.g. due to finite element or finite difference techniques, can artificially enlarge the number of alternative equilibrium stages, which can lead to severe convergence difficulties.

However, more problematic is the fact that strain softening and non-associated plasticity can lead to loss of ellipticity. The set of differential equations that govern the initial value problem become (locally) hyperbolic, which means that a propagating discontinuity is part of the solution space. This implies that in the limiting case of an infinitely fine discretisation, a failure zone of zero thickness will be obtained. Classical plasticity or damage models furnish an energy dissipation per unit area, and since the failure area collapses to a zero-thickness interface, the anomaly of failure without energy dissipation results.

This presentation will first focus on the possibility that non-uniqueness occurs as a consequence of strain softening and/or non-associated plasticity. Examples will be shown, in particular that problems can be aggrevated for finer discretisations. A perfect solution to this problem does not exist, but some possible remedies will be discussed. Simulations will be shown for a number of boundary value problems, including a numerical bifurcation analysis of a biaxial test. Next, the discussion will focus on ellipticity. The consequences will be shown at the hand of a simple example. Again, a range of possible remedies will be discussed, including discrete and continuum approaches.

The last part of the presentation will be devoted to fracture and shearbanding in fluid-saturated porous media. A subgrid scale model will be discussed that can capture convective mass transport and storage in faults, either existing or propagating, and methods to incorporate this model in discretisation techniques such as the finite element method, will be discussed. Since it is necessary for a fluid-saturated porous medium to model the pressure as an independent variable, the issue arises how to proceed at the fault. Different options exist, and the physical consequences will be discussed. Examples will be shown for fracture and shear band propagation, under quasi-static as well as under dynamic loading conditions.

Modeling the deformation of heterogeneous lithosphere: insights into rifting dynamics

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Geological and geophysical field studies document spatial lithological variations throughout the continental lithosphere. It is known form rock deformation experiments that different lithologies generally exhibit different mechanical resistance. Tectonic processes such as continental rifting, hence, act within a mechanically heterogeneous lithosphere. Most tectonic models of lithospheric rift formation have so far not focused on the impact of mechanical heterogeneities, especially on scales smaller than one kilometer, on the formation of passive margins.

Based on simple numerical simulations, we first investigate the role of mechanical layering for the extension of a purely viscous medium. This type of mechanical heterogeneity can either lead to the development of distributed pinch-and-swell structure or the generation of low-angle anastomosing detachments, controlled by the flow law of the weak layers.

Based on these results, we have developed idealized models of lithospheric extension that account for mechanical heterogeneities on the kilometre scale. These two-dimensional thermo-mechanical models employ a visco-elasto-plastic rheology but do not include the effects of material softening (e.g. plastic strain softening or grain size reduction). The use of very high spatial resolution (50 to 200 meters) was necessary for capturing deformation structures resulting from km-scale heterogeneities with the numerical simulations.

A first series of simulations explore the impact of km-scale mechanical stratification on lithospheric extension. Our results show that extension leads to the progressive boudinage of the stronger lithospheric levels. Ultimately, lateral disconnection of the locally pinched strong levels induces the mechanical connection between weaker levels. This triggers the development of a network of anastomosing low-angle detachments as well as the lateral extraction of the strong levels. Polyphase rifting and asymmetric passive margins here develop solely as a consequence of the extension of a spatially mechanical heterogeneous lithosphere.

Secondly we have designed a series of simulations that initially include heterogeneities with a finite width (elliptical heterogeneities). These models can thus better account for the morphology of some geological heterogeneities observed in the field (pluton or laccolith-type geometries). Although these model leads to more complex passive margin structuration, they rely on similar processes as the stratified models (local boudinage, network of anastomosed shear zones and extraction of strong levels) and further emphasize the impact of mechanical heterogeneities on rifting dynamics.

The presented models of a mechanically heterogeneous lithosphere are supported by a variety of structural and petrological field observations, especially from the remnants of the Alpine Tethys margins outcropping in the Eastern Alps (E Switzerland and N Italy) and the Southern Alps (N Italy).

Convergent margin dynamics and structure from coupled geodynamic and seismological modelling

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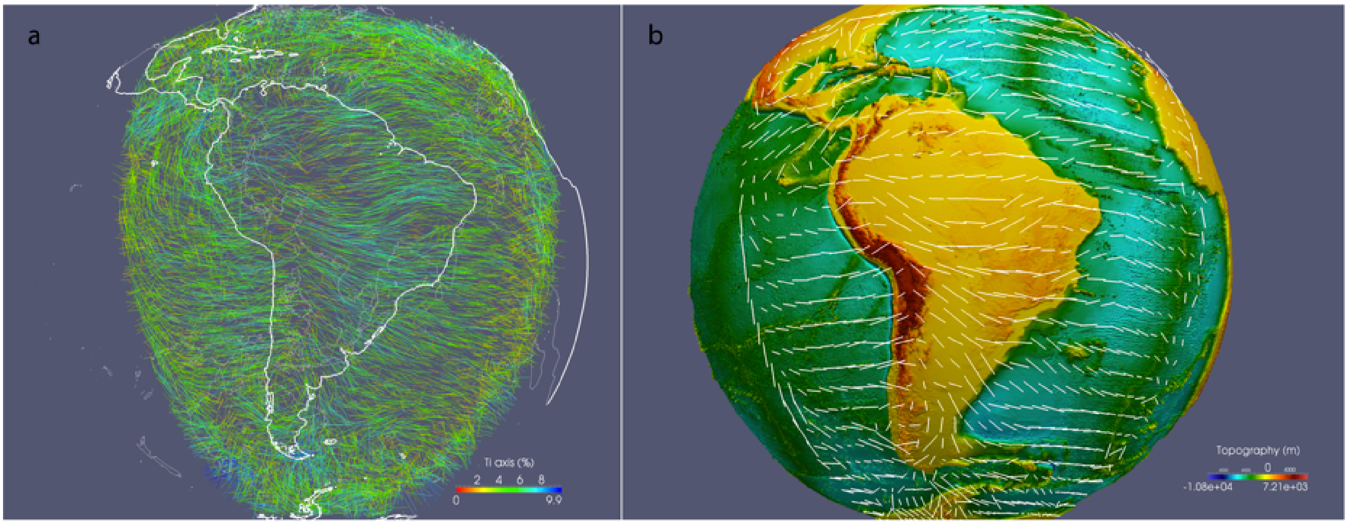
The present-day structure of subduction settings is mainly determined by means of seismological methods. The interpretation of seismological data (e.g., isotropic and anisotropic velocity anomalies) is however non-unique, as different processes occurring simultaneously at subduction zones can be invoked to explain the observations. A further complication arises when regional tomographic seismic models ignore seismic anisotropy, in which case apparent seismic anomalies due to non-uniform sampling of anisotropic areas will appear.

In order to decrease the uncertainties related to the interpretation of seismological observations, geodynamic modelling can be exploited to reproduce the micro and macro scale dynamics and structure of subduction settings, yielding a valuable first-order approximation of the rock isotropic and anisotropic elastic properties. The model output can be subsequently tested against observations by performing seismological synthetics (e.g., SKS splitting, travel-time tomography, receiver functions, azimuthal and radial anisotropy) (Figure). When the misfit between the modelled and measured seismic parameters is low, the geodynamic model likely provides a good approximation of the recent dynamics and present-day structure of the subduction setting. Such a model can then be used to give a more robust and geodynamically constrained interpretation of the observables and/or further improve the seismological model by providing a-priori information for subsequent inversions.

The methodology is still in its infancy, but we envisage that future developments could substantially improve seismological models and, overall, our understanding of complex subduction settings.



Example of upper mantle elastic anisotropy (left) and resulting SKS splitting (right) calculated for a flow model of the South America subduction zone (from Hu et al., 2017, EPSL).

Thermo-mechanical modelling of subduction zones: slab deformation in the upper mantle and slab age evolution

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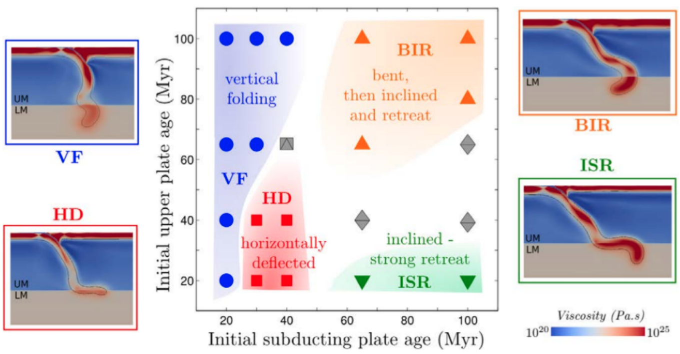
Modelling Earth's dynamics calls for a simplification of a complex, and often partly unknown, natural system. This simplified representation is necessary to solve the physical equations and to understand simulations obtained when varying the many input parameters. Building a model for mantle and plate dynamics requires "cunning" choices of simplification for geometry, rheology, boundary conditions, thermodynamics, etc. The approximations can be guided by which data the model will be evaluated against (e.g. seismic tomography, paleomagnetic ages, plate surface deformation).

Here, we first investigate how a 2D thermo-mechanical model - using the finite-element, adaptative-mesh code Fluidity - can reproduce the variety of seismically observed slab morphologies (e.g. penetrating in or stagnating above the lower mantle). We discuss how the initial downgoing and overriding plate ages controls the slab's ability to induce trench motion, and the evolution of slab strength during sinking. We build a regime diagram that distinguishes four subduction styles: (1) a "vertical folding" mode with stationary trench; (2) slabs that are "horizontally deflected" along the 660-km deep viscosity jump; (3) an inclined slab morphology, resulting from strong trench retreat; and (4) a two-stage mode, displaying bent (rolled-over) slabs at the end of upper-mantle descent, that subsequently unbend and achieve inclined morphologies, with late trench retreat.

Second, we briefly discuss the elusive correlation between slab age (from the thermal structure of the subducting plate at the trench) and slab morphology. Slab age spans a wide range, from less than 10 Myr in Central and South America to 150 Myr in the Marianas. Our thermo-mechanical modelling predicts the time-evolution of plate thermal ages, and show how initially young subducting plates can rapidly age at the surface because of a slow sinking velocity. As a consequence, different slab morphologies can exhibit similar ages at the trench provided that subduction history is different. We discuss how such models hint that we have to consider the full history of subduction zones in order to understand their present-day geometry.

[1] Garel et al., Geochemistry, Geophysics, Geosystems, 15, 2014.
[2] Goes et al., Geosphere, 13, p644-664, 2017.



In thermo-mechanical models of subduction zones, 4 modes of slab deformation in the upper mantle occur as a function of initial plates ages [2].

What do we really know about the rheology of the lower mantle?

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Viscosity jumps/hills at ∼1,000 km or greater depths, Ostwald ripening, grain-size sensitive vs. grain-size insensitive creep mechanisms, an extremely weak post-perovskite phase, inter-connectivity of weak periclase in a composite with strong bridgmanite, sensitivity of ferropericlase viscosity to spin transitions in iron, strong composition-dependence of rock viscosity, muted geoid signature due to dynamic topography of the core-mantle boundary beneath subducting slabs, firm mantle plumesthese are just some of the many issues involving lower mantle rheology that have been raised in recent years, all of which suggest that the rheology of the Earths lower mantle is far more complicated than we realized. Rock rheology exerts perhaps the strongest control on mantle convection, mixing, circulation, and mechanical coupling between deep flows and tectonics at the surface, and these new revelations justifiably raise serious doubts about our understanding of the way the lower mantle behaves. For too many years we have been treating the lower mantle as if it were a simple linear Newtonian viscous fluid, but now we have to confront evidence that deep flows may be subject to shear weakening and other complexities that were previously thought to be limited to the lithosphere. Is flow in the deep mantle characterized by strain localization along narrow shear zones? Do large compositionally distinct domains control viscosity in a way that organizes the pattern of deep mantle convection? What kind of micro-scale processes control the rheological behavior of a rock comprised of strong and weak phases at geophysically realistic strain-rates? These are all questions that the geodynamics community is well-prepared to confront, and the answers might finally settle some of the longstanding paradoxes in the Earth sciences, such as the existence of isotopic reservoirs formed prior to the Moon-forming event in spite of whole mantle convective mixing. The purpose of this talk will be to open up the dialogue for a discussion on these issues, and a call for the community to articulate grand challenge problems for a new generation of geodynamicists.

Thermochemical convection in a compositionally stratified mantle: an intermodel comparison

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One of the most sustained challenges in computational mantle geodynamics is determining how to track sharp interfaces that would be expected due to subduction of compositionally layered lithosphere and crust, during entrainment of material from the deep mantle in an upwelling plume, or to investigate computationally the process of mixing through Earth's history. The computational challenge arises from the need to accurately resolve the composition, temperature, and physical properties while neither allowing the computation to become unstable nor making the problem computationally untractable. Mathematical models of persistent compositional interfaces in the Earth's mantle may be inherently unstable, at least in some regions of the parameter space relevant to the mantle; computing approximations to solutions of such problems presents severe challenges, even to state-of-the-art numerical methods. To address this challenge, many widely- used numerical algorithms for modeling the interface between distinct compositions smear the interface at the boundary between compositions, in order to stabilize the algorithm. In this talk, I will discuss the problem and present the results of a comparison of four methods for maintaining high-resolution and sharp computational boundaries in computations of these types of problems: two new approaches, a discontinuous Galerkin method with a bound preserving limiter and a Volume-of-Fluid interface tracking algorithm, and two widely-used approaches: a high-order accurate finite element advection algorithm with entropy viscosity, and a particle method. We investigate the performance of these four algorithms on problems including computing an approximation to the solution of an initially compositionally stratified fluid with buoyancy numbers that vary from no stratification to stably stratified flow. I will discuss the advantages and drawbacks of each approach for problems relevant to the Earth's mantle.

The role of thermodynamics in the thermal evolution of the Earth

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The thermal evolution of our planet has controlled Earths geological and chemical history, from its early molten stage to the emergence of plate tectonics, from a deoxygenated world to the present habitable conditions. However, the evolution from its initial state to today remains mysterious, hidden in a scant geological, petrological and sedimentological record on continents. The modern consensus infers that the planets interior was much hotter 4 Ga. We know that material properties and their temperature dependence control that evolution. However, to date we have ignored equally crucial physics. In a hotter mantle, the mineralogy and hence the physical properties would be different. I focus on the role of mantle thermodynamics on Earths thermal evolution and the connection to key events in Earths history. As an aside I also examine the role of variations in plate motions on the subducted carbon cycle and Earths carbonate cover in the last 100 Ma.

Computational methods for two phase flow

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Subduction zones (SZs) are the crossroads of plate tectonics, where volatile-rich sediments, basalts, and lithosphere exchange mass and energy with the shallow and deep mantle. Solids descend while liquids ascend; temperatures vary by 800K; melting occurs by hydrous flux and decompression; liquids range from hydrous to silicic; energy is transported in every direction. This physical and chemical complexity means that our understanding of SZ magmatism lags behind other tectonic settings.

Progress in understanding such multi-phase, multi-component systems requires an accurate and efficient PDE modelling framework that consistently couples essential physics and allows for hypothesis testing and interpretation of observations. Developing such a framework for geodynamic processes presents a number of new technical challenges which have not been addressed by the analysis, and or progress, associated with modelling single phase, lithospheric dynamics. Specific issues unique to the two phase problem are (but not limited to): devising formulations for the conservation of mass and momentum (mechanics) which permit accurate representations of the velocity and pressure for both phases, and which also maintain their accuracy in regions of zero and or nonzero porosity; accurate methods for transport processes which are conservative and ensure physical bounds of the advected quantity are strictly preserved.

In this presentation I'll discuss work aiming to address these technical issues. With respect to the mechanics, I'll show that with a particular choice of the pressure variable, together with a suitable regularization, high order and high accuracy results can be obtained via the finite element method applied over an unstructured meshes for both the velocity and pressure fields in each phase. Efficient solvers for this discrete formulation is achieved via a novel multilevel auxiliary space preconditioner. An accurate, bound preserving discretization of the hyperbolic system associated with the porosity / chemistry is achieved via a finite volume inspired conservative semi-Lagrangian method.

The above techniques are brought together in a new framework being developed coined SubFUSc. The essential features of the framework required to enable multi-physics applications, together with representative demonstrators and examples of two phase flow will also be presented.

Resolving ductile strain localization and porous fluid channeling due to thermo- and hydro- mechanical coupling

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Plate tectonics is characterized by strain and fluid/melt extraction localized at the plate boundaries. Zooming into active plate boundaries reveals spatial and temporal intermittency of deformation and fluid/melt extraction.

Thermo-mechanical coupling often is reduced to advection of heat and temperature dependence of density and viscosity. Since viscous rheology does not lead to strain localization, more complex rheologies are employed to insure robust and sustainable strain localization. However, even linear viscous rheology may cause strain localization into shear bands if complete thermo-mechanical coupling, respecting energy conservation and conversion of mechanical work into heat, would be included into modeling.

Viscous matrix containing porous fluid/melts is either assumed to be in the lithostatic state or is modelled using incomplete coupling with dynamics of the porous phase. Weak coupling of two elliptic operators (Stokes and Darcian) does not lead to spontaneous strain and fluid flow localization. Dependence of shear viscosity on porosity may result in strain localization but would not cause spontaneous fluid/melt channeling. Full hydro-mechanical coupling and decompaction weakening are required for self-consistent modeling of channelized fluid/melt extraction [1]. Decompaction weakening is needed to avoid building of unrealistically large fluid overpressures and, thus, to account for grain scale hydro-fracturing.

Parametrization of small scale processes require its validation by fully resolved models. While numerous benchmarks are available for incompletely coupled models, they are non-existing, to the best of our knowledge, for the fully coupled thermo- and hydro- mechanical models in the parameters range allowing for spontatenous strain localization and porous fluid/melt channeling. We aim at establishing bechmarks cases for both thremo- and hydro-mechanical fully coupled models.

To resolve the scales, we employ GPU accelerators running in parallel utilizing MPI for data exchange. We use iterative matrix-free solver for 3D and 2D and crosscheck the results to direct sparse matrix solvers in 2D. Performance of a solver is normally measured by the number of billions of floating point operations performed per second, Gfs, and comparing it to the hardware peak performance. Efficiency is ideal if Gfs scales linearly with number of unknowns, N, and the proportionality constant ¡¡N. Our iterative solver is memory bound, so its performance is measured by number billions of bytes read/written per second, Gbs. We report near to harware limit performance and close to ideal scaling with number of unknowns for both 2D and 3D and both hydro- and thermo-mecanical coupling.

[1] Samuel Omlin, Ludovic Räss, Yury Y. Podladchikov, 2017, Simulation of three-dimensional viscoelastic deformation coupled to porous fluid flow, Tectonophysics, http://dx.doi.org/10.1016/j.tecto.2017.08.012.

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[1] *long title*, author 1, author 2, journal, vol, year

The key influence of melting on the thermo-chemical evolution of planetary mantles: from a magma ocean to the present day

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Melting has always played a key role in Earth evolution. Solidification of a magma ocean may have left the mantle compositionally stratified and may have continued as a long-lived basal magma ocean (BMO). Ongoing upper mantle/transition zone melting may have caused internal differentiation, resulting in dense enriched products that sink. Throughout Earth's history melting has produced crust, much of which was recycled into the interior, possibly segregating above the core-mantle boundary, joining other enriched products to produce a Basal Melange (BAM).

We can now simulate mantle evolution from a 100% molten state (magma ocean) to the present day. Following the 1-D magma ocean modelling approach of Y. Abe, dynamics occuring in regions that are mostly solid are fully resolved, while turbulent convection in regions that are mostly molten is parameterised using an effective diffusivity. A key finding from our magma ocean models is that overturn of the mostly-solid region occurs before the mantle becomes completely crystallized, thereby avoiding extreme compositional stratification that would result from pure fractional crystallization.

The early tectonic mode of Earth, including when modern-day plate tectonics started, is a topic of great debate. We have shown that continental [1] or oceanic [2] crust can greatly facilitate plate tectonics. Intrusive magmatism is more voluminous than extrusive magmatism. Thus, we have systematically investigated the effect of plutonism, in conjunction with eruptive volcanism [3,4]. In addition to the usual stagnant-lid, episodic, and mobile-lid regimes we observe and characterise a new additional regime called plutonic-squishy lid, which occurs at high intrusion efficiencies. The plutonic-squishy-lid regime may be applicable to the Archean Earthand Venus.

[1] Rolf, T., and Tackley, P. J.: Focussing of stress by continents in 3D spherical mantle convection with self-consistent plate tectonics, Geophys. Res. Lett., Vol. 38, L18301, doi:10.1029/2011GL048677, 2011.

[2] Lourenco, D., Rozel, A., and Tackley, P. J.: Melting and crustal production helps plate tectonics on Earth-like planets, Earth Planet. Sci. Lett., Vol. 439, pp. 18-28, 2016.

[3] Rozel, A. B., Golabek, G. J., Jain, C., Tackley, P. J., and Gerya, T. V.: Continental crust formation on early Earth controlled by intrusive magmatism, Nature doi:10.1038/nature22042, 2017.

[4] Lourenco, D., Rozel, A., Ballmer, M. D., and Tackley, P. J.: Plutonic-squishy lid: a new global tectonic regime generated by intrusive magmatism on Earth-like planets, Geochem. Geophys. Geosys., submitted.

Poster abstracts

Subduction zone modeling: Upper plate deformation in response to increasing trench retreat velocity

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The Mediterranean shows complex subduction systems with strongly segmented slabs. In the Aegean subduction zone, trench retreat started around 30 Ma ago and accelerated from 1cm/yr to 3 cm/yr in the last 15 Ma, which was likely related to slab tearing and subsequent narrowing. This study aims at quantifying the effect of this increase in the rate of trench retreat on deformation patterns in the upper plate. We present 2D numerical results obtained using the code Fluidity. The code simulates viscous fluids with an adaptive mesh and allows a real upper plate in the subduction setup. The model in this study simulates subduction of oceanic crust beneath a rheologically continental upper plate. The trench retreat rate is varied artificially by imposing lithospheric blocks of varying density contrasts in the subducting plate. We find that the intensity and the distribution of deformation in the upper plate increases with increasing rates of trench retreat. We show strain rate variation with distance from the trench and with varying rates of trench retreat.

Neural network emulators for geodynamics: for uncertainties, sensitivity and the impatient

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- Jeannot Trampert
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Mantle convection simulations have two frustrating properties: they are highly non-linear and they are very computationally expensive. This limits our ability to study mantle dynamics within a statistical framework. The effects of parameters, particularly when they interact with each other, are neither linear nor particularly predictable. However, we cannot run enough simulations to find the sensitivity of the system by using a sampling based approach. It also means that if we do not realise that we have made a poor choice of parameters for a particular study until a lot of computer time has been sunk into the problem!

Neural networks are a sort of machine learning algorithm. They can be taught to emulate highly non-linear functions, such as those encapsulated in a geodynamic code. Using a relatively small training set, we find that we can train a neural network to emulate the mantle convection code StagYY. The networks use the input parameters to StagYY to make inferences about expected mantle features, such as 1D density profile after a set time length of convective evolution.

The computationally expensive part of this process is creating a database of training simulations. Once the training database has been produced, network training is rapid (minutes) and evaluation takes a fraction of a second. This means that we can rapidly explore a large parameter space by changing the inputs to the network. We can then get an idea about the sensitivity of a simulation observation to any parameter combination. We can find regions of model space that seem worth exploring with a full convection simulation and we can hopefully avoid using up our computer allocation running useless simulations!

Numerical simulations of melting-crystallisation processes at the boundaries between magma oceans and solid mantle

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The idea that the Earth had a global magma ocean, mostly created by impacts, core formation, radiogenic and tidal heating, is well accepted nowadays. When this ocean starts to crystallise, if the melt is denser than the solid, a basal magma ocean is created below the solid part (e.g. [1]).

The dynamics and evolution of the solid mantle is then controlled by the influence of these two magma oceans, above and below it. Near the boundaries, the vertical flow in the solid creates a topography. If this topography is destroyed by melting/crystallisation processes in a time scale much shorter than the time needed to adjust the topography by viscous relaxation, then matter can cross the boundary. In this case, the boundary is said to be permeable. On the other hand, if this time is longer, matter cannot cross and the boundary is said impermeable.

This permeability is set by a non-dimensional phase change number, ϕ, introduced by Deguen [2]. This ϕ is the ratio of the two timescales mentioned, and sets a permeable boundary when $\phi \ll 1$, and an impermeable one when $\phi \gg 1$.

We use the convection code StagYY [3], to study the impact of magma oceans on the dynamics of the solid mantle. We use a 2D spherical annulus geometry to compute the convection of the solid part. Our results show different convection behaviours depending on the type of boundary chosen. For the permeable case, we investigate the thermo-compositional evolution of the solid domain, explicitly taking into account the compositional evolution of the magma oceans.

[1] Labrosse et al., p123-142, in The Early Earth: Accretion and Differentiation, AGU monograph Ser. 212, 2015.
[2] Deguen, Journal of Earth Science, 24, p669-682, 2013.
[3] Tackley, Phys. Earth Planet. Inter., 171, p7-18, 2008.

Dependence of slab buoyancy on composition and convergence rate: insights from kinematic modelling

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The peeling off of the lithospheric mantle from the crust and its detachment and sinking into the asthernospheric mantle is known as delamination. Lithospheric delamination is a geodynamic mechanism often invoked for the evolution of collision zones, yet there are still open questions about the conditions under which the mechanism operates. The general condition that was thought to lead to delamination is that the lithosphere must be denser than the asthenosphere ($\rho_{lith} > \rho_{asth}$) so as it sinks downwards, the buoyant asthenosphere makes contact with the crust, replacing the denser lithosphere. The densities adopted by previous studies have been considered to be temperature dependent only. We adopt here a mineral physics viewpoint, where the density depends on temperature, pressure, and composition, such that the density of the lithospheric mantle can be lower than that of the underlying asthenosphere ($\rho_{lith} < \rho_{asth}$), posing a serious problem for the initiation of the delamination process. We calculate the density of the upper mantle for given temperature and pressure conditions by computing stable mineral assemblages, using Gibbs free energy minimisation algorithm, for different types of lithosphere (Archon, Tecton, and Proton) [1,2]. The mantle mineral assemblages are calculated from major oxides composition based on mantle xenoliths/garnet peridotites in the CaO-FeO-MgO-Al2O3-SiO2 (CFMAS) framework. At a certain convergence rate, plate under-thrusting develops with a downward velocity that is fast enough to prevail on thermal re-equilibration with the surrounding asthenosphere. This facilitates the lithospheric mantle to become heavier due to pressure effect which dominates over the temperature effect. The subducted lithospheric mantle, therefore, acquires negative buoyancy, such that its density is higher than the asthenosphere, and causes it to detach from the crust and sink into the asthenosphere. We present a parametric study on the relationship between slab buoyancy and convergence rate as well as lithospheric mantle composition using a simple 2D kinematic model with thermal advection and diffusion.

[1] Afonso et al., Geochemistry, Geophysics, Geosystems, 9(5), 2008.
[2] Connolly, Earth Planet. Sci. Lett., 236, p524541, 2008.

Evolution of terrestrial planets from molten to solid

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Rocky planets are thought to evolve from an initially molten state due to the heat generated by accretion, core formation, short-lived radioisotopes, and late-stage impacts. Modelling high-melt fraction phenomena, relevant to the earliest phase of magma ocean cooling, necessitates parameterisations to capture the dynamics of turbulent flow that are otherwise unresolvable in numerical models. We present a new interior evolution model that, in a single formulation, captures both solid and melt dynamics and hence charts the complete cooling trajectory of a planetary mantle. Furthermore, it interfaces with equations of state that describe the thermophysical properties of silicate melt and solid for the pressure-temperature (P-T) range of the Earth's mantle. In recent work, we additionally enable the interior to evolve contemporaneously with a growing atmosphere enriched in H_2O and CO_2 as a consequence of degassing from the magma ocean. Our modelling advancements provide a comprehensive and versatile modelling framework for probing the far-reaching consequences of magma ocean cooling and crystallisation for Earth and other rocky planets.

The interior evolution model accounts for heat transfer by conduction, convection, latent heat, and gravitational separation. It uses the finite volume method to ensure energy conservation at each time-step and accesses advanced time integration algorithms by interfacing with PETSc. This ensures it accurately and efficiently computes the dynamics throughout the magma ocean. PETSc also enables our code to support quad-precision calculations which are necessary for the numerically challenging scenario in which crystals first form in the centre of a magma ocean. The thermodynamics of mantle melting are represented using a pseudo-one-component model, which retains the simplicity of a standard one-component model while introducing a finite temperature interval for melting (important for multi-component systems).

We demonstrate the power of our integrated dynamic and EOS model by exploring two crystallisation scenarios for Earth that are dictated by the coincidence of the liquid adiabat and melting curve. Experiments on melting of primitive chondrite composition predict that crystallisation occurs from the "bottom-up", whereas molecular dynamics simulations of $MgSiO_3$ perovskite suggest crystallisation occurs from the "middle-out". In each case, we evaluate the lifetime of the magma ocean for a selection of atmospheric growth scenarios using our model.

Variable melt production rate of the Kerguelen hotspot due to long-term plume-ridge interaction

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The Kerguelen mantle plume in the southern Indian Ocean has produced enormous amounts of magma for at least 120 million years, presently distributed over a vast area between India, Australia and Antarctica. Age determinations and volume estimates in previous studies revealed unusually long periods of high magma generation and a rather variable melt production rate - inconsistent with characteristics typically associated with plumes.

To explore the geodynamic history of the Kerguelen hotspot and, more specifically, the origin of the variable melt production rate, we set up a 3D regional viscous flow model with the mantle convection code ASPECT. Our model combines complex time-dependent boundary conditions: reconstructed plate boundaries, plate motions, a lithosphere thickness distribution and large-scale global mantle flow, and thus explicitly simulates the surrounding conditions of the Kerguelen plume.

We find that the melt production rate of the plume is mainly influenced by its distance to mid-ocean ridges, as well as the directions and velocities of nearby plate motions. Since all these parameters, in short plume-ridge interaction, change considerably over time, the variable melt production rate is rather the direct consequence of a very dynamic long-term plume history than an indication of uncommon plume properties. The general resemblance of our results to observed topographic structures, identified ages, crustal thickness estimates and calculated melt production rates suggests that our model simulates a plausible scenario of the Kerguelen hotspot history.

Numerical experiments investigating alternative extension velocity histories for the North Atlantic rifted margins

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Continental rifted margins differ in margin width, topographic elevation and fault patterns. For example, the mid-Norwegian margin is considered hyper-extended, displaying highly thinned continental crust over a wide region, but the margin in northern Norway is much narrower with higher onshore topography. Numerical experiments of continental extension show that the width of rifted margins varies with crustal rheology and extension velocity. An initially strong lower crust leads to a short margin accompanied by high rift flank uplift. An initially weak lower crust at moderate extension rates can form a long, hyper-extended crust. The crustal strength is determined by lithology, thermal gradient, crustal thickness, and the strain-rate dependence of ductile flow-laws. Geological and plate tectonic reconstructions can guide extension histories, but we commonly have little constraint on crustal thickness and rheology at the onset of rifting.

Here we use numerical models of rifting to test how alternative velocity histories for the North Atlantic region interplay with crustal rheology and initial crustal thickness. The onset of extension in the Norway-Greenland rift system is characterised by extensional collapse and the formation of Devonian sedimentary basins, following the Silurian continent-continent collision between Baltica and Laurentia. Subsequent intermittent rifting over several hundreds of millions of years finally led to seafloor spreading in the early Eocene. Several alternative regional plate reconstructions predict different relative motion histories between Norway and Greenland. Notably, the models predict varying episodes of compression or quiescence.

Our experiments of rifted margin formation use the 2D version of SULEC (developed by Buiter and Ellis). SULEC is an arbitrary Lagrangian-Eulerian finite-element code that solves the incompressible momentum equation coupled with the energy equation. An accurate pressure field is obtained through an iterative penalty (Uzawa) formulation. The surface of our experiments is a true free surface (no sticky air). We compare margin architectures that result from applying the rift velocity histories from three different regional plate reconstructions to rifted margins that formed by applying constant extension velocities. For each set we vary in addition the initial crustal thickness. One of our findings is that a long phase of initially low magnitude extension rate can cause rift jumps when thermal cooling and associated ductile strengthening render the rifting region too strong for continued rifting. Ramping up of rift velocities then causes continental break-up in the new rift region.

Water, viscosity and mantle convection: the effects of weakening and mixing

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The effect of water on mantle minerals and their viscosity is complex. Experimental work such as that by Mei & Kohlstedt [1] has shown significant rheological weakening with the addition of a few hundred ppm water contributing up to several orders of magnitude reduction in viscosity. The impact on thermal evolution and water cycling has been investigated in parametrised and two-dimensional models (e.g. [2,5]). However, the impact of different viscosity laws is often overlooked.

We examine mantle evolution arising from the implementation of viscosity laws with varying sensitivities to water content. The model, based on [2], solves for the conservation of energy and mass across the mantle and a surface ocean. Parametrised models also assume that subducted material is instantaneously incorporated into the mantle. We investigate the role of a time delay due to mixing, a process not readily implemented into these models.

Preliminary results show greater present day temperatures due to degassing. Degassing increases viscosity and the stiff mantle convects slowly allowing periods of heating. This increases temperature and reduces viscosity cooling the mantle $\sim$500°C from 1 to 4.6 Gyrs. A water independent viscosity law loses 600°C, a value greater than the upper limit of 500°C from petrology and geochemistry [1,3]. This suggests that a water dependent viscosity law is required to obtain mantle temperature changes between the expected 200°C and 500°C.

[1] Condie, Geoscience Frontiers, 7(4), p543-553, 2016.
[2] Crowley et al., Earth and Planetary Science Letters, 310(34), p380-388, 2011.
[3] Grove & Parman, Earth and Planetary Science Letters, 219(34), p173-187, 2004.
[4] Mei & Kohlstedt, Journal of Geophysical Research, 105(B9), p214-271, 2000.
[5] Nakagawa et al., Geochemistry, Geophysics, Geosystems, 16(5), p1449-1464, 2015.

Rheological effects on slab stagnation in the transition zone and uppermost lower mantle

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An endothermic phase transition in mantle material at 660-km depth constitutes a barrier that in most cases prevents the direct penetration of subducted slabs. Seismic tomography shows that subducted material is in many subduction zones trapped at the bottom of the transition zone, just above the 660-km phase boundary. Recent tomographic models however also report subducted material that penetrates to the shallow lower mantle, and there it is observed to flatten at about 1000-km depth. Models of slab dynamics that generally assume a sharp rheological transition at 660-km depth, however, mostly predict slab stagnation at the bottom of the transition zone. Recent deformation experiments on ferropericlase indicate that viscosity may gradually increase in the uppermost 300 km of the lower mantle, rather than changing abruptly at the upper-lower mantle boundary. Here we present the results of a modelling study focused on the effects of rheological transition between the upper and lower mantle material on slab deformation and stagnation. We test the effects of smoothing the viscosity increase over 200 km and of shifting it to the depth of 1000 km or even deeper. We show that slab ability to penetrate to the lower mantle is mainly controlled by the trench migration ratio and that in turn is affected by the crustal viscosity. The lubrication of the contact between the subducting and overriding plates thus plays a key role in controlling slab penetration to the lower mantle and stagnation at the bottom of the transition zone or in the shallow lower mantle. The models with strong crust and consequently negligible rollback display penetration to the lower mantle without much hindrance and display no stagnation above or below the 660-km interface regardless of the viscosity stratification of the shallow lower mantle. The models with weak crust are characterised by fast rollback, and penetration is thus very limited. Such slabs generally buckle and flatten above the 660-km boundary. The most interesting models from the point of view of shallow lower mantle stagnation are models with intermediate crustal viscosity. Here rollback is efficient, though slower than in weak-crust cases. Horizontally lying slab segments are trapped in the transition zone, if the sharp viscosity increase occurs at 660 km, but shifting the viscosity increase to 1000 km depth allows for efficient sinking of the flat-lying part and results in stagnation below the upper-lower mantle boundary at about 1000 km depth.

Tectonic predictions with mantle convection models

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Over the past 15 years, numerical models of convection in Earth's mantle have made a leap forward: they can now produce self-consistently plate-like behavior at the surface together with deep mantle circulation. These digital tools provide a new window into the intimate connections between plate tectonics and mantle dynamics. Therefore they can be used for tectonic predictions, in principle. This contribution explores this assumption. I first build guessed initial conditions at 30 Ma, 20 Ma, 10 Ma and 0 Ma, driving a convective flow by imposing reconstructed plate velocities at the surface. I then compute instantaneous mantle flows in response to the guessed temperature fields without imposing any plate boundary. Plate boundaries self-consistently emerge at correct locations except for small plates close to subduction zones. As already observed for other types of instantaneous flow calculation, the structure of the boundary layer and upper mantle slab is first-order for accurate predictions of surface velocities. Perturbations of the rheological parameters have little impact. Plumes have imperceptible effects on the surface tectonics of the model. I then compute fully dynamic models evolutions from 30 and 10 Ma to 0 Ma, without imposing plate boundaries nor plate velocities. Contrarily to instantaneous calculations, errors in kinematic predictions are substantial, although the plate layout and kinematics in several areas remain consistent with the expectations for the Earth. For these calculations, varying the rheological parameters makes a difference for plate boundary evolution. Also, identified errors in initial conditions contribute to first-order kinematic errors. This experiment shows the tectonic predictions of dynamic models over 10 My are highly sensitive to uncertainties of rheological parameters and initial temperature field in comparison to instantaneous flow calculations. Indeed, the initial conditions and the rheological parameters can be good enough for an accurate prediction of instantaneous flow, but not for a prediction after 10 My of evolution. Therefore, inverse methods using short term fully dynamic evolutions with surface kinematics as the data to match are promising tools for a better understanding of the state of the Earth's mantle.

Volumes and patterns of asthenospheric melt inferred from the space-time distribution of seamounts

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Although partial melt in the asthenosphere is important geodynamically, geophysical constraints on its abundance remain ambiguous. We use a database of seamounts detected using satellite altimetry to constrain the temporal history of erupted asthenospheric melt. We find that intraplate volcanism on young seafloor ($<$60 Ma) equates to a $\sim$20 m thick layer spread across the seafloor. If these seamounts tap partial melt within a $\sim$20 km thick layer beneath the ridge flanks, they indicate extraction of an average melt fraction of $\sim$0.1%. If they source thinner layers or more laterally restricted domains, larger melt fractions are required. Increased seamount volumes for older lithosphere suggest either more active ridge flank volcanism during the Cretaceous or additional recent melt eruption on older seafloor. Pacific basin age constraints suggest that both processes are important. Our results indicate that small volumes of partial melt may be prevalent in the upper asthenosphere across ocean basins.

Numerical modeling of large-scale lateral collapses in volcanic edifices

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The evolution of volcanic islands is marked by the interaction between volcanic growth and destruction processes. Worldwide have been reported evidences for large-scale lateral gravitational destabilization, either slow and focused along discrete structures, as slumps, or as fast and catastrophic, as debris avalanches. Debris avalanches are especially hazardous, considering the large volume of material transported (up to thousands of km^3) and the associated potential to tsunami triggering.

However, the physics of this process is not completely understood. The role of factors such as the volcanic edifices strength (viscosity, cohesion, friction angle), dimensions, geometry, and existence of weak layers remain to be addressed.

Here we perform numerical simulations to study the interplay between viscous and plastic deformation on the gravitational collapse of a volcanic edifice (diffuse deformation vs. localization of failure along discrete structures). We focus on the contribution of the edifices strength parameters for the mode of deformation, as well as on the type of basement.

Systematic tests were performed for a large volcanic edifice (7.5 km high, 200 km long), for purely viscous (overall volcano viscosities between $10^{19} - 10^{23}$ Pa.s), or viscoplastic rheology (within a range of cohesion and friction angle values). Results show that (a) for a strong basement (no slip basal boundary condition), the deformation pattern suggests wide/diffuse listric deformation within the volcanic edifice, without the visible development of discrete plastic failure zones; (b) for a weak basement (free slip basal boundary condition), rapid collapse of the edifice through the propagation of plastic failure structures within the edifice occurs.

Tests for a smaller volcanic edifice (4.5 km by 30 km) show that high cohesion values lead to focused deformation along long-lasting deep listric structures, while smaller cohesion values lead to a quick progression of failure towards the superficial sectors of the volcanic flanks.

Tests with a weak layer underlying part of the volcanic edifice base show deformation focused along discrete structures, mainly dipping towards the distal sector of the volcano. When added the effect of a basal convex shape for the volcanic edifice, the failure zones become less numerous and narrower, involving the transport of blocks apparently less disrupted internally. These tests for a small volcanic edifice constitute a promising basis for the study of a currently active slump in the SE flank of Pico Island (Azores, Portugal).

StagLab: Post-processing and visualizing mantle and lithosphere dynamics

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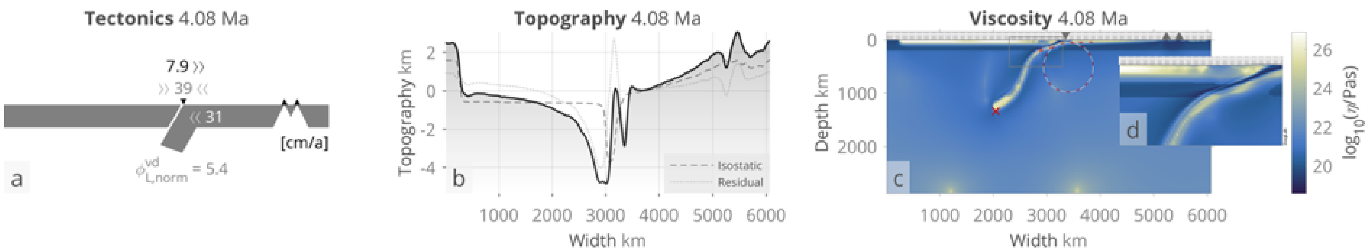
Despite being simplifications of nature, todays numerical models of mantle and lithosphere dynamics can, often do, and sometimes have to become very complex. Additionally, a steadily-increasing amount of raw model data results from more elaborate numerical codes and the still continuously-increasing computational power available for their execution. The current need for efficient post-processing and sensible visualisation is thus apparent.

StagLab (`www.fabiocrameri.ch/software`) provides such much-needed strongly-automated post-processing in combination with state-of-the-art visualisation. Written in MatLab, StagLab is simple, flexible, efficient and reliable. It produces figures and movies that are both fully-reproducible and publication-ready.

StagLabs post-processing capabilities include numerous diagnostics for plate tectonics and mantle dynamics. Featured are accurate plate-boundary identification, slab-polarity recognition, plate-bending derivation, mantle-plume detection, and surface-topography component splitting. These and many other diagnostics are derived conveniently from only a few parameter fields thanks to powerful image processing tools and other capable algorithms.

Additionally, StagLab aims to prevent scientific visualisation pitfalls that are, unfortunately, still too common in the Geodynamics community. Misinterpretation of raw data and exclusion of colourblind people introduced with the continuous use of the rainbow (a.k.a. jet) colour scheme is just one, but a dramatic example (e.g., Borland and Ii, 2007, IEEE Computer Graphics and Applications). StagLab therefore uses a novel set of scientifically-tested, perceptually-uniform colour maps that are additionally freely available (see `www.fabiocrameri.ch/visualisation`).

StagLab is currently optimised for binary StagYY output (e.g., Tackley 2008, PEPI), but is adjustable for the potential use with other Geodynamic codes. Additionally, StagLabs post-processing routines are open-source.



StagLab performs various plate- and mantle diagnostics, and produces publication-ready figures and movies.

Abrupt upper-plate tilting during slabtransition-zone collision

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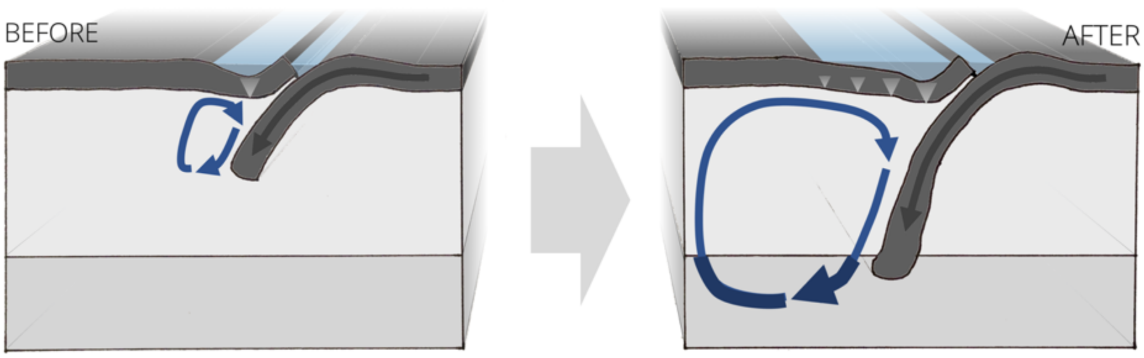
The sinking remnant of a surface plate crosses and interacts with multiple boundaries in Earths interior. The most-prominent dynamic interaction arises at the upper-mantle transition zone where the sinking plate is strongly affected by the interaction with the higher-viscosity lower mantle. Within our model, we unravel, for the first time, that this very collision of the sinking slab with the transition zone induces a sudden, dramatic downward tilt of the upper plate towards the subduction trench.

The slab-transition zone collision sets parts of the higher-viscosity lower mantle in motion. Naturally, this then induces an overall larger return flow cell that, at its onset, tilts the upper plate abruptly by around 0.06 degrees and over around 10 Millions of years. Such a significant and abrupt variation in surface topography should be clearly visible in temporal records of large-scale surface elevation and might explain continental tilting as observed in Australia since the Eocene or North America during the Phanerozoic.

Unravelling this crucial mantle-lithosphere interaction was only possible thanks to state-of-the-art numerical modelling (powered by StagYY; Tackley 2008, PEPI) and post-processing (powered by StagLab; see previous abstract). The new model that is introduced here to study the dynamically self-consistent temporal evolution of mantle convection features accurate subduction-zone topography, robust single-sided subduction, stronger plates close to laboratory values, an upper-mantle phase transition, and simple continents at a free surface. The physical model diagnostics like slab geometry, mantle flow pattern, upper-plate tilt angle and trench location are derived in a post-processing step fully-automatically.



Schematic illustration comparing flow dynamics and resulting topographic adjustments before and after slabtransition-zone interaction.

Under the hood of the earthquake machine: Toward predictive modeling of the Himalayan seismic cycle

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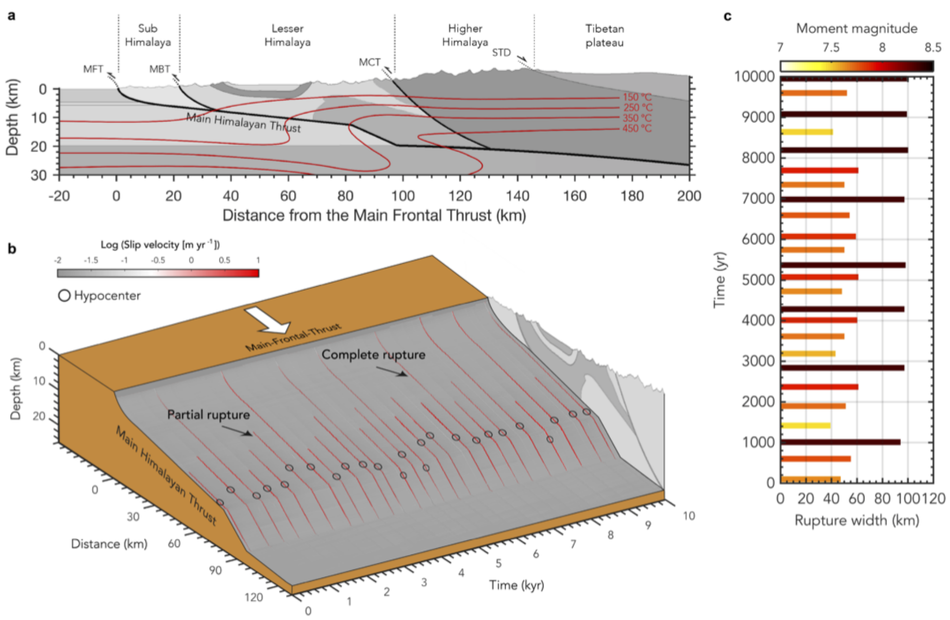
Over the last years, our understanding of how megathrusts behave over the seismic cycle has evolved significantly due to both advances in numerical modeling and geodetic monitoring techniques. For instance, the 2015 Gorkha earthquake provided an outstanding opportunity to better characterize the geometry of the Main Himalayan Thrust (MHT) fault. Yet, it is unclear how these observations could help assess future earthquakes. Here, we bridge the gap with observations by developing a modeling approach that combines 2D, visco-elasto-plastic seismo-thermo-mechanical (STM) model and various geophysical and geological constrains of the Nepal Himalaya. This allows us to design an accurate setup of the present-day lithospheric structure and geometry of the MHT (Fig. a). By considering different megathrust geometry as end-member cases, we can get a grip on how well the models fit observational constraints.

Our modeling results explain many puzzling, yet robust observations of the crustal deformation in the Himalaya. Such instantaneous models establish the dependence of earthquake rupture pattern on fault friction and non-planar geometry of the MHT. These results show that an increase in fault friction leads to a transition from ordinary cycles—of similar sized complete ruptures—to irregular cycles. These irregular cycles are even more clearly visible when the model accounts for a realistic ramp-flat-ramp geometry of the MHT, since a steep frontal ramp increases the depth-dependent strength. Consequently, the strength excess in the frontal part of the seismogenic zone also increases. It takes longer and more events to reach a critical stress state at which eventually a large event ruptures the entire seismogenic zone (Fig. b). These results demonstrate how great earthquakes (M7+) can re-rupture downdip regions that have already ruptured in recent smaller earthquakes and how mega-earthquakes (M8+) may propagate up to the surface, driven by residual stress following many centuries of smaller earthquakes (Fig. c). We conclude that such along-dip stress evolution of the MHT is the simplest mechanism governing the bimodal seismicity in the Himalaya. Our study opens an avenue for predicting seismic rupture patterns that the MHT can produce based on its friction and geometry, and provide new ways to assess seismic hazards.



*Setup and seismic fault behaviour computed in the 2D model. Panel **a** shows a zoom of the initial model setup and temperature. **b**, Spatiotemporal evolution of slip on the MHT for the reference model. Red lines show slip during the simulated earthquakes, whereas black circles indicate hypocenters. **c**, Time evolution of rupture width. Colorbar indicate the corresponding moment magnitude.*

Chemical trends in ocean islands explained by plume–slab interaction

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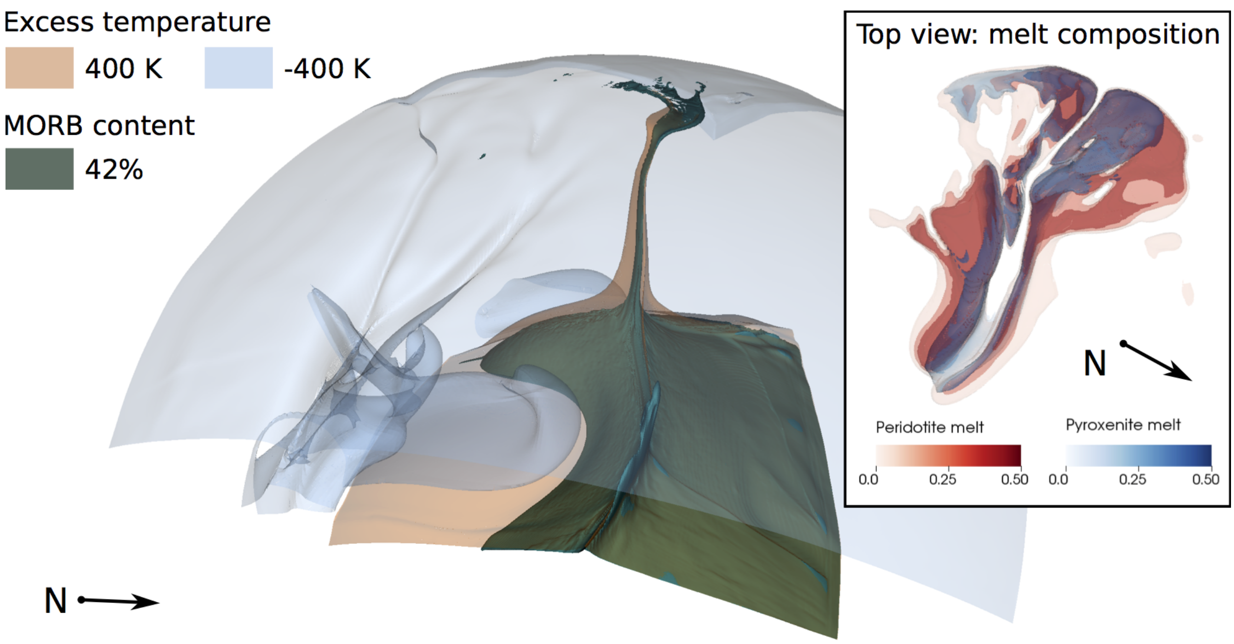
Earth's surface shows many features whose genesis can only be understood through their connection with processes in Earth's deep interior. Recent studies indicate that spatial geochemical patterns at oceanic islands correspond to structures in the lowermost mantle inferred from seismic tomographic models. This suggests that hot, buoyant upwellings can carry chemical heterogeneities from the deep lower mantle towards the surface, providing a window to the composition of the lowermost mantle. The exact nature of this link between surface and deep Earth remains debated and poorly understood. Using computational models, we show that subducted slabs interacting with dense thermochemical piles can trigger the ascent of hot plumes that inherit chemical gradients present in the lowermost mantle. We identify two key factors controlling this process: (i) If slabs induce lower mantle flow perpendicular to the edges of these piles where plumes rise, the pile-facing side of the plume preferentially samples material originating from the pile and bilateral chemical zoning develops. (ii) The composition of the melt produced reflects this zoning if the overlying plate moves roughly perpendicular to the chemical gradient in the plume conduit. Our results explain observed geochemical trends of oceanic islands and provide insights into how these trends may originate.



Time snapshot of a simulation of a bilaterally asymmetric zoned plume in the geographical setting of the South Pacific. The main figure shows isosurfaces of excess temperature and composition. Subducted slabs (blue) arriving from the south push material against the thermochemical pile in the lowermost mantle (green) and trigger the ascent of a zoned plume (orange and green). The figure inset displays a top view with isosurfaces of generated melt; melt generated from average mantle (peridotite melt) shown in red and melt generated from recycled crust (pyroxenite melt) shown in blue.

Plume-induced subduction and accretion on convecting planets: experiments and scaling relationships

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We recently observed plume-induced subduction in laboratory experiments where a brittle viscous-elasto-plastic lithosphere was self-consistently developing on top of a convecting mantle. The experimental fluids were heated from below to produce upwelling plumes, which in turn produced tensile fractures in the lithosphere-like skin that formed on the upper surface. Plume material upwelling through the fractures then spread above the skin, analogous to volcanic flooding, and lead to bending and eventual subduction of the skin along arcuate segments. Necessary conditions were derived as a function of the mechanical properties and thermal structure of the lithosphere and mantle, the buoyancy of the lithosphere and the buoyancy and size of the mantle plume. They suggest that this regime with limited, plume-induced subduction is favored by a hot lithosphere, such as that found on early Earth or present-day Venus. Moreover, in this regime, subduction proceeds primarily by roll-back and the coronae expands through time at velocity that could reach 10 cm/yr. A second set of experiments focusing on accretion processes (see poster by Sibrant et al.) suggests that accretion dynamics depends on the strength of the lithosphere, as well as the spreading velocity. Venus hot surface temperature would then act to decrease the lithosphere strength, and therefore weaken the ridge axis. The latter would become highly unstable, showing large sinuosity and producing a number of micro-plates. This would explain well the features seen in Artemis coronae, the largest coronae on Venus.

Intra-plate volcanism: the role of plumes, plate motion, plate motion changes and lithospheric structure

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Most of Earth's volcanism is concentrated at tectonic plate boundaries. However, an important and widespread class of volcanism occurs within plates, or across plate boundaries. These so-called intra-plate volcanic provinces are often associated with mantle plumes: hot buoyant columns that rise from Earths core-mantle-boundary to its surface. The best-studied example is the HawaiianEmperor chain, but the emergence of two sub-parallel volcanic tracks along this chain, namely Loa and Kea, and the systematic geochemical differences between them, have remained unexplained. The emergence of these tracks coincides with the appearance of other double volcanic tracks on the Pacific plate. In the first part of this talk, I will summarise our recent work that links the emergence of these double volcanic tracks to a recent azimuthal change in Pacific plate motion and simultaneously explains their distinct geochemical characteristics [1].

It is becoming increasingly evident that several of Earths intra-plate volcanic provinces cannot be explained by the mantle plume hypothesis. These provinces are best explained by alternative mechanisms, involving the interplay between mantle flow and the base of Earths heterogeneous lithosphere. The applicability and relative importance of these mechanisms, however, is unclear, and likely varies from one geological setting to the next. Furthermore, our understanding of the interaction between these shallow processes and deep-rooted mantle plumes remains in its infancy. In the second part of this talk, I will utilize the record of Cenozoic volcanism on the Australian continent to highlight the important role of lithospheric structure and plate motions in dictating the volume, composition and location of erupted magmas [2,3]. Our results also hint at complex interactions between mantle plumes and sub-lithospheric mantle flow.

[1] Jones et al., Nature, 545, p472-476, 2017.
[2] Davies et al., Nature, 525, p511514, 2015.
[3] Davies & Rawlinson, Geology, 42, p1031-1034, 2014.

Modeling of solitary porosity waves with new viscosity laws

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Magmatic phenomena such as volcanic eruptions on the earth's surface show, among others, that melt is able to ascend from partially molten regions in the earth's mantle. Thereby it firstly flows through the partially molten source region and then through the unmolten lithosphere until it eventually reaches the surface. The governing processes in this source region are poorly understood.

Since McKenzie [1] introduced his equations for two-phase flow, which include a fluid phase (melt) and a porous deformable matrix, the physics of this region are of broad interest. One of the features which were studied is the emergence of solitary porosity-waves, whose ascent is the main focus of this work.

By now most analytical and numerical solutions for these waves used strongly simplified modells for the shear- and bulkviscosity. They are too high or neglected the porosity-dependence of the bulkviscosity. Further studies show that this porosity-dependence has a great influence on the dispersion-behaviour of the wave but has a minor influence for very small meltfractions [2].

In this work we take viscosity-laws from Schmeling et al. [3], which predict that the viscosity decreases very rapidly for small meltfractions. We use them for numerical modelling of these solitary waves. These modells are carried out with FDCON, a 2D Finite Difference convection code with two-phase flow.

As there are no analytical solutions for the shape of solitary porosity-waves in 2D, we use Gaussian-like belle-shaped curves as first approach for the initial wave. The phase velocity and the amplitude of these waves are taken and used for comparison in dispersion-curves. The results show that shortly after starting the model the bell-shaped curves emerge into a solitary wave. These waves, with smaller viscositys, are still comparable with the simplified analytical and numerical solutions but also have differences which are considerable.

[1] McKenzie, Journal of Petrology, 25(3), p713-765, 1984.
[2] Richard et al., Physics of the Earth and Planetary Interiors, 198, p61-66, 2012.
[3] Schmeling et al., Geophysical Journal International, 190(3), p1571-1578, 2012.

Towards modelling of water inflow into the mantle

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The transport and storage of water in the mantle significantly affects various material properties of mantle rocks and thus water plays a key role in a variety of geodynamical processes (tectonics, magmatism etc.) Geological and seismological observations suggest different inflow mechanisms of water via the subducting slab like slab bending, thermal cracking and serpentinization [3,4].

Most of the previous numerical models do not take different dip angles of the subduction slab and subduction velocities into account, while nature provides two different types of subduction regimes i.e. shallow and deep subduction [5]. To which extent both parameters influence the inflow and outflow of water in the mantle still remains unclear. For the investigation of the inflow and outflow of fluids e.g. water in the mantle, we use high resolution 2D finite element simulations, which allow us to resolve subducted sediments and crustal layers. For this purpose the finite element code MVEP2 [6] is tested against benchmark results [2]. In a first step we reproduced the analytical cornerflow model [1] used in the benchmark of van Keken et al. [2] as well as the steady state temperature field.

Further steps consist of successively increasing model complexity, such as the incorporation of hydrogen diffusion, water transport and dehydration reactions. Systematic simulations are performed to assess the influence of different model parameters on various target parameters such as dehydration depth, volcanic line position etc., the ultimate goal being the derivation of scaling laws for water transport in the mantle.

[1] Batchelor, Cambridge University Press, Cambridge, UK (1967)
[2] van Keken et al., Phys. Earth Planet. Int., 171, p187-197 (2008).
[3] Faccenda et al., Nature Geoscience, 2, p790-793 (2009).
[4] Korenaga, Earth Planet. Sci. Lett., 457, p1-9 (2017).
[5] Li et al., Earth Planet. Sci. Lett., 301, p65-77 (2011).
[6] Kaus, Tectonophysics,484, p36-47 (2010).

Mantle convection: clues from lithosphere sinking at subduction zones

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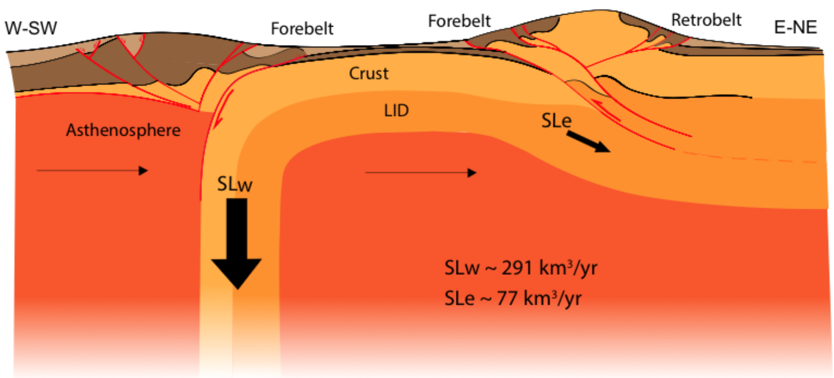
Subduction zones show a worldwide asymmetry that can be observed in slab dip, kinematics of the subduction hinge, morphology, structural elevation, gravity anomalies, heat flow, metamorphic evolution, subsidence and uplift rates, depth of the decollement planes, mantle wedge thickness, magmatism, backarc development or not, etc. This asymmetry could be easily explained if related to the geographic polarity of the sinking slabs. In fact, geophysical and kinematics constraints show that all the plates move westward. This preferential flow of plates would suggest a relative eastward mantle flow. If we look then to subduction dynamics within this set of conditions, this eastward mantle flow should have an important role in influencing subduction dynamics itself. Furthermore, along westward-directed subduction zones slabs sink with a higher velocity with respect to the easterly or northeasterly-directed ones. The faster westerly-directed slabs determine that the volume of lithosphere recycled into this kind of subduction is larger than that along the converse ones. This should determine a more vigorous counterflow within the mantle below westward-directed subductions with respect to the one below eastward to northeasterly-directed ones. Starting from these observations we attempted to estimate volumes of lithosphere that are currently subducting below the principal subduction zones: our results show that there are about 291 km^3/yr of lithosphere currently subducting below westward-directed subduction zones, while only about 77 km^3/yr of lithosphere are currently subducting below eastward to northeasterly-directed subduction zones.

Since subduction rate (VS) seems to have a determining role in causing this volumetric difference between the two subduction settings, we used this data to run some numerical experiments, in support to our calculation. Our numerical results confirm the asymmetric amount of lithosphere currently re-entering into the mantle below westward-directed subduction zones, giving us more elements to speculate about mantle convection and its relationship with subduction zones.



Sketch in which results of our calculation are shown.

Interpreting continental break-up from surface observations: analysis of 1D partial melting using synthetic waveform propagation

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Low shear-wave velocity zones underneath margins of continental break-up are believed to be related to presence of melt from upwelling mantle rock undergoing decompression melting. Many models have attempted to model the process of melt production and transportation at sites of mantle upwelling, yet there is a currently a disconnect between the geodynamic models, seismic observations, and petrological studies of melt flow velocities. Geodynamic models that emulate melt retention of ~ 2 % [1] at the onset of melting, as suggested by shear-wave velocity anomalies, fail to adequately reproduce the seismic signal as seen in the corresponding receiver functions [2]. Furthermore, numerical models of melt migration through porous, compactible media conclude mean melt flow velocities up to $1,3\ \mathrm{m\,yr^{-1}}$ [3], whereas Uranium isotope migration rates advocate velocities up to one to two orders of magnitude higher. This study aims to reconcile the diverting assertions on the partial melting process and its role in defining the structure of the lithosphere by analysing the effect of melt presence on the coda of the seismic signal.

A 1D forward model has been created to emulate melt production in an upwelling mantle environment that solves the advection-diffusion equations for temperature using a Crank-Nicolson discretisation. Melt production and advection is computed through a forward differencing scheme with the assumption of Darcy flow for melt transportation. Scenarios have been modelled for variable upwelling velocities $\overline{v}$ ($1 - 100\ \mathrm{mm\,yr^{-1}}$), initial temperatures T_0 ($1200 - 1800\,^{\circ}\mathrm{C}$) and permeabilities k_0 ($10^{-9} - 10^{-5}\ \mathrm{m^2}$). The 1D model parameters for each scenario are converted to anharmonic seismic parameters using look-up tables from phase diagrams [4] in order to generate synthetic seismograms with the Direct Solution Method. The maximum frequency content of the synthetics is up to $1,25$ Hz, sampled at a 20 Hz sampling frequency and filtered to $0,1$ Hz. A comparison between the synthetics and seismic observations of the La Reunion mantle plume from the RER Geoscope receiver is performed using a Monte-Carlo approach.

The synthetic seismograms show highest sensitivity to the presence of melt in S-waves within epicentral distances of 0-20 degrees. In the 0-10 degree range only a time-shift is observed proportional to the melt fraction at the onset of melting. Within the 10-20 degree range the presence of melt causes an additional change in the coda of the signal compared to a no-melt model. By analysing these altered synthetic waveforms we search for a seismic signature corresponding to melt presence to form a benchmark for the comparison between the Monte-Carlo results and the seismic observations.

[1] Forsyth & MELT Seismic Team, Science, 280, p1215-1218, 1998.
[2] Armitage et al., Earth and Planetary Science Letters, 418, p78-90, 2015.
[3] Weatherley & Katz, Geochimica et Cosmochimica Acta, 172, p39-54, 2016.
[4] Goes et al., Journal of Geophysical Research, 117, B12, p403, 2012.

Efficient and practical Newton solvers for nonlinear Stokes systems in geodynamic problems

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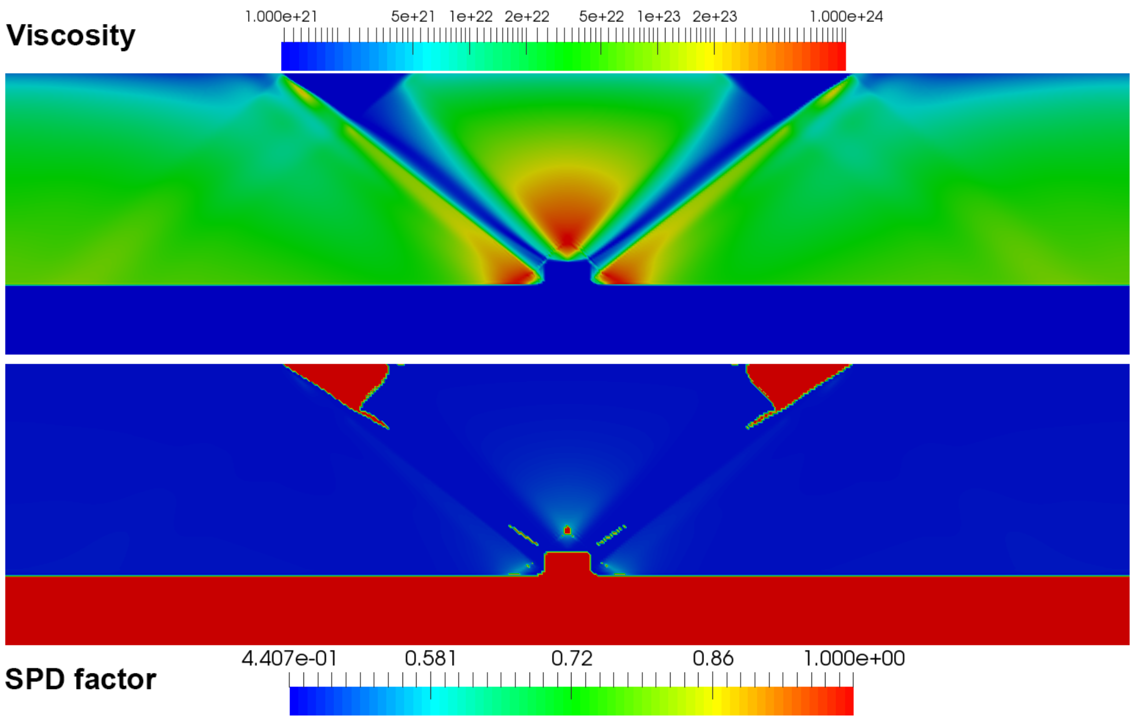
The most commonly used method by the geodynamical community for solving non-linear equations is the Picard fixed-point iteration. However, the Newton method has recently gained interest within our community because it theoretically yields quadratic convergence close to the solution as opposed to the global linear convergence of the Picard iteration. In mantle dynamics, a blend of pressure and strain-rate dependent visco-plastic rheologies is often used. While for power-law rheologies the Jacobian is theoretically guaranteed to be Symmetric Positive Definite (SPD), for more complex rheologies, especially in combination with compressible models, the Jacobian may become non-SPD. In practice though, even power-law rheologies may yield a non-SPD Jacobian in some extreme cases. Here we present a new method for efficiently enforce the Jacobian to be SPD, necessary for our current highly efficient Stokes solvers, with a minimum loss in convergence rate. Furthermore, we show results for both incompressible and compressible models. The figure below shows the viscosity (top) and the factor used to force the Jacobian to be positive definite, the SPD factor (bottom), for the toughest case ($\eta_1 = 5 \times 10^{25}$ and $U_0 = 12.5$) of the Spiegelman et al. [1] benchmark. A value of one in the SPD factor figure means that the Jacobian is not changed, while a lesser value scales the derivative in the assembly of the Jacobian down, with a zero value resulting in a normal Picard iteration in that location. As the figure shows, a significant scaling is needed to keep the Jacobian positive definite in this case.

[1] Spiegelman et al., Geochemistry, Geophysics, Geosystems, 17(6), 22132238, 2016.



The viscosity (top) and the factor used to force the Jacobian to be positive definite, the SPD factor (bottom), for the toughest case ($\eta_1 = 5e25$ and $U_0 = 12.5$) of the Spiegelman etal. (2016) benchmark.

Plate like convection with viscous strain weakening and corresponding surface deformation pattern

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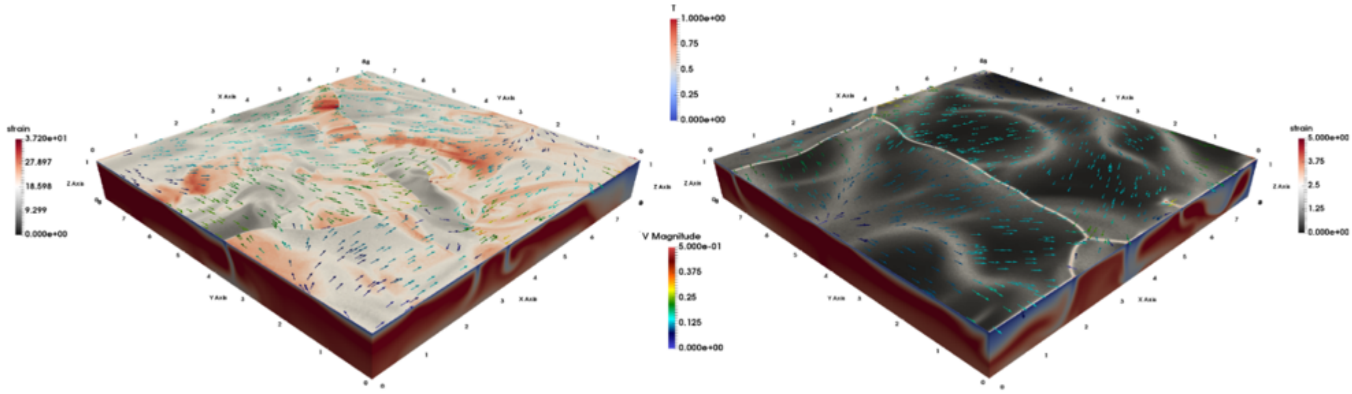
How plate tectonic surface motions are generated by mantle convection on Earth and possibly other terrestrial type planets has recently become more readily accessible with fully dynamic convection computations. However, it remains debated how plate-like the behavior in such models truly is, and in particular how the well plate boundary dynamics are captured in models which typically exclude the effects of deformation history and memory. Here, we analyze some of the effects of viscous strain weakening on plate behavior and the interactions between interior convection dynamics and surface deformation patterns. We use the finite element code CitcomCU to model convection in a 3D Cartesian model setup. The models are internally heated, with an Arrhenius-type temperature dependent viscosity including plastic yielding and viscous strain weakening (VSW) and healing (VSWH). VSW can mimic first order features of more complex damage mechanisms such as grain-size dependent rheology. Besides plate diagnostic parameters (Plateness, Mobility, and Toroidal: Poloidal ratio) to analyze the tectonic behavior our models, we also explore how plate boundaries link to convective patterns.

In a first model series, we analyze the general surface deformation patterns without VSW (left figure). In the early stages, surface deformation patterns are clearly co-located with up- and downwelling limbs of convection. Along downwellings strain-rates are high and localized, whereas upwellings tend to lead to broad zones of high deformation. At a more advanced stage, however, the plates interior is highly deformed due to continuous strain accumulation and resurfaced inherited strain. Including only VSW leads to more localized deformation along downwellings. However, at a more advanced stage plate-like convection fails due an overall weakening of the material. This is prevented including strain healing (right figure). Deformation pattern at the surface more closely coincide with the internal convection patterns. The average surface deformation is reduced significantly and mainly governed by the location of the up- and downwellings. VSWH thereby affects plate dynamics due to two main properties: the intensity of weakening with increasing strain and the strain healing rate. As both increase, mobility increases as well and strain becomes more localized at the downwellings.



Surface deformation pattern, surface velocity vectors and temperature for a viscous strain weakening models without (left) and with (right) healing. The Rayleigh number for each model is 10^5, with temperature dependent viscosity contrasts of 10^4, and a constant yield stress of $2 \cdot 10^3$ (non-dimensional).

Towards ASPECT 2.0: Features and software structure

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Computations have helped elucidate the dynamics of Earth's mantle for several decades already. The numerical methods that underlie these simulations have greatly evolved within this time span, and today include dynamically changing and adaptively refined meshes, sophisticated and efficient solvers, and parallelization to large clusters of computers. At the same time, many of these methods were developed and tested primarily using model problems that lack many of the complexities that are common to the realistic models our community wants to solve today.

We here revisit some of the algorithm designs and discuss the incorporation of more complex physics into the geodynamic modelling software ASPECT [1]. In particular, we re-consider mesh refinement algorithms, evaluate approaches to incorporate compressibility, and discuss dealing with strongly varying material coefficients, latent heat, and how to design the algorithms to be both flexible and optimal. Taken together and implemented in a high-performance, massively parallel code, the techniques discussed here then allow for high resolution, 3D, compressible, global mantle convection simulations with phase transitions, strongly temperature dependent viscosity and realistic material properties based on mineral physics data.

[1] Heister et al., Geophysical Journal International, 210(2), 833-851, 2017.

The effects of lateral heterogeneity on mantle convection in terrestrial planets

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Global geodynamic and seismic tomography models indicate that whole-mantle convection has efficiently mixed the mantle over time scales shorter than the age of the Earth. The resulting compositional similarity throughout the mantle, however, is at odds with isotope geochemical constraints from 182W anomalies that show the persistence of primordial heterogeneity somewhere in the Earths mantle. Additional cosmochemical evidence indicates that the lower mantle should be Si-enriched with respect to the upper mantle. Recent geodynamic models have started to address the discrepancies between geochemical and geophysical data by exploring the effects of large-scale lateral heterogeneity on mantle mixing; this heterogeneity may be associated with viscosity variations as a function of depth and composition. However, these models have used a simplified rheology and Cartesian geometry.

In this contribution, we use StagYY to create geodynamic models in spherical geometry with plate-like behaviour and self-consistent planetary cooling to study the effects of lateral heterogeneity on convection and mixing in the mantle. The goal of these models is to investigate the effects of variations in physical parameters on both the style of mantle convection and the mixing of the mantle before implementing more rigorous initial conditions. We find that mixing efficiency of compositional heterogeneity decreases, while the survival time increases, with increasing intrinsic viscosity contrasts. Additionally, intrinsic density contrasts control the shape and location of large-scale heterogeneity in the mantle. Finally, we find the behaviour of compositional heterogeneity over time to depend on the initial conditions of the model, such as primordial layer thickness and initial temperature. In the future, we intend to rigorously define an initial mantle compositional profile using semi-analytical models of element partitioning during magma ocean freezing, and afterwards compare the simulation results with geophysical and geochemical observations.

Boundary-element modeling of two-plate interaction at subduction zones: scaling laws and a geophysical constraint

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This work uses the boundary-element method (BEM) to explore the dynamics of subduction of a dense lithospheric plate (subducting plate, SP) beneath an overriding continental plate (OP). For simplicity, the model is two-dimensional, the plates are purely viscous, and the ambient fluid is infinitely deep. The negative buoyancy of the slab is the only driving force, and subduction is triggered by a finite-amplitude perturbation in the form of a short proto-slab.

First, we study the SP kinematics focusing on two characteristic instantaneous velocities: the convergence speed (V_{Conv}) and the plate speed (U_{SP}). We find that V_{Conv} is strongly controlled by the width d_2 of the lubrication layer separating the SP and the OP and by the SP's flexural stiffness St. Turning to U_{SP}, we find that this parameter depends not only on d_2 and St, but also on the lengths L_{SP} and L_{OP} of the SP and the OP. The dependence of U_{SP} on L_{SP} is exactly logarithmic, both with and without an OP.

Next, we explore the deformation of the OP, which occurs by a combination of extension/compression and bending. The OP deformation is compression-dominated close to the trench and bending-dominated along the remaining portion of the OP that undergoes significant deformation. For a positively buoyant OP, back-arc extension is also observed.

Finally, we estimate the subduction interface viscosity η_{SI} of the central Aleutian subduction zone, running our BEM model with the appropriate geometry according to Lallemand et al. [1]. The comparison between the predicted V_{Conv} and the observed value suggests $\eta_{\mathrm{SI}} = (0.36 - 4.43) \times 10^{19}$ Pa s.

[1] Lallemand et al., Geochemistry, Geophysics, Geosystems, 6(9), 2005.

3D Numerical rift modeling with an application to the East African Rift System

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As key components of plate tectonics, continental rifting and the formation of passive margins have been extensively studied with both analogue models and numerical techniques. Only recently however, technical advances have enabled numerical investigations into rift evolution in three dimensions, as is actually required for including those processes that cause rift-parallel variability, such as structural inheritance and oblique extension.

We use the massively parallel finite element code ASPECT [2,4] to investigate rift evolution. ASPECTs adaptive mesh refinement enables us to focus resolution on the regions of interest (i.e. the rift center), while leaving other areas such as the asthenospheric mantle at coarse resolution, leading to kilometer-scale local mesh resolution in 3D.

Furthermore, we implemented plastic and viscous strain weakening of the nonlinear viscoplastic rheology required to develop asymmetric rift geometries (e.g. [3]). Additionally created plugins to ASPECT allow us to specify initial temperature and composition conditions based on geophysical data (e.g. LITHO1.0 [5]) or to prescribe more general along-strike variation in the initial strain seeding the rift.

Employing the above functionality, we construct regional models of the East African Rift System (EARS), the worlds largest currently active rift. As the EARS is characterized by both orthogonal and oblique rift sections, multiphase extension histories as well as magmatic and a-magmatic branches (e.g. [1]), it constitutes an extensive natural laboratory for our research into the 3D nature of continental rifting.

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[5] Pasyanos et al. (2014). J. of Geophys. Res., 119, 3, 21532173.

3D instantaneous dynamics modeling of present-day Aegean subduction

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To study the sensitivity of surface observables to subduction and mantle flow, i.e. the coupling of crustal tectonics and the underlying mantle dynamics, we have developed 3D numerical models of the instantaneous crust-mantle dynamics of the eastern Mediterranean. These models comprise both a realistic crust-lithosphere system and the underlying mantle. For this presentation we focus on the regional crustal flow response to the present-day Aegean subduction system.

The set-up of our curved model domain measuring 40°x40°x2900km is based on geological and geophysical data of the eastern Mediterranean. We first create a 3D synthetic geometry of the crust-lithosphere system in a stand-alone program, including the present-day configuration of the plates in the region and crust and lithosphere thickness variations abstracted from Moho and LAB maps. In addition we construct the geometry of the Aegean slab from a seismic tomography model and earthquake hypocenters. Geometries are then imported into the finite element code ASPECT [2,3] using specially designed plugins.

The mantle initial temperature conditions can include deviations from an adiabatic profile obtained from conversion of seismic velocity anomalies to temperature anomalies using a depth-dependent scaling. We model compressible mantle flow for which material properties are obtained from thermodynamics P-T lookup-tables (Perple_X [1]) in combination with nonlinear viscoplastic rheology laws. Plate motion is prescribed at the model sides in terms of relative as well as absolute plate motion velocities, while a free-slip surface accommodates internal deformation. In short, the forcing in our models comprises lateral pressure gradients, mantle buoyancy and forcing related to the prescribed plate motions.

Based on the above initial and boundary conditions, we obtain model predictions of the regional flow field. Focusing on the crust, these represent predictions of the GPS velocity field that we can compare to actual GPS data. Our initial models provide a good overall fit to the direction and magnitude of these GPS velocities (see Figure). Subsequent models include constructed variations in subduction morphology, slab segmentation, fault zone geometry and boundary conditions. Changes in the resulting model predictions either improve or lessen our fit to the GPS velocity field and help determine the controls of mantle dynamics on present-day tectonic deformation in the Aegean region. This enables us to characterize the general sensitivity of surface observables to plate motions, mantle flow and slab dynamics and to further quantify the coupling of crust and mantle dynamics.

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[2] Heister et al. (2017). Geophys. J. Int., 210, 833851.
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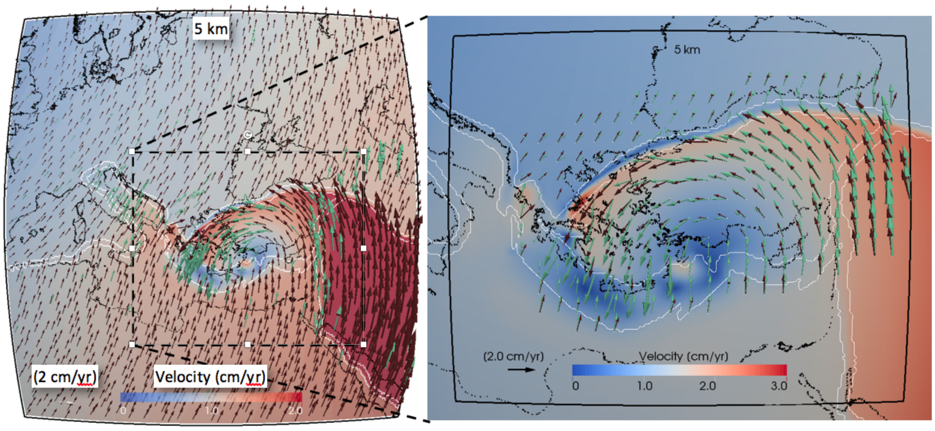

A good overall match between predicted crustal velocities at 5 km depth in maroon and the GPS velocities of Nocquet (2012, Tectonophysics, 579) in green. Background colors indicate the predicted velocity magnitude. Left: top view of whole model domain. Right: zoom-in of Aegean region.

Post-magma ocean mixing of reservoirs inside the angrite parent body

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Angrites are a rare group of mafic volcanic-plutonic meteorites with only 28 samples listed by the Meteoritical Society that formed within the first 10 Myr after the formation of the solar system. Studies of siderophile elements showed that core formation in the angrite parent body occurred at super liquidus temperatures. Despite experiencing an early magma ocean, Hf-W data suggest the presence of at least two distinct mantle reservoirs. A possible explanation for the isotopic variations (coupled with elemental variations) could be delivery of new planetesimal material during the post-magma ocean stage and imperfect mixing of the resulting mantle reservoirs. To test this theory we use the 2D/3D finite difference marker-in-cell code family I2ELVIS/I3ELVIS to study the mixing of reservoirs in bodies with radii ranging from 50 to 300 km. Numerical results show that mixing in 3D models is more efficient than in their 2D counterparts. Based on the numerical results we derive a semi-analytical scaling law describing the mixing efficiency. Using the available constraints on formation time of the angrites, the activity of an early dynamo and the modelled thermal evolution, we put constraints on the size of the angrite parent body.

The slab-mantle interaction, deformation and its translated surface topography effects

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The subduction of the Earths top boundary layer, into the mantle, is a fundamental process, unique to our planet [2,3]. However, despite its central role in shaping the Earths surface, and its role as an enabler for the emergence and evolution of life, very little is known about this process at depth, the interaction of the subducted slab with the mantle, particularly at the transition zone and how this is translated to the surface [1,2,3].

Here we present a 2D self-consistent, one sided subduction model, with variants that include a continental overriding plate, a mantle wedge above the subducting slab and a variable viscosity profile. Our model is solved by the finite difference/volume multigrid code StagYY [4] and uses the sticky air approach which allows for the generation of realistic topography at the trench, subducting and overriding plates.

This study investigates various subduction parameters such as; the slab-mantle viscosity contrast, slab geometry, the slab strength and its ability to resist deformation. This in order to constrain related surface observables such as back-arc basins and island-arcs, and trench mobility. We attempt to identify which of these parameters are most important to generate the observed topography at subduction zones and if any other factors are required to sustain the interplay between the gravitational and viscous forces that produce rollback and slab stagnation. We also analyse the dual nature of the upper-lower mantle transition zone in an attempt to identify the effects of viscosity and phase changes on the slab evolution, its stagnation or transition into the lower mantle and the resulting topography at the surface.

This approach tests different types of subduction parameters and the resulting slab and surface behaviour through a realistic Earth-like model in an attempt to identify the key players in slab and surface evolution. This will not only allow us to understand surface, slab and mantle behaviour at various depths with different viscosities, but will also provide insights into subduction dynamics both at present day and in the past.

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Influence of detachment faults on intra-oceanic subduction initiation: 3D thermomechanical modelling

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Extensional detachment faults have been widely documented in slow-spreading ridges on Earth and due to their weakness can effectively localize deformation. It has been proposed that these weak detachments provide ideal conditions for the nucleation of a subduction zone parallel to the ridge axis when ridge-perpendicular compressional forces are applied, i.e. like in the western Neotethys in Jurassic times [1]. However, only 2D numerical models were carried out to support this theory. To explore the concept of intra-oceanic subduction initiation along detachment faults, we conducted 3D numerical modelling experiments with the I3ELVIS code [2] in order to investigate both the formation of detachment faults in slow oceanic spreading systems and their response upon inversion from oceanic spreading to convergence.

According to the numerical experiments, the formation of detachment faults strongly depends on the magnitude of the healing rate of faulted rocks in oceanic lithosphere. The detachment faults formed in our numerical models deviate from the simple conceptual model of oceanic detachment faulting where fault footwalls are rotated, leading to the formation of oceanic core complexes [3]. The controlling parameters for oceanic core complexes are not necessarily similar to those for detachment faults, and the formation of detachment faults is therefore less strongly coupled with the formation of oceanic core complexes than formerly proposed.

Upon compression, an asymmetric spreading pattern is prone to asymmetric inversion, where underthrusting of one oceanic plate under the other occurs. The detachment faults localize extensive deformation, but the conceptual model for the direct inversion of a single detachment fault into an incipient subduction zone has not been supported numerically. Our results show instead a widespread interaction of multiple detachment faults when convergence is being applied. The nascent subduction zone cuts through the base of several detachment faults, thereby forming an initial accretionary wedge in the incipient fore-arc.

Our results therefore call for further research on three-dimensional modelling of the interplay between detachment faults and oceanic core complexes and on the initiation of a self-sustaining subduction zone adjacent to a pre-existing oceanic ridge.

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Layer-formation in the early Earth's mantle

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The thermal history of the Earth, it's chemical differentiation and also the reaction of the interior with the atmosphere is largely determined by convective processes within the Earth's mantle. A simple physical model, resembling the situation,shortly after core formation, consists of a compositionally stable stratified mantle, as resulting from fractional crystallization of the magma ocean. The early mantle is subject to heating from below by the Earth's core and cooling from the top through the atmosphere. Additionally internal heat sources will serve to power the mantle dynamics. Under such circumstances double diffusive convection will eventually lead to self organized layer formation, even without the preexisting jumps is material properties. We have conducted 2D and 3D numerical experiments in Cartesian and spherical geometry, taking into account mantle realistic values, especially a strong temperature dependent viscosity and a pressure dependent thermal expansivity. The experiments show that in a wide parameter range. distinct convective layers evolve in this scenario. The layering strongly controls the heat loss from the core and decouples the dynamics in the lower mantle from the upper part. With time, individual layers grow on the expense of others and merging of layers does occur. We observe several events of intermittent breakdown of individual layers. Altogether an evolution emerges, characterized by continuous but also spontaneous changes in the mantle structure, ranging from multiple to single layer flow. Such an evolutionary path of mantle convection allows to interpret phenomena ranging from stagnation of slabs at various depth to variations in the chemical signature of mantle upwellings in a new framework.

The influence of internal heat sources on mantle convection with phase transitions

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Changes of mineral phases (e.g. *olivine* $\mapsto$ *wadsleyite, ringwoodite* $\mapsto$ *perovskite*) are known global features within the Earth's mantle affecting the style of convection. For example the endothermic phase change at 660 km depth is supposed to break down convection into two layers. In general, phase transitions are characterised by a density jump $\Delta\rho$ and the Clapeyron-slope $\gamma = \mathrm{d}p/\mathrm{d}T$, where exothermic phase transitions ($\gamma > 0$) enhance convection and endothermic phase transitions ($\gamma < 0$) impede convection. Since phase transitions correspond to a certain temperature and pressure it is likely that they are affected by the rising internal temperature due to internal heat sources. To examine how, and under which circumstances internal heating influences phase transitions, a systematic numerical study has been carried out using a two-dimensional, isoviscous mantle convection model.

The results exhibit that the phase transition is deflected from its equilibrium depth in the presence of internal heat sources. The strength of this deflection depends on the magnitude of the Clapeyron-slope and the amount of internal heating on the total heat flux. Besides, the study indicates that the transition from single- to double-layer convection gets broader and less sharp for an increased internal heating rate. Using the mass flux across the phase boundary as a measure for the degree of layering, one can show that internal heating produces a more permeable phase transitions if convection is layered. Contrary the phase transition gets less permeable in the case of single-layer convection. Despite the influence of an internal heat production on the equilibrium depth and the width of transition from single- to double-layer convection there is no evidence for a shift of the actual threshold to layered convection, i.e. the critical Clapeyron-slope appears to remain unaffected by internal heat sources.

Impact of the overriding plate rheology on convergence zone dynamics

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Most of deformation at the surface of the Earth is localized at tectonic plate boundaries. This deformation is accommodated in very different ways depending on the tectonic setting. In convergence zones, oceanic or continental subduction/collision can form contrasted structures in terms of unit size, morphology and metamorphism (e.g., the Andes vs. the Alps). Moreover, some convergent zones with apparently similar tectonic settings (e.g. continent-continent convergence) show very different deformation styles, either very localized (e.g. in the Alps) or, at the opposite, distributed over thousands of kilometers (such as in the Himalaya/Tibet). Finally, other convergent zones seem to show similar structures (e.g. Tibetan and Altiplano/Puma plateaus) beside their different tectonic settings.

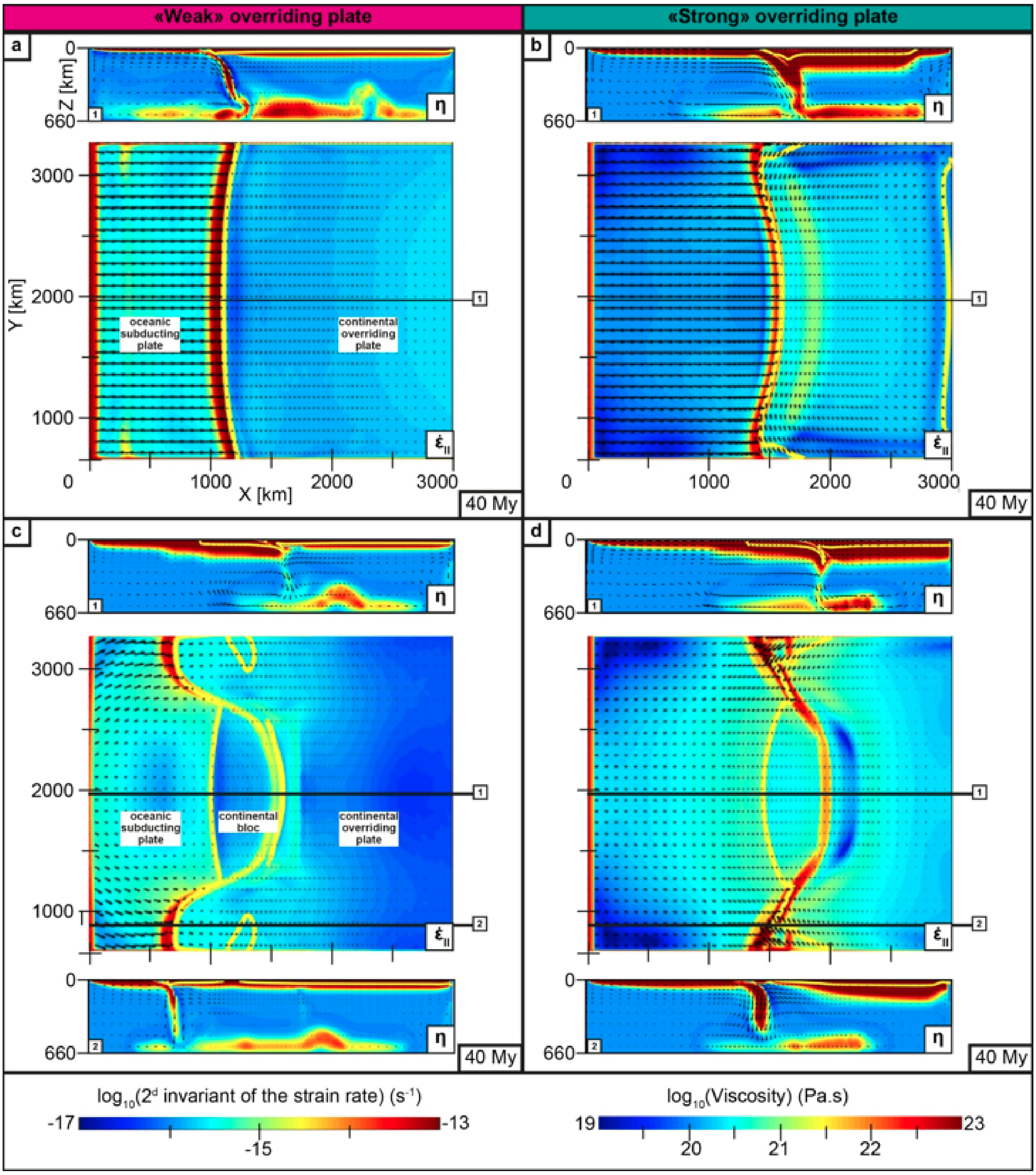
Hence, although the mechanism of plate convergence appears to be the same in each case, the structures obtained at the surface seem to be unique. Rheology of both the lower subducting plate and of the plate interface is known to influence the convergence zones dynamics. However, the influence of the overriding plate rheology on the convergence zones dynamics and deformation style at plate boundaries remains poorly understood.

In this study, we present 3D thermo-mechanical numerical models, for oceanic and continental subduction/collision settings where the rheological properties of the overriding plate are tested. For this, we modified the overriding lithosphere geotherm in order to control the thicknesses of the thermal plate ranging from 40 km (corresponding to a "weak" overriding plate) to 150 km (corresponding to a "strong" overriding plate).

Our first results show that the overriding plate rheology (which highly depends on the initially imposed temperature profile) has a high impact on the convergence zone dynamics:

- First, some noticeable geometrical differences appear cross section view. In the case of a "strong" overriding plate, the slab dip, the coupling at the subduction interface and the topography are higher. The slab break-off occurs at shallower depth and the asthenospheric flow is more localised all around the slab.
- In plan view, the trench location and shape are strongly linked to the overriding plate rheology. The trench is more mobile with a "weak" overriding plate.
- Our models also show some differences in terms of kinematics. Trench motions are faster for the "weak" model whereas the timing of slab break-off is delayed and its impact on the asthenospheric flow is observable over a longer period of time for the "strong" overriding plate.
- Finally, the strengthof the overriding plate controls the distribution of its own deformation. The location and the amount of strain differ between the two end-members. The "weak" model shows a diffuse deformation in the whole overriding plate while in the "strong" model the deformation is much more localised at the trench.

This study question the classical vision of the convergence zones. Our results lead to reconsider the convergence zone dynamic as a whole, i.e., considering also the overriding plate and its influence and not only the subducting plate.



Horizontal views presenting the distribution of the second invariant of the strain rate close to the surface (Z = 10 km depth) and XZ sections of the viscosity field at the center of the box for a) oceanic subduction with weak overriding plate, b) oceanic subduction with strong overriding plate, c) continental subduction/collision with weak overriding plate and d) continental subduction/collision with strong overriding plate. Yellow lines and black arrows correspond to crustal-lithospheric mantle boundaries and velocity field, respectively.

Life on a dry Planet

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An outstanding question in mantle convection modeling is the water content of the Earths mantle since small amounts have very large effects on rheology. Here we share a work in progress that seeks to understand the minimum amount of water in the atmosphere-ocean-rock system to constrain the formation and dynamics of Earth-sized terrestrial planets. After formation and solidification of a crust, we assume a planet in which the surface contains some amount of liquid water circulating in the ocean-atmosphere system.Given that hydrogen loss to space is inevitable for Mars to Earth-size planets, these planets are on a downhill slide toward becoming too dry to develop or support a global surface biosphere.Here we define a global biosphere one that is capable of altering the planets atmosphere for thousands of years.The more water the planet has at its surface and interior after formation, the longer it has to develop feedbacks to slow the rate of hydrogen loss, or the higher it is on thewater slide. For example, the Earths biosphere dramatically slowed hydrogen loss following the Great Oxidation Event around 2.5 Gyr due to oxygenic photosynthesis.We also consider the possiblility that the biosphere itself can increase the rate of hydrogen escape if it releases hydrogen from rock into the ocean-atmosphere system.If the planets exchange of volatiles through the interior and ocean-atmpohsere does not develop feedbacks that trap hydrogen, the surface water will eventually disappear and lead to a biosphere collapse. We find that a Mars size body will likely lose an equivalent of an Earth ocean in around 1 Gyr, while an Earth-mass body could have up to 10 Gyr.

Recent craton growth by slab stacking beneath Wyoming

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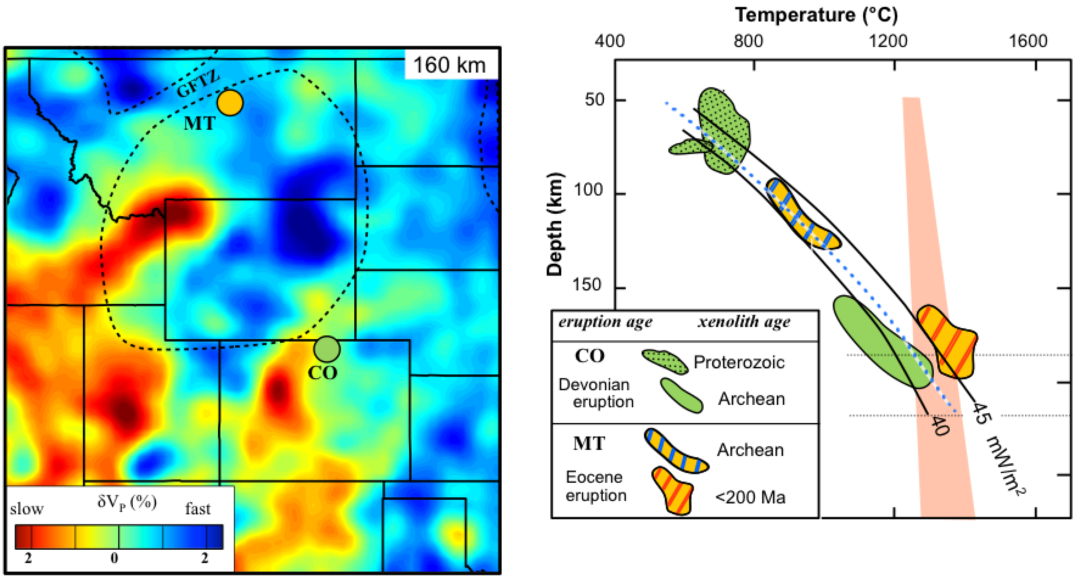
Seismic tomography images high-velocity mantle beneath the Archean Wyoming craton extending to >250 km depth. Although xenoliths and isostatic arguments suggest this mantle is depleted of basaltic component, it is not typical craton: xenoliths suggest that the mantle beneath ∼150 km is only ∼170 m.y. old, and that the base of Archean mantle was truncated from ∼190 to ∼150 km depth sometime after the Devonian. The Sever-Laramide orogeny is the only significant tectonic event to have affected the region during this time, and presumably caused the truncation. Apparently, the base of the Wyoming craton was removed and young, depleted mantle was emplaced beneath the Wyoming craton during the Sevier-Laramide orogeny. This inferred modification of craton deep within a continental interior seems difficult to explain. However, the Shatsky Rise conjugate ocean plateau subducted beneath North America and arrived beneath Wyoming just where and when needed. We argue that the Wyoming craton experienced a ∼75 Ma phase of growth through a three-stage process. (1) Farallon flat-slab subduction removed ∼40 km of the Wyoming craton base. (2) This was followed in the early Laramide by emplacement of basalt-depleted (buoyant) ocean plateau mantle lithosphere of the Shatsky Rise conjugate. (3) The geologic recorded of vertical motions suggest Farallon crust eclogized beneath the Wyoming-Colorado region, causing downwarping, and then escaped into the Earths interior at 70-75 Ma, causing uplift. The initiation of uplift is coincident with initiation of Colorado Mineral Belt magmatism, which trends along side of the reconstructed position of the Shatsky Rise conjugate at that time, and it is the only significant Laramide-age magmatism in the western U.S. The Wyoming region now stands 1-2 km above the sea-level position it occupied for ∼1 Ga prior to Sevier-Laramide orogeny.



Xenolith sampling of the deep lithosphere. (left) The two kimberlites sites that sampled to depths of ∼200 km. Dashed lines show the approximate boundaries of cratons. The Colorado (CO) site erupted in the Devonian just south of the Proterozoic-Archean suture. The Montana (MT) site erupted in Archean crust during the Eocene. Background image is the P-wave model at 160 km depth. (right) Temperature-depth plot of the two xenoliths sites.The Devonian Colorado xenoliths (green) define a cool geotherm to ∼200 km depth, and the deeper population sampled depleted Archean mantle. The Eocene Montana xenoliths (orange) have two distinct populations. A depleted Archean low temperature population (blue stripes) extends to depths of ∼140 km and lies on a cool geotherm typical of cratons. The extension of this geotherm to mantle solidus temperatures defines a pre-Laramide craton of 170-230 km thickness. A depleted high temperature population (red stripes) lies on a warm geotherm and samples depths of ∼160-200 km. Unlike the other xenoliths plotted on this figure, these xenoliths have a young age (∼170 Ma). Apparently the cool, ∼200-km thick craton was truncated at 140-160 km depth, with the deeper mantle being replaced by relatively young and depleted mantle that was created at relatively high temperature.

The Columbia River Flood Basalts: Initiated from below, driven from above

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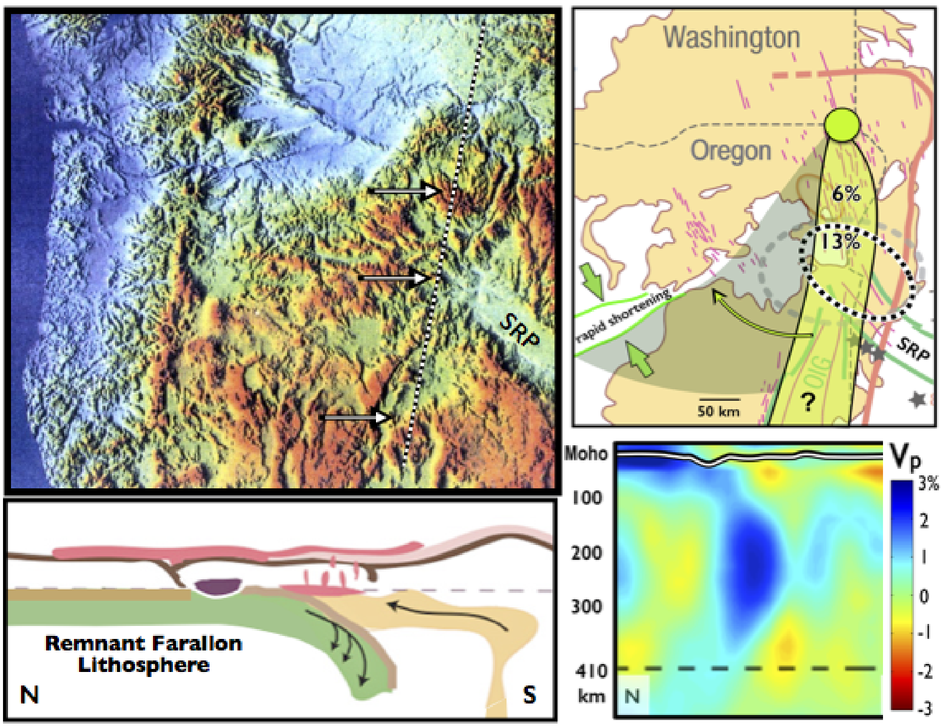
The Columbia River flood basalts started nearly 17 Ma in southern Oregon (bottom arrow in topography frame). But strangely, they did so without observable pre-eruptive uplift, and they then propagated rapidly off track to the north, where they erupted 80% of their basalt. We attribute northward propagation to a melt-enabled S-to-N delamination of Farallon slab that was flat against the base of the continent (bottom panels). A major magma chamber was established beneath what now is the westernmost Snake River Plain (middle arrow in topography frame). Slab delamination and continent heating weakened North America, allowing the existing stress field to rotate a wedge of crust (gray in upper right panel), associated with NNE-directed contraction in central Oregon up to ∼13% E-W extension near the magma chamber that occurred during the time of the large eruptions. We attribute the magmatic flareup to this extension. Delamination also allowed the garnet-rich (dense) root to the Wallows batholith to founder at a time that is not well constrained. Starting 10 Ma, faulting allowed this batholith (and only this batholith) to rise above adjoining crust by 2 km, creating the Wallowa Mts (top arrow in topography frame). Thus, although flood basalt activity was initiated by the arrival of a small plum head, lithospheric instabilities triggered by the plume were responsible for the large and strange volcanic behavior, and the buoyancy-driven uplift of the Wallowa Mts. We remain uncertain about what created the topographic bullseye centered on the Wallows Mts, seen in the topography panel.



Top left. Topography. The dotted line is the cross-section line for the bottom two panels. Bottom left. Illustration of Farallon slab delaminating from the base of the continent, enabled by plume-generated melt (red) that ponded at the Moho and detached the slab. The dense Wallowa batholith root is shown with the dark shape at the base of North America crust. Bottom right. Composite P-wave tomographic image of the crust and upper mantle, showing the inferred Farallon slab in blue. Top right. Representation of the block rotation (gray area) related to the main phase of flood basalt eruption. N-S trending dikes occupy ∼13 % of the crust near the inferred magma chamber (dotted line), and are common throughout the region near the Idaho-Oregon border, shown in bright green. The pink line separates Ancient continental crust from the accreted terranes that hosted the flood basalt dikes.

Self-consistent generation of primordial continental crust in global mantle convection models

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We present the generation of primordial continental crust (TTG rocks) using self-consistent and evolutionary thermochemical mantle convection models [1]. Numerical modelling commonly shows that mantle convection and continents have strong feedbacks on each other. However in most studies, continents are inserted a priori while basaltic (oceanic) crust is generated self-consistently in some models [2]. Formation of primordialcontinental crust happened by fractional melting and crystallisation in episodes of relatively rapid growth from late Archean to late Proterozoic eras (3-1 Ga) [3] and it has also been linked to the onset of plate tectonics around 3 Ga. It takes several stages of differentiation to generate Tonalite-Trondhjemite-Granodiorite (TTG) rocks or proto-continents. First, the basaltic magma is extracted from thepyrolitic mantle which is both erupted at the surface and intruded at the base of the crust. Second, it goes through eclogitic transformation and then partially melts to form TTGs [4,5]. TTGs account for the majority of the Archean continentalcrust.

Based on the melting conditions proposed by Moyen (Lithos 2011), the feasibility of generating TTG rocks in numerical simulations has already been demonstrated by Rozel et al. [6]. Here, we have developed the code further by parameterising TTG formation. We vary the ratio of intrusive (plutonic) and extrusive (volcanic) magmatism [7] to study the relative volumes of three petrological TTG compositions as reported from field data. Furthermore, we systematically vary parameters such as friction coefficient, initial core temperature and composition-dependent viscosity to investigate the global tectonic regime of early Earth. Continental crust can also be destroyed by subduction or delamination. We will investigate continental growth and destruction history in global compressible models spanning the age of the Earth.

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A quantitative analysis of transtensional margin width

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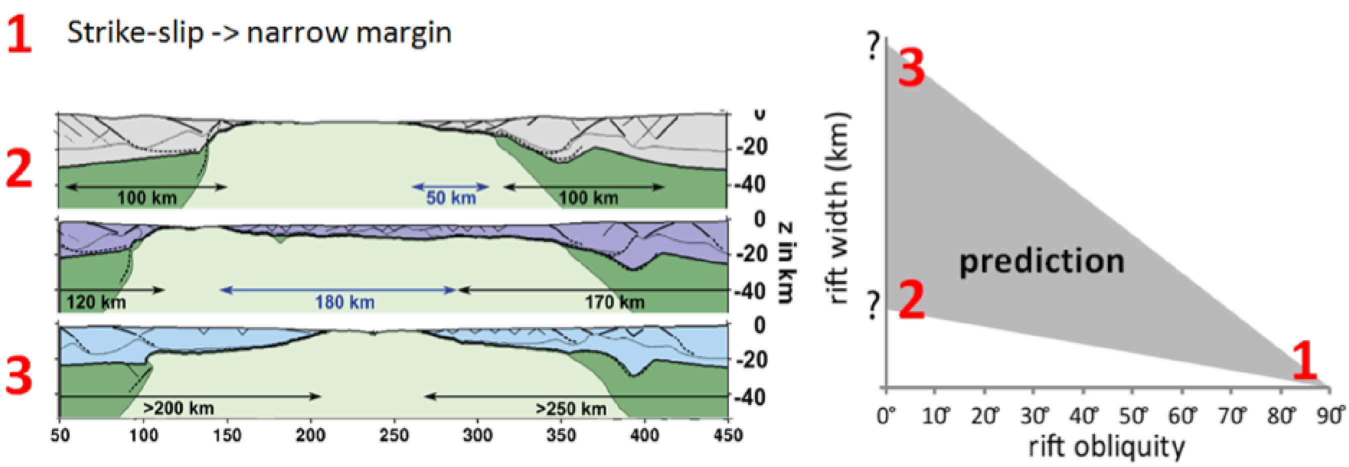
Rifted continental margins show variations in their width from a few hundred to almost 1000 km. During the Oligocene-Miocene, rifting in the Gulf of Aden led to deformation width of less than 200 km, while during the Late Jurassic, the separation between Iberia and Newfoundland led to deformation width more than 800 km. The movement direction was oblique to the rift trend, 65 for the Gulf of Aden, and orthogonal for the Iberia-Newfoundland with a rifting obliquity less than 10. Analogue and numerical modelling suggest that the deformation width of rifted margins may have a relationship to their obliquity of divergence, with high oblique margins narrower than low oblique margins (Figure). We test this by analysing the obliquity and rift width for 26 transtensional conjugate rifted margins segments margins in the Atlantic and Indian Oceans.

Plate reconstruction software GPlates (`www.gplates.org`) is used with several plate rotation models in order to estimate the movement direction and magnitude of rifts from the initial phases of continental rifting until breakup. The rifted margin deformation width corresponds to the distance between the onshore maximum topography and the offshore limit where the continental crust is thinner than approximately 10 km. For narrow rifted margins, the offshore limit usually corresponds to the Continent-Ocean Boundary, here defined as the last identified continental crust, while for extended rifted margins, such as the Norwegian margins, we consider the 10 km thick continental crust limit. The maximum topography limit is determined using the global relief model etopo1 (Amante and Eakins, 2009).

From our analysis of the 26 transtensional rifted margin, we found a weak but positive correlation between the obliquity of rifting and deformation width. Highly oblique margins are narrower than orthogonal margins, as expected from analogue models. This correlation may imply that the required strain for breakup is less for oblique margins, which has been argued for on the basis of numerical models.



Theoretical expectation of rift width versus rift obliquity with high obliquity margins narrower than low obliquity. In particular, numerical models such as Brune et al. (2014) suggest that orthogonal margins can be narrow or wide (2 and 3).

Geodynamic model of recent deformation in central Eurasia

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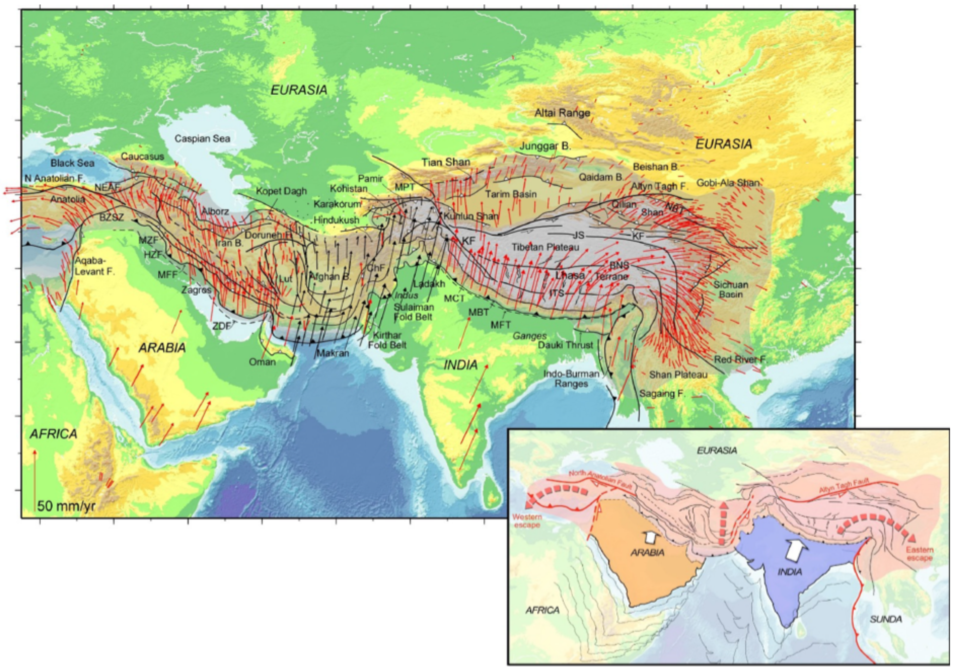
Central Eurasia hosts wide continental orogenic belts between India and Arabia with Eurasia, showing diffuse or localized deformation occurring up to hundreds of kilometres from the primary plate boundaries. Although numerous studies have investigated the neotectonic deformation in central Eurasia, most of them have focused on limited segments of the orogenic systems. Here we explore the neotectonic deformation of all of central Eurasia, including both collision zones and the links between them. We use a thin-spherical sheet approach in which lithosphere strength is calculated from the lithosphere structure and its thermal regime. We investigate the contributions of variations in lithospheric structure, rheology, boundary conditions, and fault friction coefficients on the predicted velocity and stress fields. Results (deformation pattern, surface velocities, tectonic stresses, slip rates on faults) are constrained by independent observations of tectonic regime, GPS and stress data. The modelled velocity field shows two large west- and east-directed continental escape toroidal velocity fields along the NW corner of Zagros-Iran and the NE corner of Himalaya-Tibet orogenic systems fitting GPS measurements. These modelled tectonic extrusions were the result of both strain rate and crustal and lithospheric thickness variations between the harder Eurasia plate and the softer amalgamated continental blocks that configured the southern margin of Eurasia before collision. The northern boundaries of Western and Eastern continental escapes are the North Anatolian fault and the Altyn Tagh fault, respectively. The linking zone between the Arabia-Eurasia and India-Eurasia collisions across the Afghan block shows an homogeneous N-directed velocity field with no deflection caused by the Arabia or India continental indentors.

To simulate the observed extensional faults in the Tibetan plateau a weaker lithosphere is required, provided by a change in the rheological parameters. A softer Tibetan plateau is compatible with the proposed lithospheric thinning beneath it. The southward movement of the SE Tibetan plateau can be explained by the combined effects of the Sumatra trench retreat, a thinner lithospheric mantle, and strik-slip faults in the region. This study offers a comprehensive model for regions with little or no data coverage, like the Arabia-India inter-collision zone, where the surface velocity is northward showing no deflection related to Arabia and India indentations.



Tectonic map of the collision zone between Arabia and India plates with Eurasia plate, integrating GPS-derived velocities (red arrows) and horizontal velocities calculated from the model (black arrows). The sketch in the lower corner shows the inferred northward velocity direction of the inter-collision zone (Pakistan and Afghan block), as well as the Eastern and Western escape tectonics produced by the westernmost Arabia and the easternmost India indenters. Thin black lines indicate the northward drift of Arabia and India plates.

Mechanical characterization of the Eastern Central Atlantic hotspots

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The Canary archipelago (NW Atlantic African margin) is one of the best studied volcanic chains in the world yet its structure and geodynamic evolution are still under considerable debate. Recently, Fullea et al. [1] analysed the 3D lithospheric-uppermost mantle thermochemical structure beneath the Canary Islands using an integrated and self-consistent geophysicalpetrological approach, and their results suggest that its lithosphere should be mechanically strong, in line with the range of thermal lithospheric thicknesses obtained in that study. This issue motivates us to explore to what extent the lithosphere beneath the Canary Islands is mechanically strong.

A useful proxy for the long-term lithospheric strength is given by the effective elastic thickness, T_e, which is related to the flexural rigidity, D, of a thin elastic plate by $D = ET_e^3/12(1\nu^2)$, where E is Youngs modulus and ν is Poissons ratio. Thus, T_e corresponds to the thickness of an idealized elastic plate that would bend similarly to the actual lithosphere under the same applied loads, and is related to the integrated mechanical strength of the lithosphere (e.g. [2]).

In this study we present high-resolution regional maps of the effective elastic thickness of the lithosphere, as well as of their associated surface and subsurface loading mechanisms, for an extensive area of the Eastern Central Atlantic, including the Canary Islands, but also Azores, Madeira and Cape Verde islands, and the Great Meteor Seamount (see Fig. 1).

To estimate the effective elastic thickness we calculate the coherence function relating topography and Bouguer anomaly (i.e. Bouguer coherence) by using the wavelet transform [3, 4]. We consider a simple thin elastic plate subjected to both surface and subsurface loads, following the load deconvolution procedure of Forsyth [5].

This analysis will constrain the mechanical structure of the lithosphere beneath the Canary Islands and other Eastern Central Atlantic hotspots, to advance the knowledge and understanding about their geodynamic evolution.

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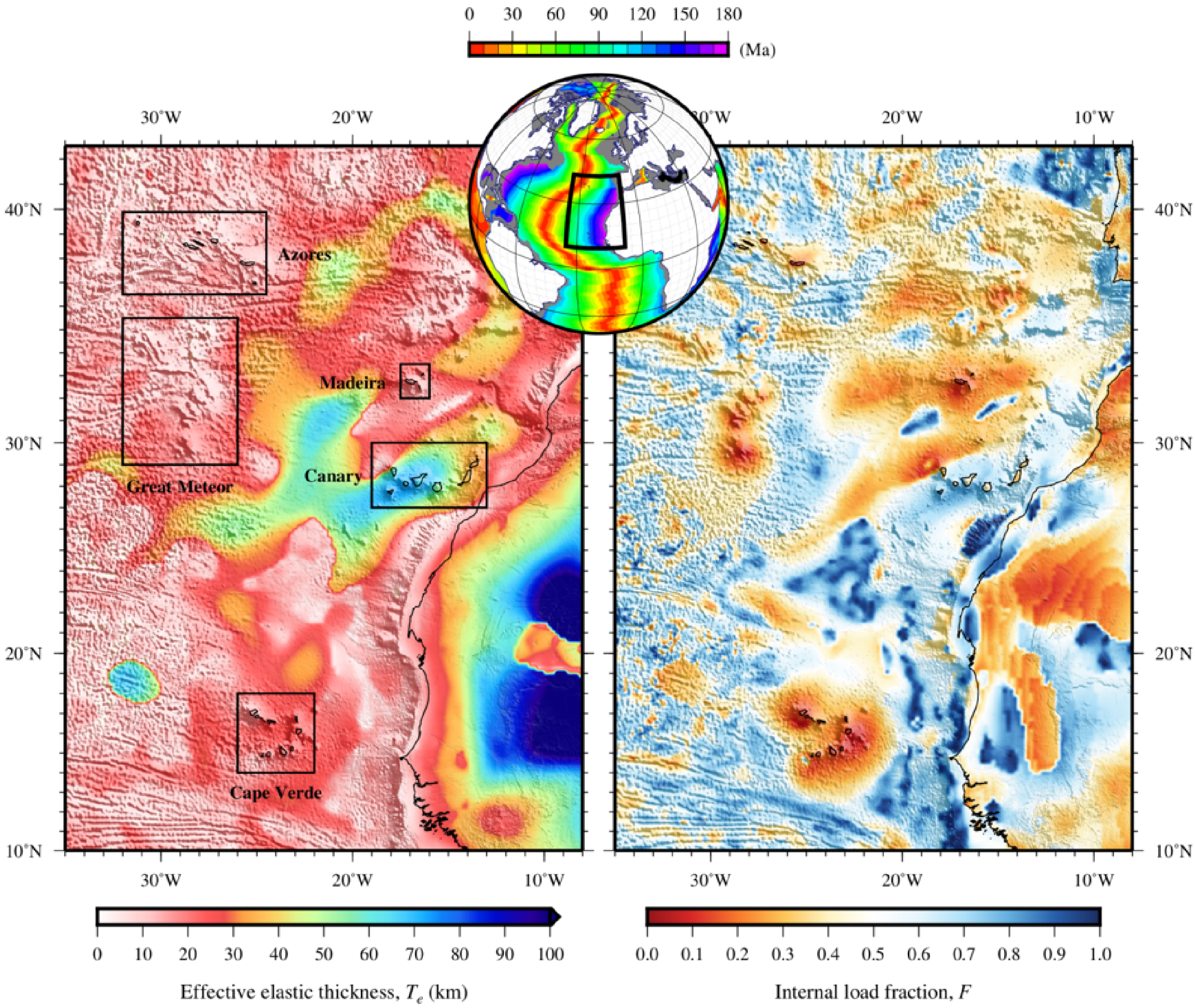

Effective elastic thickness (Te) and internal load fraction (F) over the Eastern Central Atlantic region, showing seafloor age data for context. In both images, topography shaded relief is superimposed.

Regularized non-local plasticity models for geodynamic simulations

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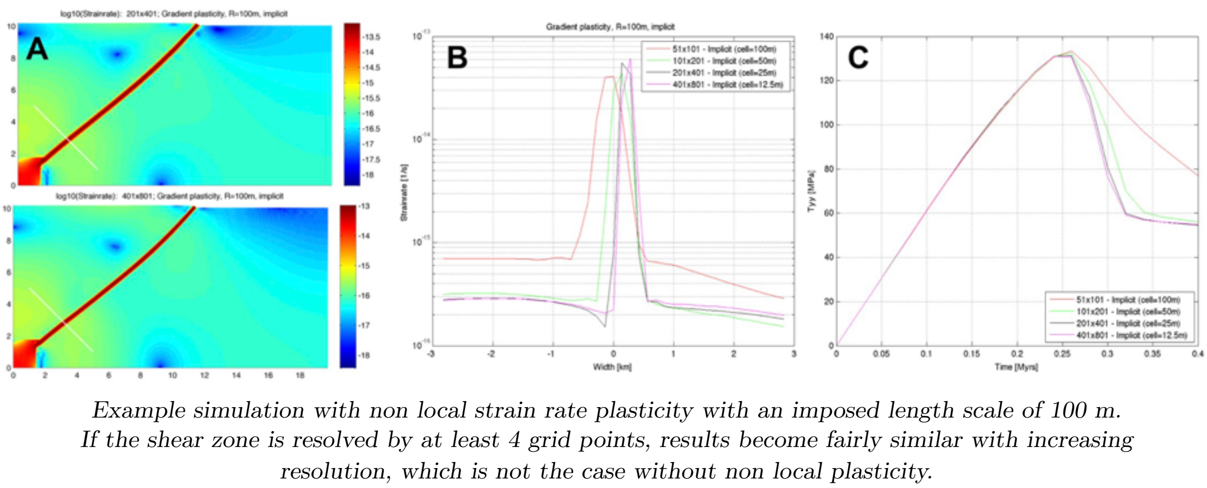
The Drucker-Prager or Mohr-Coulomb non-associative plasticity models commonly employed in geodynamic simulations are well-known to be mesh sensitive. As a result, benchmarks studies involving plastic localization do not give identical results, and stress-strain curves of the simulations not collapse on a single curve with increasing resolution. A related problem is that non-linear iterative solvers do not converge during certain time steps. If localization is caused by shear heating, however, such problems do not occur, as the width of the shear zone is set by the balance of heat production and diffusion [1].

Similar mesh-sensitivity issues have been described by the computational mechanics community decades ago [2,3], and a number of solution have been proposed which essentially add an (additional) internal length scale to the problem. There are several ways in which this can be done, but for the method to be widely employed within the geodynamics community, it is important that it can be easily added to existing codes and that it is computationally efficient.

Here, we test a number of previously proposed non-local plasticity models in which the length scale is set by either smoothening properties within a circle of specified radius, or by employing a diffusion-type algorithm with diffusivity adjusted to fit a specified diffusion length scale. We test both strain and strain rate weakening algorithms in a number of codes. Results suggest that non local strain weakening applied to the cohesion and friction angle does regularize the strain field but mesh sensitivity remains in the strain rate field. Non-local strain rate weakening, in the other hand, performs better in this respect. There is little difference between circular and diffusion-type smoothening algorithms, but the diffusion type algorithm is computationally considerably faster and easier to adapt to parallel architectures as it requires only a minor modification of existing temperature diffusion solvers (which most geodynamic codes include already).

We will discuss some of the issues that remain to be solved, the effect of rheology (viscoplastic vs. viscoelastoplastic) and how it affects the performance of the nonlinear solvers.

[1] Schmalholz et al., Tectonophysics, 613. p160-175, 2014.
[2] de Borst et al., Engineering Computations, 10(2), p99-121, 1993.
[3] Bazant & Jirasek, Journal of Engineering Mechanics, 128(11), 2002.



Example simulation with non local strain rate plasticity with an imposed length scale of 100 m. If the shear zone is resolved by at least 4 grid points, results become fairly similar with increasing resolution, which is not the case without non local plasticity.

The dynamics of Adria: a unique complexity unraveled in laboratory models

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The present geology of the Alpine-Mediterranean region was established during the late Cenozoic by subduction and suturing of small oceanic fragments and collision of continental blocks. This study is specifically focused on the Adria plate, which had ongoing subduction since the Miocene beneath the Apennines-Calabrian-arc and the Dinarides-Hellenic arc. Moreover, geophysical and geological evidences show, that along the Apennines chain a slab window developed during the last 2 Myr. Therefore, the Central Mediterranean offers a natural laboratory, to study a unique combination of geodynamical complexities, such as the double-sided subduction system and the subduction of a slab window.

The aim of this study is to investigate the effects of such complexities in subduction systems by means of laboratory models. We designed a set of models where we studied the effect of a) double-sided subduction; b) slab window subduction; c) the combined effect of those two ingredients. The experiments take place in a tank of 150x150x50 cm^3, filled with glucose syrup, which is used as the analog of the Earth mantle. The lithosphere is modeled with silicon putty, a mixture of pure silicon and iron fillers. Furthermore, the 660 km discontinuity is represented by an impermeable Plexiglas layer. In the slab window models, the window is represented by a pre-cut 1x6 cm2 hole on the plates center.

The experimental results show that: a) the double sided subduction occurs with a slightly smaller trench retreat rate with respect to a single subduction with a fixed trailing edge condition. The evolution of the double-sided subduction occurs in phases: 1)an initial free sinking phase of the slabs into the upper mantle; 2) slabs interaction with the 660 km discontinuity; 3) steady state subduction with the two slabs lying on the 660 km discontinuity; 4) slab-slab interaction when the two trench approach within a distance of ca 500 km. Trench velocities are slower and the escaping mantle flux is increased; 5) final steady state condition occurring when each slab exits from the area of reciprocal influence with the nearby subduction zone. b) The subduction of a slab window in a single subduction setting produces a peculiar stage characterized by a triple arcs geometry. Once the slab window is consumed, the subduction resumes at the center of the plate with a very fast trench retreat rate, resulting in a final single arc geometry. c) When slab window subducts in a double-sided subduction situation, the three arcs geometry also occurs and remains until the end of the model. On the opposite side, the subduction rate increases with respect to the simple double-sided models. This happens especially in the later phase, when the two subduction zones are close to each other. The increasing subduction rate is mostly the result of the movement of the plate towards the active subduction.

The modeling results are used to unravel the tectonic complexity of the Central Mediterranean.

Lithosphere erosion and breakup due to interaction between extension and plume upwelling

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We present the results of thermo-mechanical modelling of extension and breakup of a heterogeneous continental lithosphere, subjected to plume impingement in presence of intraplate stress field [1]. We incorporate partial melting of the extending lithosphere, underlying upper mantle and plume, caused by pressuretemperature variations during the thermo-mechanical evolution of the conjugate passive margin system. Effects of melting included in the model account for thermal effects, causing viscosity reduction due to host rock heating, and mechanical effects, due to cohesion loss. Our study provides better understanding on how presence of melts can influence the evolution of rifting. Here we focus particularly on the role of melting for the temporal and spatial evolution of passive margin geometry and rift migration. Depending on the lithospheric structure, melt presence may have a significant impact on the characteristics of areas affected by lithospheric extension. Pre-existing lithosphere heterogeneities determine the location of initial breakup, but in presence of plumes the subsequent evolution is more difficult to predict. For small distances between plume and area of initial rifting, the development of symmetric passive margins is favored, whereas increasing the distance promotes asymmetry. For a plume-rifting distance large enough to prevent interaction, the effect of plumes on the overlying lithosphere is negligible and the rift persists at the location of the initial lithospheric weakness. When the melt effect is included, the development of asymmetric passive continental margins is fostered. In this case, melt-induced lithospheric weakening may be strong enough to cause rift jumps toward the plume location.

[1] Lavecchia et al., Earth and Planetary Science Letters, 467, p89-98, 2017.

Pulses of continental break-up, causes and consequences

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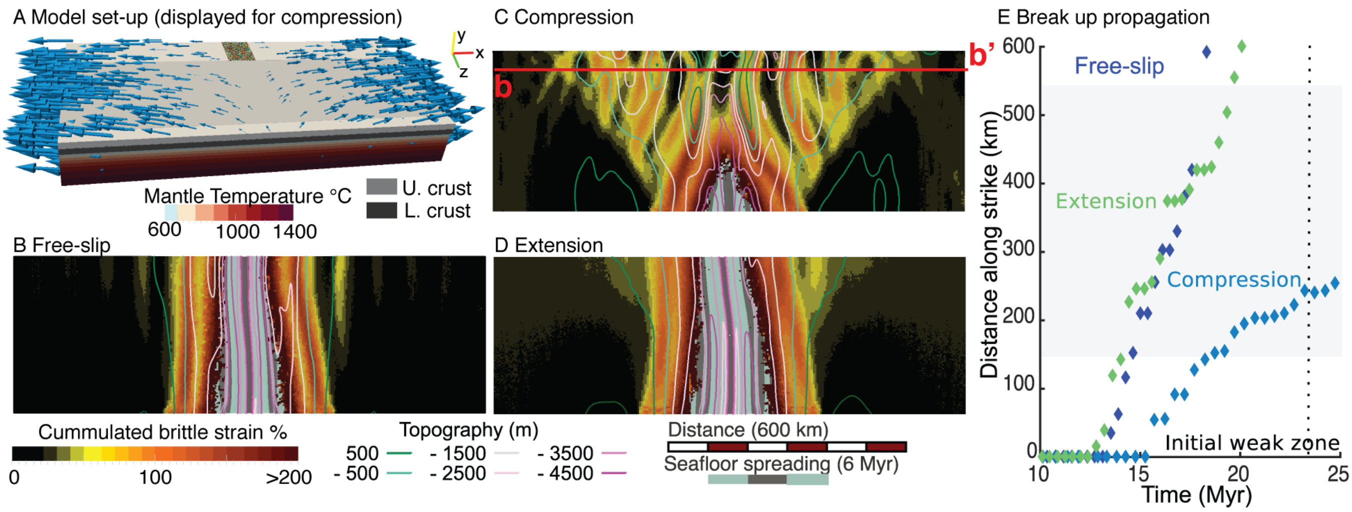
V-shaped oceanic propagators are often attributed to along strike variation in rate of stretching due to the proximity of the pole of rotation, often referred as scissors opening. Yet, similar decrease in rate of propagation of break-up emerges from more realistic lithospheric models where two offset oceans propagate in opposite direction. These models produce tens of millions years long break-up stagnation which can explain the formation of V-shaped oceanic propagators. However, in most natural cases, break-up of continent followed by oceanisation propagates in one direction and no propagator coming from opposite direction can explain the periods of slow propagation. Here, we study how a small amount of compression or extension acting normal to the direction of propagation influences the rate of break-up propagation with the help of three thermo-mechanical models: a reference cylindrical experiment, and two experiments in which a small amount of shortening or stretching is applied in the third dimension (Figure A). All three models contains a weak zone in which break-up occurs after 10 to 15 Myr of stretching before propagating across the model. After 23 Myr of evolution, the break-up has propagated in the pristine part of three models. Finite plastic strain outlines the orientation of major faults bounding the passive margin. In the models using free slip boundary condition (Figure B) or 2.5 mm/yr extension in z direction (Figure D), the passive margins are almost straight and very little difference are observed along strike. The model with 2.5 mm/yr compression along z (Figure C) shows the formation of a wide continental rift at the front of a V-shaped propagator. The models with no tectonic forcing or out of plane extension display a clear linear trend with break-up propagation rates of approximately 150 km/Myr.The rate of propagation of the experiment in compression is best approximated by a square root function. We will show how this mode of stalled propagation applies to the opening of the South China Sea.



A model set up; B plastic strain after 23 Ma for free slip BC; D; plastic strain after 23Ma for compressional BC. D plastic strain after 23Ma for extensional BC; E Rate of propagation of continental Break-up with time.

The influence of the orogenic lithospheric strength on foreland deformation patterns

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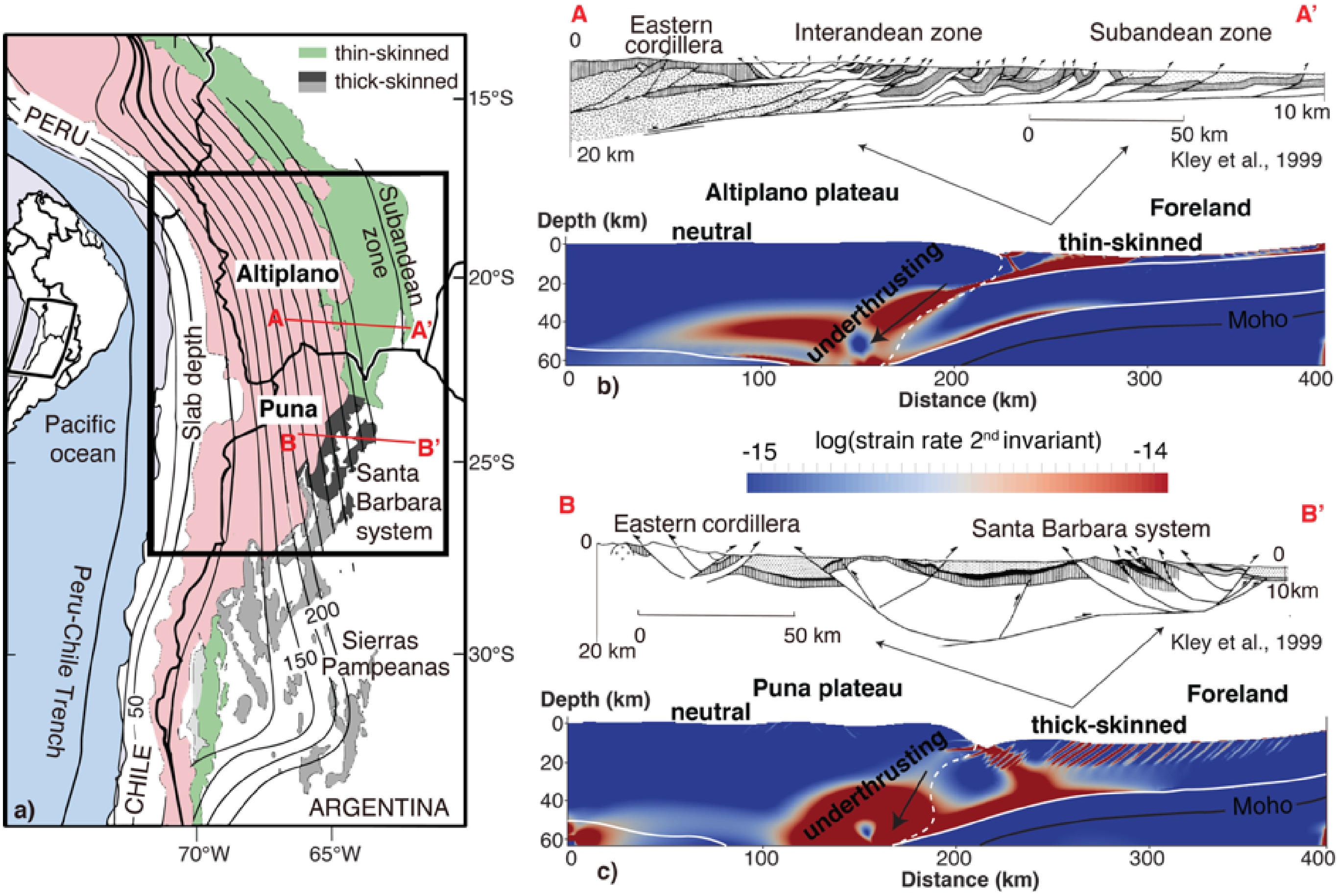
Deformation in foreland fold-thrust belts adjacent to the orogen wedge commonly includes shallow thin-skinned and deep thick-skinned structures, which are distinguished by the basement-involved shortening. A good example is the N-S oriented deformation diversity in central Andean Orogen including a broad thin-skinned Sub-Andean thrust belt in the foreland of Altiplano Plateau and the thick-skinned deformation in the Santa Barbara system in south Puna foreland. The mechanism of different deformation patterns in the orogenic foreland remain controversial. Previous studies suggested that they might be controlled by strength variations of the lithosphere in which the lithosphere and crust thickness, the thermal structure, as well as sedimentary loads and strength of sediments play an important role.

Here we use high-resolution numerical models to investigate these factors. The models show that the pure shear shortening occurs when the lithosphere under the orogen is thicker (stronger) than the foreland lithosphere with the same thick crust. When the orogenic lithosphere is weaker with either thinner lithosphere or thicker crust, by contrast, the foreland crust underthrusts beneath the orogen in simple shear shortening mode. The thick-skinned structure results mostly from pure shear shortening, but may also take place during limited foreland underthrusting when the mechanically weak sedimentary layer is absent in foreland. A transition to thin-skinned thrusting requires both mechanically weak foreland sediments and the process of foreland underthrusting. The amount of thin-skinned deformation is increasing with the orogenic crust thickening.

The factors of wet/dry composition of the lower crust and mantle and strain rate have small effect on the foreland deformation. The high-resolution model results are consistent with previous numerical studies with application to the foreland of the Altiplano-Puna Plateau (Figure). Future work will be focused on the application to other foreland regions in Southern Andes, Colorado Plateau, and Tibet Plateau.

[1] Kay & Coira, Geological Society of America Memoirs, 204 (June), p229-259, 2009.



The case of the foreland deformation of Altiplano-Puna Plateau (a, modified from [1]), which has two different styles of deformation(b, c).

Intraplate volcanism in northeast China due to upwellings rising from the stagnant slab

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Major intraplate hotspot volcano chains are well explained by plume theory. However, the mechanisms for non-hotspot continental intraplate volcanism remains controversial. Intraplate continental volcanism commonly occurs in regions located above stagnant subducted slabs, such as in northeast China. Here, we explore the role of the stagnant slab and of mineral water stored in the transition zone for the formation and evolution of intraplate volcanoes in northeast China. We explore two-dimensional regional models of convection in the upper and mid mantle. The effect of water on melting behavior and density are considered. We find that the stagnant slab is unstable and will extend laterally in the transition zone. Upwellings rise from the edges of the slab, out of the warm and buoyant harzburgite underbelly of the slab, as well as from the hydrous layer atop the slab within a couple of Myrs. They rise to $\sim$400 km depth and are then entrained by sub-lithospheric small-scale convection cells to reach the base of the lithosphere after a couple of tens of Myrs. The volumes, patterns and composition of related decompression melting depend on model parameters, such as e.g. the water content in the hydrous layer above the slab. We also explore the effects of lateral heterogeneity within the slab and find that even small heterogeneity is sufficient to significantly advance convective instability, and thus the timing and volumes of related mantle melting. The study of intraplate continental volcanism can indeed improve our understanding of upper-mantle and transition-zone dynamics.

Timing and distribution of magmatism at magma-poor margins: Controls from crustal rheology and depleted cratonic lithosphere

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Continental rifting and formation of rifted margins are fundamental processes in plate tectonics. The thinning of continental lithosphere creates accommodation for upwelling of asthenospheric mantle and results in magmatism at passive margins. Yet, the timing and distribution of magmatism remains incompletely understood. Classical models of rifting, such as pure-shear or simple-shear extension, often predict a simple breakup of the lithosphere and therefore associate the variation of magmatism to temperature change of sub-lithospheric mantle. However, observations have shown complex, depth-dependent extension and revealed large lateral variation of magmatism that is not explained by thermal effect alone. Type examples of depth-dependent rifting are defined at (1) the Iberia-Newfoundland conjugate margins (Type I, narrow) and (2) some central South Atlantic margins (Type II, wide). Here we use 2-D numerical models to investigate melt generation for margins with various rifting styles. We consider four end-member models (I-A/C, II-A/C) that focus on the effects of margin width (Type I versus Type II) and lithospheric counterflow (C models). We show that the crustal rheology is the key factor that controls the width of margin, and that both margin width and lithospheric counterflow have significant influence on magmatism. Model I-A develops narrow margins with normal magmatism, whereas model II-A develops wide margins with thick (>18 km) igneous crust without the presence of high temperature anomaly. Lithospheric counterflow may suppress magmatic activity, leading to the formation of narrow margins with exhumed continental mantle (model I-C) or non-volcanic wide margins with hyper-extended crust (model II-C). We illustrate that our models are comparable with observations at the Gulf of Aden, Iberia-Newfoundland and some central and southern South Atlantic conjugate margins.

Continental underplating after slab break-off

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We investigate the evolution of continental collision, particularly the fate of the subducted continental lithosphere after slab break-off. We perform three-dimensional numerical models of a subducting oceanic plate that has a 2000 km wide continental block in the middle that collides with a continental overriding plate. We vary the width of the oceanic sides and the density structure of the continental indentor to investigate what controls the occurrence of underplating and its dynamics.

We find that in some scenarios the subducting continental lithosphere underthrusts the overriding plate not immediately after it enters the trench, but after oceanic slab break-off. In this case, the continental plate first subducts with a steep angle and then, after the slab breaks off at depth, it rises back towards the surface and flattens below the overriding plate, forming a thick horizontal layer of continental crust that extends for about 200 km beyond the suture. This type of behaviour depends on the width of the oceanic plate marginal to the collision zone: wide oceanic margins promote continental underplating and marginal back-arc basins; narrow margins do not show such underplating unless a far field force is applied.

Our models show that, as the subducted continental lithosphere rises, the mantle wedge progressively migrates away from the suture and the continental crust heats up, reaching temperatures >900°C. This heating might lead to crustal melting, and resultant magmatism. We observe a sharp peak in the overriding plate rock uplift right after the occurrence of slab break-off. Afterwards, during underplating, the maximum rock uplift is smaller, but the affected area is much wider (up to 350 km). These results can be used to explain the dynamics that led to the present-day crustal configuration of the India-Eurasia collision zone and its consequences for the regional tectonic and magmatic evolution.

Mechanical anisotropy in the upper mantle: a comparison between experimental observations and model predictions

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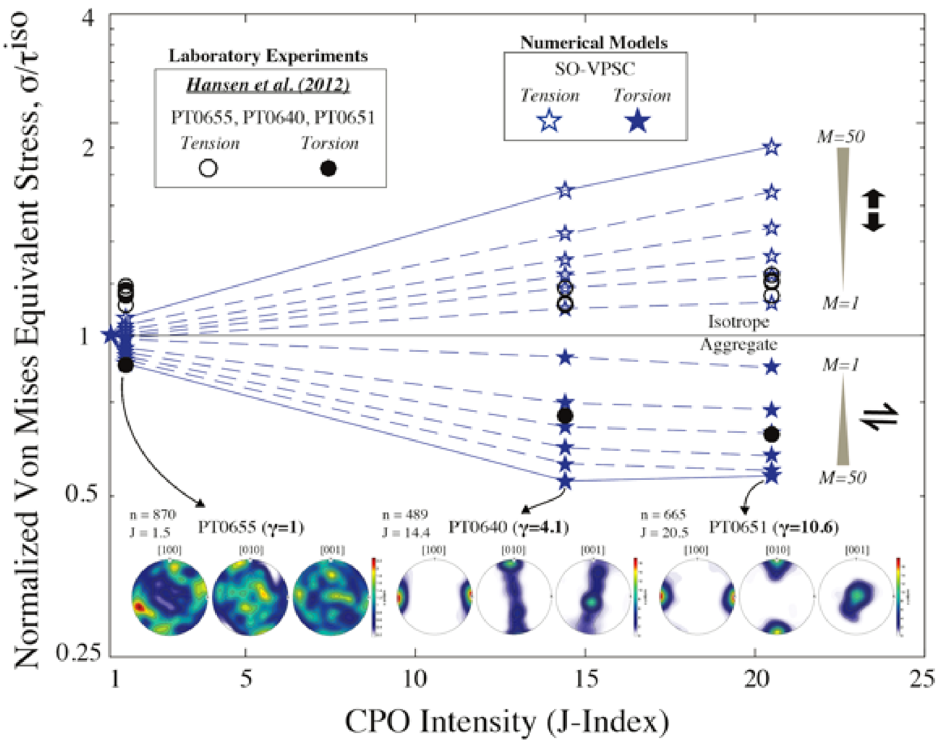
Upper mantle rocks may develop a strong viscoplastic anisotropy due to development of preferred orientation of olivine crystals during deformation (texture). Laboratory experiments show that olivine aggregates first deformed in torsion and then in extension have tensional strengths up to 1.9 times higher than the torsional ones. These experiments directly constrain the mechanical anisotropy but for a limited number of solicitation-texture pairs. Thus, models are needed to estimate the mechanical behaviour of a polycrystal as a function of the full range of orientation relations between the imposed solicitation and the texture, and for all texture types. Here we test for the robustness of these predictions by comparing the models to experimental observations. Standard viscoplastic self-consistent (VPSC) simulations predict higher anisotropies than those measured experimentally. The difference between model predictions and laboratory results is consistent with activation, in the fine-grained experimental polycrystals, of other deformation mechanisms in addition to dislocation creep. Modified VPSC models that include additional isotropic deformation processes do reproduce the experimental data. The predictions of the standard (M=50) and modified (M=2) VPSC models represent therefore upper and lower bounds for the texture-induced mechanical anisotropy in the Upper Mantle.

This project has received funding from the European Unions Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No 642029 - ITN CREEP



Von Mises Equivalent stress (normalized by the behavior of a random olivine polycrystal) as a function of the texture (olivine crystal preferred orientation) intensity for laboratory and numerical experiments in which a simple shear 12 (lower part of the plot) or an extension 22 (upper part of the plot) are imposed. M values indicate the contrast in strength between the easiest glide system [100](010) and the isotropic deformation mechanism in the different models.

Edge-driven convection: Geodynamic modelling and implications for volcanism

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Small Scale Convection (SSC) has proven to be a suitable convection mode for explaining several features of non-plume related intraplate volcanism. Edge-driven convection (EDC) is a particular case of SSC that is triggered by 'steps' of thickness in the lithosphere. These steps are typical of the transition between oceanic and continental lithosphere, where EDC could be related to oceanic volcanism. Here we show 2D EDC models computed with the finite elements code CITCOM. We study the onset and behavior of EDC for different 'edge' geometries, plate velocities and viscosities. We also explore the possibility of interaction with a mantle plume, which could be enhanced or displaced by EDC. In addition, we discuss the possible melting relations that result from this kind of dynamics. Finally, we predict the distribution and volume of mantle melting and related volcanism. For this purpose, we use a novel melting parameterization that has been fitted to match experimental data and thermodynamic modelling. In our geodynamic models, convection cells develop with a vigor and wavelength that depend on mantle viscosity and the age of the overlying lithosphere. These parameters also control whether SSC occurs everywhere or just near the edge. The shape of the original anomaly does not play a major role in terms of the final geometry of convection, because EDC is ultimately self-imposing an edge geometry. Accordingly, once an edge geometry is established, it is sustained by convection, and so is EDC. Another interesting feature is that the highest upwelling velocities occur systematically in the oceanic domain, not below the edge. This is particularly important because it may explain near-continental volcanic systems such as the Canary Islands, Cape Verde and Bermudas. As expected, highest volumes of melting occur where upwelling velocities are highest, and the overlying lithosphere is thinnest.

Non-thermal equilibrium two-phase flow for melt migration and ascent

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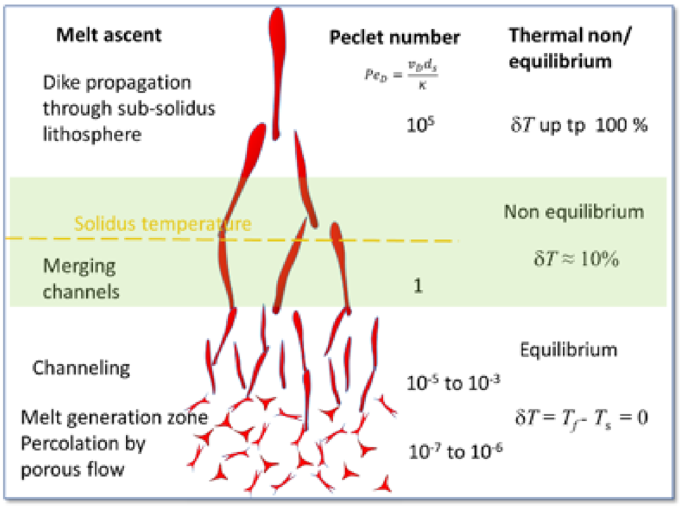
We develop a theory for heat exchange between a fluid phase in a solid porous matrix where the temperature of the fluid and of the matrix are different, i.e. not in thermal equilibrium. The formulation considers moving of the fluid within the porous matrix as well as moving of the matrix in an Eulerian grid.

The theory involves the energy conservation equations for the fluid and the solid phase which are coupled by a heat exchange term. We derive an expression based on a Fourier approach for periodic half-waves for a macroscopic description of the non-equal temperatures in the fluid and the solid considering the relative volumetric fractions and surface to volume relation of the phases. We present a formulation for the heat exchange between the two phases considering different thermal conductivities of the fluid and the solid and following the temporal evolution of the heat exchange, the latter leads to a convolution integral in case of a resting matrix. The evolution of the temperature in both phases with time is derived upon inserting the heat exchange term in the energy equations. We test this formulation by a finite element model on the microscopic scale.

We test the theory for a simple 2D case of sudden temperature difference between fluid and solid and vary fluid fractions and differential velocities between fluid and solid to obtain the requisites for the maximum Fourier coefficient and the time increments for numerical integration. The necessary time increments are small and strongly depend on the fluid fraction. The maximum Fourier coefficient need to be as high as 500 to resolve properly the sudden heat exchange between fluid and solid. Our results agree well with an analytical solution for non-moving fluid and solid and support an approximative solution by Minkowycz et al. [1]. The temperature difference between solid and fluid depend on the Peclet number (i. e. the differential velocity). For Peclet numbers up to 100, the temperature difference after one diffusion time is as large as $0.15\overline{T}$ (where $\overline{T}$ is a scaling temperature, e. g. the initial fluid temperature). Thus, our results imply that thermal non-equilibrium can play an important role in melt migration and the depth of melt solification.

[1] Minkowycz et al., Int. J. Heat and Mass Transfer, 42 (18), p3373-3385, 1999.



Melt migration and the region for non-thermal equilibrium

Implications of solid-state convection onset during magma ocean solidification

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The fractional crystallization of a magma ocean causes the formation of a compositional layering that can play a fundamental role for the subsequent long-term dynamics of the interior [1]. In case of magma ocean solidification from the bottom up to the surface, we show that the high temperature (thus low viscosity) conditions favor the onset of solid-state convection in the underlying solid cumulates prior to complete crystallization, even for moderate solidification times (∼1 Myr), for terrestrial planets like the Earth or Mars [2]. By the end of magma ocean crystallization, convective mixing provides a mechanism to homogenize the mantle compositional layering, which is induced by the fractionation process, ruling out a whole mantle overturn scenario that is incompatbile with long-term subsequent thermal convection in the case of Mars [1,3]. In the lunar case, it provides a way to mix back into the mantle the late crystallized ilmenite bearing cumulates, which otherwise remain trapped in the stagnant lid for reasonable values of the viscosity [4]. To test these scenarios, we performed 2D numerical simulations in a cylindrical geometry using parameters specific for the Moon and Mars. We treat the liquid magma ocean in a parametrized way while we self-consistently solve the conservation equations of thermochemical convection in the growing solid cumulates accounting for pressure- and temperature-dependent viscosity. We study different tectonic regimes for Mars using a parametrized yield stress to account for plastic yielding, and focus on a realistic crystallization sequence for the Moon, that we computed with pMELTS.

[1] Tosi et al., JGR: Planets 111, 15121528, 2013
[2] Maurice et al., JGR: Planets 122, 577598, 2017
[3] Plesa et al., EPSL 98, 5065, 2014
[4] Eklins-Tanton et al., EPSL 196, 239249, 2002

Nonlinear elasto-plasticity for finite-strain deformations

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The aim of this work is the numerical simulation of continental rifting processes, motivated by the fact that these geological phenomena play a very relevant role in geodynamics investigations. In this sense a good portion of the research currently done about this topic by scientists consists in the analysis of analogical models, named sandbox, which try to reproduce the real behavior of the rifting phenomena. The development of a *numerical sandbox*, that was the objective of this work, is explained by the several issues inherent to the analogic experiments: they are expensive, they are extremely simplified, their results are mostly qualitative. The constitutive laws that control the motion of the numerical sandbox are described by a fully-nonlinear elasto-plastic rheology which is best suited for finite-strain deformations. The motion is described in a Lagrangian way since the spatial physical quantities that represent the variables of the problem are parametrized on the reference configuration. Thanks to the nondimensionalization of the equations a quasi-static motion is assumed. For the numerical discretization a three-field variational formulation of the problem has been taken into account in order to prevent the volumetric locking arising from the enforcement of a nearly isochoric deformation, as stated in [1]: an independent volume field is introduced together with its dual variable that can be interpreted as the Kirchhoff pressure. This leads to an additive decomposition of the Helmoltz free energy into its isochoric and volumetric parts. The implicit update of the state of the system is computed by means of the Newton-Raphson method. Using the Kröner-Lee decomposition, the deformation gradient is multiplicatively decomposed into its elastic and plastic parts. The constitutive update is computed point-wise on the spatial quadrature nodes: an elastic trial is firstly computed; if the trial deformation lies outside the elastic domain then the plastic exponential return map brings the nodal deformation back on the boundary of the elastic domain. A Drücker-Prager yield failure criterion and a non-associative flow rule have been considered since these are really good choices for geological applications, as stated in [2]. The developed code is written in C++, it is based on the deal.II finite element library, it works in parallel by means of the MPI and multi-threading paradigms, it handles three-dimensional geometries. The results show the natural formation of shear bands with a V-pattern that the most-diffused softwares for geodynamics simulations are able to catch only if a weak seed is artificially added into the domain.

[1] Simo, in Handbook of Numerical Analysis, Elsevier, 6, 183–499, 1998. .
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Controls on the formation and evolution of microplates in scaled laboratory experiments

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Observations along divergent plate boundaries, mid-ocean ridges, reveal the presence of small (<1000 km diameter) tectonic plates, microplates, that rotate in place for millions of years before finally attaching to a neighboring tectonic plate. Previous studies suggest that microplates form by ridge propagation with rotation being driven by tectonic coupling along the boundary between the microplate and the neighboring plates. Ridge configurations prior to microplate formation are thought to include overlapping spreading centers or segmented transform faults. However, the processes controlling the initiation of microplates have yet to be quantified. Here, we use geometrically and dynamically scaled laboratory experiments of plate spreading in colloidal fluids to assess the magmatic and tectonic controls on microplate formation and evolution. Experiments are performed in a Plexiglas tank with two Plexiglas plates suspended a fixed distance above the base of the tank. The plates meet along a straight boundary striking oblique to perpendicular to the spreading direction, depending upon the experiment. The tank is filled with the colloidal fluid to just above the top of the suspended plates and a thin layer of saline water is spread across the surface. The saline water interacts with the colloidal fluid to form a visco-elastic-brittle skin overlaying a viscous fluid below. Spreading is initiated by separating the suspended Plexiglas plates at a fixed rate, resulting in cracks, faults, axial ridge structures, and occasional microplates. Microplates form in the laboratory at overlapping spreading centers, transform offsets, and along oblique ridge axes. Microplates are more prevalent for experiments started with oblique spreading axes. Using a non-dimensional axial strength parameter (see poster by Sibrant et al.), we observe a minimum axis obliquity at which microplates initiate that decreases with axial strength, suggesting that microplates will be favored across a broader range of local ridge obliquities at higher magma fluxes or faster spreading rates. We compare these results to observations on Earth and discuss the implications for the evolution of fast-spreading mid-ocean ridges.

Oroclines development in context of slab retreat

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Oroclines are curved topographic features related to subduction systems. Several of these structures, such as the Gibraltar Alboran orocline, or the Scotia arc, occur in contexts of slab retreat, following a mode-3 tearing process at the edges of the slab (out of the plane fracture propagation), respectively in continental and oceanic domain. Oroclines evolution, as any topographic feature related to subduction zones, is affected by 1) slab and mantle dynamics, 2) material displacement at the surface due to erosion and sedimentation processes.

In this work we study the evolution of self sustained narrow retreating subduction zones in oceanic domain, using 3D numerical modeling. To understand topography development with mode-3 tearing and retreat mechanisms, we need to study subduction taking into account surface processes and deep dynamics. To do so, we perform simulations involving both thermo-mechanical processes and material diffusion and advection at the surface. In this purpose we use two coupled codes: I3ELVIS (Gerya et al., 2007), a 3D thermo-mechanical code, and FDSPM, a new robust surface processes model, adapted to geodynamic modelling.

In our experiments, we model slab and surface evolution from subduction initiation to advanced slab retreat. We initiate subduction via 1) plume induced subduction initiation and 2) a strong age contrast between a young lithosphere window enclosed by shear zones and the surrounding lithosphere (”fracture zone collapse subduction initiation”). By varying surface processes intensities in the first set of experiments and the length and thickness of the shear zones and age transition location in the second set of experiment, we want to assess the influence of these parameters on the tearing process and the development of topography.

According to our preliminary results, it is possible to trigger subduction initiation and slab retreat in oceanic domains via fracture zone collapse in oceanic domain as well as using plume induced subduction initiation. Narrow retreating subducting slab forms as a natural result of a spontaneous paired mode-3 tearing process in both sets of experiments. A curved trench is built along with slab retreat. We also note a strong narrowing of the slab during the retreat. In the first set of experiments, surface processes intensity tends to influence strain rate patterns at the surface and hence the topography, as well as deep dynamics. The topography evolution and tearing trajectory appear to be dependent on the initial shear zones and young window dimensions in the second set of experiments.

On the evolution of water ocean in plate-mantle dynamics system

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The Earth has been covered with the water in 70 percent of its surface as the ocean. Various geologic records indicate that the amount of ocean may be gradually decreased by transportation in plate subduction (e.g. [1]). However, the total amount of water in the Earth's system is still controversial for between early planetary formation and mineral physics constraints. On the early planetary formation, the total amount of water in the Earth could range from 5 to 10 Ocean Masses (1 Ocean Masses = 1.4×10^{21} kg including sea ice) but not clear where and how the water comes from. On the mineral physics constraint, the silicate mantle may have $\sim$1 Ocean Mass. (e.g. [2]) and the total water in the Earth could be $\sim$2 Ocean Mass and found for the successful scenario on co-evolution of ocean and deep interior [3] but the mantle dynamics model has been too simplified, which was based on parameterized mantle convection. As the computational power becomes powerful, more complicated processes including mantle water migration can be incorporated into fully-dynamical and numerical mantle convection simulations [4]. In order to solve such a contradiction on the amount of water in the Earth's system, co-evolution model of water ocean and deep mantle in numerical mantle convection simulations is developed here. Using this model, the water ocean may be dried-up to a few 100 million years to 1 billion years if the total water in the system is assumed for 2 Ocean Masses in vigorous plate motions. On the other hand, the water ocean is still found in 4.6 billion years for 5 Ocean Masses in the system. This suggests that an implications from mineral physics seems to be significantly underestimated for the amount of water in the Earth's system. Including the latest hydrous mineral phase that could be stable in pressure and temperature conditions of the lower mantle (phase-H), the required amount of water in the Earth's system would be increased because of the high water solubility of phase-H (e.g. [5]). Therefore, including some accomplishments from recent mineral physics, the total water in the Earth's system could be consistent with an implication from early planetary formation rather than mineral physics constraint.

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Modelling the interaction between edge-driven convection and mantle plumes: Preliminary results using ASPECT code

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The observation of the close location between many hotspots, in particular African hotspots, and the edges of cratonic lithosphere has led to the hypothesis [1] that these hotspots could be explained by small-scale mantle convection at the edge of cratons (Edge Driven Convection, EDC, e.g. [2]). The Canary Volcanic Province hotspot (central eastern Atlantic) represents a paradigmatic example of this situation due to its close location to the NW edge of the African Craton. Geochemical evidence, prominent low seismic velocity anomalies in the upper and lower mantle, and the rough NE-SW age-progression of volcanic centers consistently point out to a deep-seated mantle plume as the origin of the Canary Volcanic Province. It has been hypothesized [3] that the plume material could be affected by upper mantle convection caused by the thermal contrast between thin oceanic lithosphere and thick (cold) African craton. Deflection of upwelling blobs due to convection currents would be responsible for the broader and more irregular pattern of volcanism in the Canary Province compared to the Madeira Province.

In this study we design a model setup inspired on this scenario to investigate the consequences of possible interaction between ascending mantle plumes and EDC. The Finite Element code ASPECT (Computational Infrastructure for Geodynamics organization; [4],[5]) is used to solve convection in a 2D box. Free slip along all boundaries and constant temperature at top and bottom boundaries are assumed. Melt fraction of peridotite is estimated by means of a postprocessor. Model setup assumes a viscosity structure based on a thick cratonic lithosphere progressively varying to a thin (or initially inexistent) oceanic lithosphere. The initial temperature distribution assumes a small long wavelength perturbation.

Preliminary modelling results show that a very thin oceanic lithosphere ($<$ 30 km) is needed to generate partial melting by EDC. In this case partial melting can occur as far as 700 km away from the edge of cratonic lithosphere. The size of EDC cells is relatively small (diameter about 300 km) for lithosphere/asthenosphere viscosity contrasts of 1000. In contrast, models assuming temperature-dependent viscosity and large viscosity variations evolve to large-scale (upper mantle) convection cells. Upwelling of hot material is enhanced by cold downwellings at the edge of cratonic lithosphere (see Figure).

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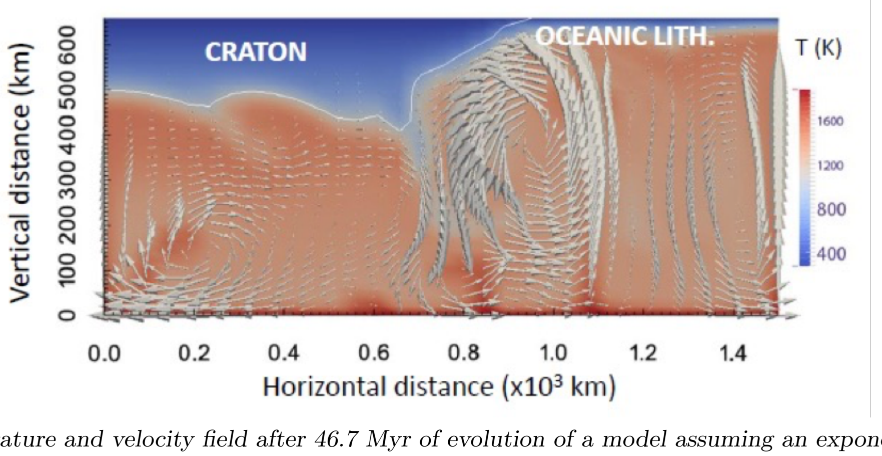

Temperature and velocity field after 46.7 Myr of evolution of a model assuming an exponential temperature dependence of viscosity. Cold downwelling at the craton edge enhance the upwelling of spontaneous mantle plumes and a large convection cell is formed.

Magmatism by delamination: Bimodal melting patterns inferred by numerical models

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Melt production by the decompression melting of the asthenospheric mantle occurs in the course of the lithospheric foundering process. The magmatic imprints of such foundering process are often described as anorogenic magmatism and this is usually followed by the orogenic magmatism, related to the subduction events in the Mediterranean region. Here, by using numerical geodynamic experiments we explore various styles of magmatism, their interaction with each other and the amount of magma production in the ocean subduction to slab peel away/delamination configuration. Model results show that the early stage of the ocean subduction under the continental lithosphere is associated with the short pulse of wet melting-orogenic magmatism and then the melting process is mostly dominated by dry melting-anorogenic magmatism, until the slab break-off occurs. While the melt types mixes/alternates during the evolution of the model, the wet melting facilitates the production of dry melting because of its uprising and emplacement under the crust where dry melting is present. The melt production pattern and the amount does not change significantly with different depths of the slab break-off (160-200 km). Model results can explain the transition from the calc-alkaline to alkaline volcanism in the western Mediterranean (Alboran domain) where ocean subduction to delamination has been interpreted.

Seafloor spreading without magma

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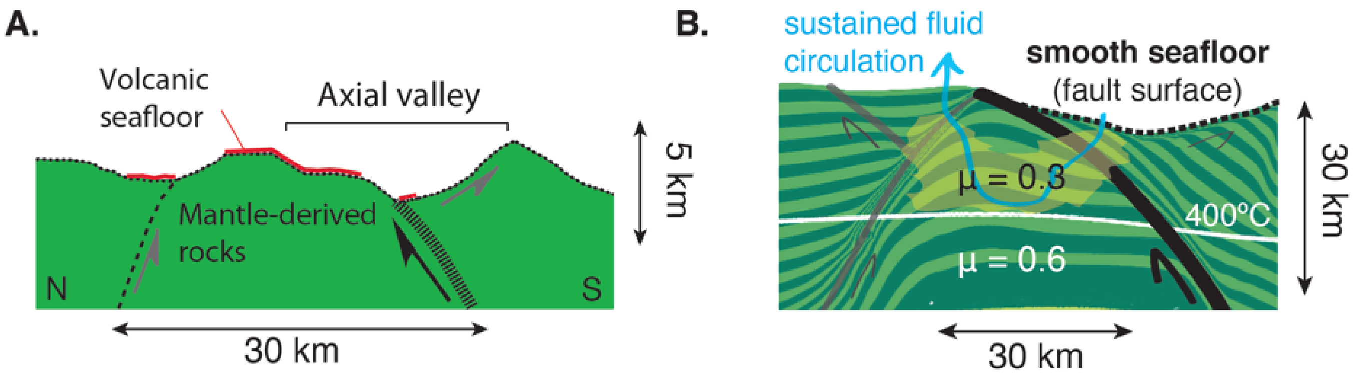
Magma-starved sections of ultraslow mid-ocean ridges (see Figure) challenge our understanding of seafloor spreading in multiple ways. First, they feature unusually deep seismicity indicative of brittle deformation 20-30 km below the ridge axis. Second, they are primarily made up of crosscutting, large-offset (>10 km) detachment faults exposing altered mantle units at the seafloor, even though lithosphere of commensurate seismogenic thickness primarily deforms through short-offset normal faulting (e.g., East-African or Baikal Rifts). Third, they show evidence for vigorous hydrothermal activity in spite of a very low magma supply. We use geodynamic modeling to infer the thermo-mechanical conditions that allow large-offset normal faults to form in a 30-km thick brittle oceanic lithosphere. This requires either a very low coefficient of friction (0.1) throughout the lithosphere, or moderate friction (0.3) in areas colder than 500C coupled with very low friction in fault zones. The latter scenario is compatible with geophysical evidence for pervasive hydrothermal alteration down to 15 km below seafloor. It however suggests that hydrothermal circulation can occur over this range of depths in a sustainable fashion. We propose that deep hydrothermal circulation is primarily sustained by grain-scale cracking due to thermal stresses and volume changes induced by serpentinization reactions. To test this idea, we design a model for hydrothermal convection in which permeability evolves according to a set of simple cracking rules calibrated on laboratory experiments. This model indicates that the downward propagation of a fracture front down to ~10 km can mine enough heat to fuel slowly decaying convection for ~100 kyr. Sustained hydrothermal alteration at magma-starved ridges may not require a continuous supply of magmatic heat, but instead magmatic intrusion events every 10-100 kyr to periodically reinvigorate convection. While the tectonics of slow- to fast-spreading ridges primarily reflects feedbacks between magmatic intrusions and faulting, the architecture of magma-starved ridges may be controlled by pervasive hydrothermal alteration reducing the frictional strength of the oceanic lithosphere by ~ 50% down to ~15 km. The ultraslow end-member of mid-ocean ridges thus provides a novel perspective on the mechanics of seafloor spreading.



A. Cross-section of the ultraslow-spreading Southwest Indian Ridge at 62° 20'E, from Sauter et al. [2013, Nat. Geosci.], showing large-offset detachment faults of alternating polarity. B. Numerical model of an incipient detachment fault (thick black line) cross-cutting a recently abandoned detachment of offset >40 km (gray line). Green layers (initially horizontal) track the accumulated deformation of fault-bounded blocks.

Constraining upper mantle viscosity and plate boundary friction using global plate motions and lithosphere net rotation

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Lithospheric plates move over the low viscosity asthenosphere balancing several forces. The driving forces include basal shear stress exerted by mantle convection and plate boundary forces such as slab pull and ridge push, whereas the resisting forces include inter-plate friction, trench resistance, and cratonic root resistance [2,3,4]. These generate plate motions, the lithospheric stress field and dynamic topography, which are observed with different geophysical methods. We use a global 3D lithosphere-asthenosphere model (SLIM3D) [6] with visco-elasto-plastic rheology coupled to a spectral model of mantle flow [4] at 300 km depth to quantify the influence of the intra-plate friction and asthenospheric viscosity on plate velocities. We account for the brittle-ductile deformation at plate boundaries (yield stress) using a plate boundary friction coefficient to predict the present-day plate motion and net rotation of the lithospheric plates. Previous modeling studies [1,5,7,8] have suggested that small friction coefficients ($\mu < 0.1$, yield stress ~ 100 MPa) can lead to plate tectonics in models of mantle convection. Here we show that in order to match the observed present-day plate motion and net rotation, the frictional parameter must be < 0.05. We obtain a good fit with the magnitude and orientation of the observed plate velocities (NUVEL-1A) in a no-net-rotation (NNR) reference frame with $\mu < 0.04$ and a minimum asthenosphere viscosity of $\sim 5{\cdot}10^{19}$ Pa·s to 10^{20} Pa·s. Our estimates of net rotation (NR) of the lithosphere suggest that amplitudes $\sim 0.1 - 0.2$ (°/Ma), similar to most observation-based estimates, can be obtained with asthenosphere viscosity cutoff values of $\sim 10^{19}$ Pa·s to $5{\cdot}10^{19}$ Pa·s and friction coefficients $\mu < 0.05$.

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Initiation of subduction by small scale convection: new insights from viscoelastic models with a free surface

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Abstract

Understanding the mechanisms that lead to initiation of subduction is a key to explaining dynamic evolution of the Earth and its fundamental difference to all other rocky planets. Several processes have been proposed to provide lithospheric scale shear zones, which are necessary for subduction to develop, one of them being small scale convection in the sub-lithospheric mantle [1]. In thermal convection models with visco-plastic rheology, the stresses that develop in upper thermal boundary layer due to pull of downwellings may be large enough to break the entire lid. Crameri [2] later argued that, to correctly capture the value of critical yield stress necessary for this to happen, one must perform numerical models with a free surface instead of the traditional free-slip boundary condition. It is because much larger stresses form in the lithosphere when its bending is allowed, and bending cannot occur in models with vertically fixed surface. However, Patocka [3] demonstrated that the amplitudes of stresses are exaggerated in numerical models with a free surface, as long as elastic properties of the lithosphere are not considered. The bending stresses of highly viscous lids are generally governed by the value of their shear modulus, and not the viscosity, resulting in a significant stress reduction in viscoelastic models when compared to viscous models. In the present work we use the code StagYY [4] to repeat the analysis of Crameri [2], but with visco-elasto-plastic rheology instead of the original visco-plastic rheology.

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PoGlaR - A finite element code for high performance simulation of Post Glacial Rebound

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From the mechanical point of view the interior of the Earth can be considered as composed of four main layers: the inner and outer core, the mantle and the lithosphere. The lithosphere can be assumed to be elastic and the solid mantle beneath behaves as a viscous fluid. The long term equilibrium pressure at a given depth in the Earth is due to the weight of the material above this depth. Deviations from this equilibrium state lead to material transport from regions of higher pressure towards lower pressure. If left undisturbed over time the mantle and the lithosphere reach an equilibrium, in which the depth of the base of the lithosphere will mainly depend on the thickness of the lithosphere. The growth of ice sheets during a glacial period concentrates mass on the Earth's surface to glaciated areas; this fact increases the pressure in the layers below, resulting in a sinking of the lithosphere and in a transport of mantle material away from the region. At the end of the glacial period, when the ice sheets melt away, the pressure on the lithosphere is reduced and the material will flow back causing the surface to uplift.

PoGlaR is a C++ code for the simulation of the Post Glacial Rebound at global scale; this code is mainly based on the deal.II Finite Element Library [1]. It is a discontinuous Galerkin finite element parallel code for forward modelling of the viscoelastic response of a three dimensional elastically compressible Earth to an arbitrary surface load. The code is able to perform global simulation of the rebound process, with a more refined results on a selected geographical region. The model implemented in PoGlaR consists of two parts: an Earth model and an ice reconstruction, where the latter is imposed as a boundary condition on the former. Different methods to set up the Earth model exist (in the code the Earth is assumed to be a layered WGS84 ellipsoid where the thickness and the material properties of each layer are taken from the PREM model [2]; the topography and the depth of the Moho are included as well), while the ice reconstruction is usually based on observed data or taken from thermo-mechanical modeling (the ice model included in the code is the ICE-6G model [3]). In the timescale of the post-glacial adjustment process the deformations of the Earth are viscoelastic. This means that when loaded the mantle initially responds like an elastic medium, then it flows like a viscous fluid over long timescales, but complications arise due to the presence of initial stress in the interior of the planet.

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Analogue modelling of opposite subduction retreating in adjacent plates

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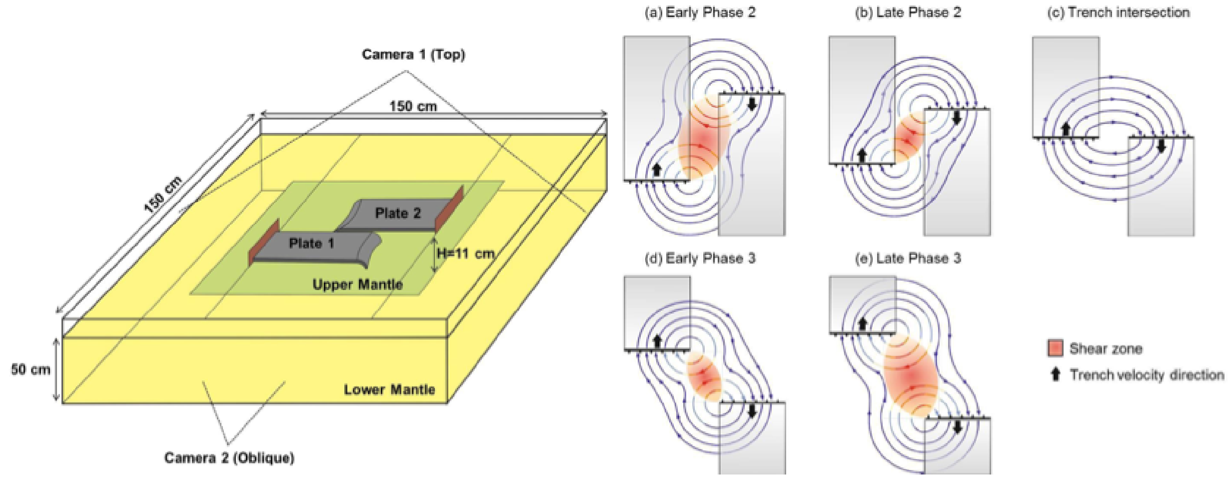
Opposite subduction retreating in adjacent plate segments has been proposed in several regions of the Earth and particularly in the Westernmost Mediterranean (Vergés et al., 2012; Casciello et al., 2015). Recent numerical experiments show a strong interaction between the induced mantle flows of each retreating plate (Király et al., 2016). In this work we show the result of a series of analogue models based on viscous syrup (representing the mantle) and silicone putty (representing the subducting plate), which have been designed to simulate the evolution of a double subduction system. The basic setup contains a pair of plates subducting in opposite directions. The plates are fixed at their trailing edge to enforce slab rollback behaviour and subduction is started by deflecting manually the leading edge of the plate (i.e., initial slab pull, phase 1). Different setups were designed to test the influence of two variables on the system: i) the width of the plates, that varies from 10 cm to 30 cm (1 cm in model corresponds to 60 km in nature) and ii) the lateral distance between the two subducting plates, that varies from 10 to 0.5 cm. Our results show that trench velocities increase during the stage of approaching trenches (phase 2) and then decrease after trenches pass each other (phase 3). On the other hand, the trench curvature increases linearly during the entire evolution whereas the lateral distance increases along time, indicating that effective lateral stresses are produced associates with the asymmetry of toroidal flows. This behaviour indicates a strong interaction between the stresses produced by the two retreating slabs that propagate through the mantle flow, which in turn depends on the initial plate separation.



Left panel: Scheme of the experimental setup. The tank is full of viscous syrup (in yellow) representing the mantle. The oceanic plates are made with silicone putty and subduct in opposite directions. Right panel: Scheme of the interaction of toroidal mantle flows produced by two retreating slabs at different stages of the evolution.

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Effect of crustal differentiation on the geodynamics of the Early Earth

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The geodynamic processes that were active during the Archean remain enigmatic. Based on geochemical and geological data, several working hypotheses exist, which suggest that the most crucial unsolved problems are: a) when and how was felsic crust generated and what are the geodynamic implications of it? b) how did cratonic lithosphere form and survive? c) did plate tectonics exist? Here, we test the feasibility of some of these hypotheses using a modeling approach in which we couple chemical evolution and melt extraction using state-of-the art mafic thermodynamic melting models with a viscoelastoplastic geodynamic finite element code. Results show that dripping and delamination are ubiquitous and caused by differentiation of the mafic crust and to a minor extend by eclogitization reactions. The extraction of felsic crust generated dense unstable residue that triggers gravitational instabilities, which may result in large intraplate deformation generating small protocontinent as function of the model parameters (e.g., initial Moho temperature, mantle potential temperature, amount of intrusion and rheological structure). The coupling between differentiation of the mafic crust, dripping and delamination instabilities not only generates a sudden increase in the formation of felsic crust, but also promotes the chemical evolution and cooling of the mantle. This suggests that high mantle potential temperature could not have persisted throughout the whole upper mantle. Moreover, our results suggest that the generation of a stable lithosphere cannot have been contemporaneous with the production of felsic crust. Differentiation of the crust and mantle dynamics are thus intimately linked during early Earth conditions.

The effect of oblique convergence on temperature in subduction zones: insights from 3D numerical modelling

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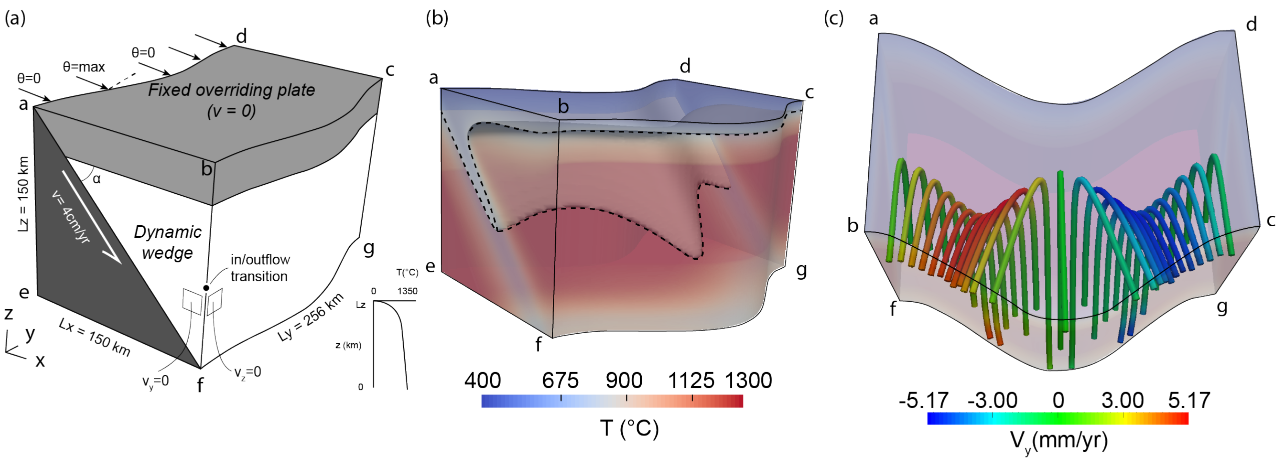
In subduction zone the geotherm is thought to vary as a function of subduction rate and the age of the subducting lithosphere. Along a single subduction zone the rate of subduction can strongly vary due to changes in the angle between the trench and the plate convergence vector, namely the subduction obliquity. This phenomenon is observed all around the Pacific (i.e. Marianna, Sunda-Sumatra, Aleutian...) and is supposed in the geological record of Turkey. However due to observed differences in subducting lithosphere age or lateral convergence rate in nature, the quantification of temperature variation due to obliquity is not obvious and need to be better constrained. In order to investigate this effect, 3D generic numerical models were carried out using the finite element code ELEFANT. We designed a simplified setup to avoid interaction with other parameters. An ocean/ocean subduction setting was chosen and the domain is represented by a 150 x 256 x 150 km deformed Cartesian box. The trench geometry is prescribed by means of a simple sine function. The mantle flow is computed in the mantle wedge by solving the equation of mass and momentum conservation. The energy conservation equation is then applied to this flow solution and solved in the entire domain until steady-state is reached. The results are analysed (i) in terms of mantle wedge flow with emphasis on the trench-parallel component and (ii) in terms of depths-temperature trajectories computed along the plate interface. We show that the effect of the trench curvature on the geotherm with respect to the convergence direction is not negligible. A small obliquity yields to a small but important trench parallel mantle flow that has effects on the advection of heat. In consequences, the isotherm re-adjust to the mantle flow and are deflected with respect to the geometry (different case are presented here: concave, convex or S-shaped). We observe differences of few hundred degrees on the depth-temperature path computed at the interface that is of interest for our understanding of dehydration reaction during subduction related metamorphism and their link to seismicity.



(a) Model setup. (b) Side view of the model with the 550°C isotherm plotted. Note the shape of the isotherm signing a different temperature along the plate interface. (c) Top view of the flow in the mantle wedge

Physical and numerical ingredients of a 3D continuum seismic cycle code

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Faults evolve over millions of years. The state of stress, distribution of materials, and strength and structure of the interface between two opposing blocks is intricately tied to a host of time-dependent physical processes, such as friction, damage, temperature, (nonlinear) viscous relaxation, and fluid migration. In addition, the fault interface has a complex three-dimensional geometry that evolves with time and can adjust in response to a changing stress environment or in response to impinging topographical features, and can branch off as a splay fault. All in all, the behaviour of earthquakes at the millisecond to minute timescale is heavily dependent on the pattern of stress accumulation during the $\sim$100 year inter-seismic period, the events occurring on or near the interface in the past thousands of years, as well as the extended geological history of the region.

To deal with most of these considerations, we present our attempt to combine the advantages of three distinct modelling paradigms into one code: 1) the self-consistent long-term (Ma) evolution of faults and the regional distribution of materials in well-established geodynamic and tectonic codes, 2) the wide range of time-scales (Ka to s) resolved in current seismic cycle simulation codes 3) at least the first-order interactions of the dynamic rupture with the medium simulated at dynamic (s to ms) timescales.

To accomplish this, we model a rate-and-state-dependent friction law with Drucker-Prager plasticity, limiting stresses in an otherwise compressible (nonlinear) visco-elastic medium. The governing equations are discretized in space using staggered-grid finite differences. Nonlinearity is resolved using a combined Picard-Newton iteration scheme. We employ the BDF2 time integration scheme suitable for an adaptive time-step. MPI-parallel computing is achieved through the Petsc library.

It was clear from the start that this attempt would bring with it (for us) unforeseeable physical and numerical considerations. That is why particular attention has been paid to ensuring a physics-unaware coding style, and using the algorithmically flexible numerics library Petsc. This has resulted in a code where physics are entered close to their symbolic representation, and dimensionality is just a compile-time constant. Here, we will showcase this approach, and hope to present – and foster an exchange of ideas on – the various ingredients of continuum seismic cycle models.

Seismicity and branching of evolving strike-slip faults in undamaged rock

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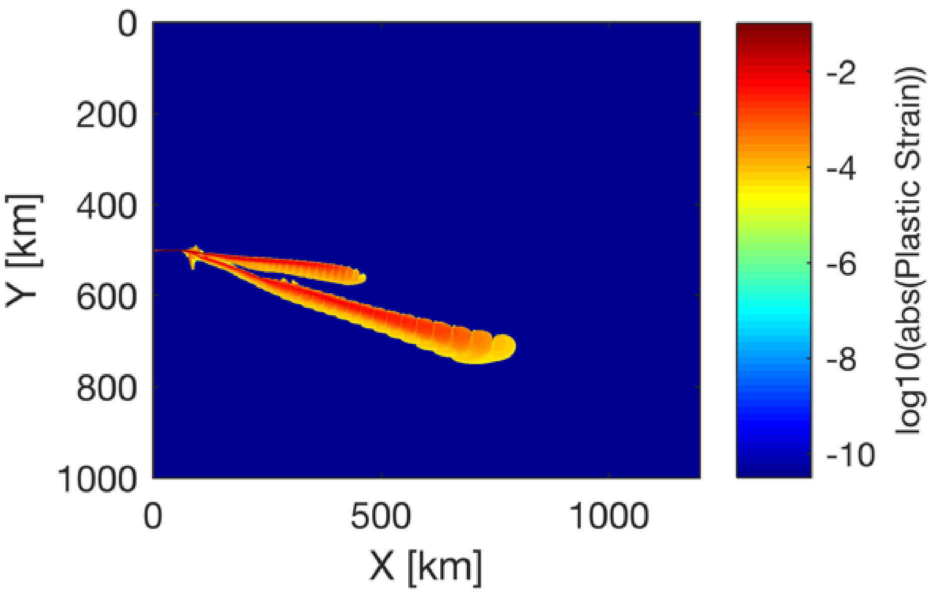
Strike-slip fault systems are capable of producing large earthquakes on both their main fault and on secondary and potentially unknown faults. A recent example is the 2016 Mw 7.8 Kaikoura earthquake that resulted in surface ruptures along at least 12 major crustal faults. Strike-slip faults are surrounded by inelastic offfault deformation zones whose displacement accounts for up to 60% of the total displacement. Secondary faults in California accommodate up to 43% of the total fault slip rate of mapped faults taken from the SCEC catalog, while unknown faults arguably accommodate up to 30% of the long-term strain.

To better understand these complexities and the long-term evolution of branching fault structures, we quantify the parameters influencing branching structure with a particular focus on the role of seismicity.

We incorporate the relevant dynamics of both long-term fault evolution and short-term seismogenesis using the continuum visco-elasto-plastic tools of Seismo-Thermo-Mechanical (STM) modeling approach (van Dinther et al., 2013, Herrendoerfer et al., in prep). Long-term fault evolution is governed by Drucker-Prager plasticity and plastic strain weakening of cohesion, while frictional weakening and rapid slip is governed by either strongly rate-dependent (RDF) or rate-and-state friction (RSF). A comparison of RDF and RSF shows that results are to first-order comparable in terms of recurrence time, amount of slip and stress drop. However, usage of RSF results in realistic coseismic duration and the correct regularity of events. We use a 2D, plane view, natural scale model setup (1200 km x 1000 km), which contains the end of a dextral mature strike-slip fault on one side.

Episodic slip events on this pre-existing fault patch propagate into the undamaged host rock. As faults grow they develop a fan-like plastic strain envelope, whose width keeps increasing with fault length and accumulated on-fault slip. We interpret this zone as a splay-fault network, which is typically seen ahead of propagating fault tips.

Results show that a single event is capable of producing a several hundreds of km long fault in homogeneous host rock. Enhanced RDF weakening results in decreasing fault angles, earlier and more rapid fault formation and thus in less structural complexity. Additionally, we will study the influence of shear modulus, viscous deformation with depth, characteristic slip distance and crustal thickness.



Accumulated plastic strain after 46311 years of simulation indextral strike-slip model with predefined fault patch

Investigations with melting in plate driven mantle convection models

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Observations from geochemistry and seismology continue to suggest a range of complex heterogeneity in Earth's mantle. At the core-mantle boundary, two large low velocity provinces (LLVPs) have been regularly observed in seismic studies [5], with their longevity and composition compared to the surrounding mantle still debated. The cause of these observed LLVPs is also uncertain, with previous studies advocating either a thermal or thermo-chemical cause [2]. Evidence suggests these structures could provide chemically distinct reservoirs within the mantle [4], with recent studies also suggesting there may be additional reservoirs within the mantle, such as bridgmanite-enriched ancient mantle structures (BEAMS) [1]. One way to test these hypotheses is by using computational models of the mantle, with models that capture the full 3D system being both complex and computationally expensive.

Here we present the continuation of our development of the global mantle model TERRA. So far our model includes our new method of tracking bulk composition and trace element concentrations, with the melting occurring at self consistent, evolving melting zones [3]. By imposing plate reconstructions we are able to generate structures that closely mimic those observed within Earth (such as subduction and spreading ridges). Furthermore, the effect of water concentrations within the system have been shown to provide additional interactions within the system. We therefore look to incorporating the effects of water in melting, rheology and density in our models, which will improve our ability to replicate mantle dynamics. With these additions in our model, we can then look at investigating the observations from seismology and geochemistry.

[1] Ballmer et al., Nature Geosci., 10, p236-240, 2017.
[2] Garnero et al., Nature Geosci., 9, 2016.
[3] van Heck et al., Geosci, Model Dev., 9, p1399-1411, 2016.
[4] Jackson et al., Nature, 542, p340-343, 2017.
[5] Koelemeijer et al., Geophys. J. Int., 204, 2016.

Formation and stability of a double subduction system: a numerical study

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Examples of double subduction systems can be found in both modern (Izu-Bonin-Marianas and Ryukyu arcs, e.g. Hall [1997]) and ancient (Kohistan arc in Western Himalayas, e.g. Burg [2006], Burg et al. [2006]) tectonic record. A double subduction system has been proposed to explain the high convergence rate observed for the India-Eurasia convergence [Aitchison et al., 2000, Jagoutz et al., 2015; Holt et al., 2017]. Rates of convergence across coupled double subduction systems can be significantly faster than across single subduction systems because of slab pull by two slabs.

However, despite significant geological and geophysical observations, our understanding about this process is limited, and questions regarding double subduction remain largely unexplored. For example, it is unclear how a double subduction system forms and remains stable over millions of years. Previous numerical studies of double subduction either introduced weak zones to initiate subduction [Mishin et al., 2008] or both the subduction systems were already initiated [Jagoutz et al., 2015, Holt et al., 2017], thus assuming a priori information regarding the initial position of the two subduction zones.

Moreover, the driving forces initiating a stable double subduction system remain unclear. In the context of India-Eurasia, Cande and Stegman [2011] found evidence the Reunion mantle plume head provided an ephemeral driving force on both the Indian and African plates for as long as 25 Million years, and had significant influence on plate boundaries in the region. How this influenced the fast plate motion of India during the Cenozoic remains a central question for understanding plate tectonics.

In this study, we perform 2D and 3D numerical simulations to investigate i) subduction initiation of a secondary system in an already initiated single subduction system, and ii) the dynamics and stability of the newly formed double subduction system. For this, we employ the code LaMEM [Kaus et al., 2016] capable of simulating lithospheric deformation while simultaneously taking mantle flow and an internal free surface into account. We start from a single subduction setup, where subduction is already initiated (mature) and we stress the system by controlling the convergence rate of the system (i.e. imposing influx/outflux boundary conditions). Under certain conditions, a second subduction may develop and transform into a stable double subduction system. Results suggest that the fate of the incipient secondary subduction depends on internal factors (i.e. buoyancy and rheology), but also on the dynamics of the primary subduction zone and the boundary conditions (i.e. convergence rate).

Localised two-phase flow: Application of implicit matrix-free pseudo-transient method

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Evidences of two-phase flow are numerous on Earth, from deep interior up to the near surface. At shallow depths (e.g. sedimentary basins) all around the world, seismic surveys unveil the existence of subsea bedded vertical pipes, which develop and trigger fast vertical fluid transfers. Deeper, metasomatism and dehydration reactions produce fluid excess that migrates following preferential pathways. Beside their discrepancy in length and time scales, these systems share the localised nature of flow allowing transfer rates much higher than expected by the respective background Darcy regimes.

The investigated two-phase processes result from an interplay between nonlinear Darcy flow coupled to complex poro-viscoelastoplastic rheology for the porous matrix. In a specific regime, high porosity instabilities travel as porosity waves and evolve in either blob or channel like features. The resulting travelling wave velocities are much higher than buoyancy driven single phase Stokes flow.

Within this work, we demonstrate the flexibility and viability of Pseudo-Transient (PT) method as alternative to Direct-Iterative (DI) solvers. Both approaches show convergence to identical nonlinear and implicit solution of the two-phase system over a large number of time steps. The PT method is matrix-free, can be vectorised and efficiently ported to parallel implementation using both shared and distributed memory machines, as well as hardware accelerators such GPUs or MICs. These possibilities enable resolving 3D setups in an efficient way. The DI solver is developed in Matlab and shows time to solution for 2D problems of 1200x1200 grid points close to 1 minute; Cholesky factorisation on symmetric blocks and vectorised assembly makes it possible.

We developed two type of solving strategies to investigate two-phase flow dynamics in complex rheologies. The predicted buoyancy driven fluid flow is focused within high porosity regions and travels in a wave like motion at rates much faster than expected by the Darcian regime. The matrix-free PT approach is already competitive compared to the DI solvers in 2D. For 3D implementation, a GPU MPI version of the matrix-free PT is used and shows linear weak scaling up to 5200 GPUs.

Understanding the Yellowstone magmatic system using geodynamic simulations

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The Yellowstone magmatic system is one of the largest magmatic systems on Earth. Thus, it is important to understand the geodynamic processes that drive this very complex system on a larger scale ranging from the mantle plume up to the shallow magma chamber in the upper crust. Recent geophysical results suggest that two distinct magma chambers exist: a shallow, presumably felsic chamber and a deeper and massive partially molten chamber above the Moho (Huang et al., 2015). Why melt stalls at different depth levels above the Yellowstone plume, whereas dikes cross-cut the whole lithosphere in the nearby Snake River Plane is puzzling. Therefore, we employ lithospheric-scale 2D and 3D geodynamic models to test the influence of different model parameters, such as the geometry of the magma chamber, the melt fraction, the rheological flow law, the densities and the thermal structure on their influence on the dynamics of the lithosphere. The melt content and the rock densities are obtained by consistent thermodynamic modelling of whole rock data of the Yellowstone stratigraphy. In order to create a consistent geodynamic model we invert for the gravity anomaly data by varying the magma chamber temperatures. We present derivations in the stress field around the Yellowstone plume, diking areas and different melt accumulations. Our model predictions can be tested with available geophysical data (uplift rates, melt fractions, seismicity).

An analytical finite-strain parameterization for texture evolution in deformed olivine polycrystals

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Current methods for calculating the evolution of flow-induced seismic anisotropy in the upper mantle describe crystal preferred orientation (CPO) using ensembles of $10^3 - 10^4$ individual grains, and are too computationally expensive to be used in three-dimensional time-dependent convection models. We propose a much faster method based on the hypothesis that CPO of olivine polycrystals is a unique function of the finite strain. Our goal is then to determine how the CPO depends on the ratios r_{12} and r_{23} of the axes of the finite strain ellipsoid and on the two independent ratios p_{12} and p_{23} of the strengths (critical resolved shear stresses) of the three independent slip systems of olivine. To do this efficiently, we introduce a new analytical representation of olivine CPO in terms of three 'structured basis functions' (SBFs) $\mathcal{F}_s(\mathbf{g}, r_{12}, r_{23})$ $(s = 1, 2, 3)$, where $\mathbf{g}$ is the set of three Eulerian angles that describe the orientation of a crystal lattice relative to an external reference frame. Each SBF represents the virtual CPO that would be produced by the action of only one of the slip systems of olivine, and can be determined analytically to within an unknown time-dependent amplitude. The amplitudes are then determined by fitting the SBFs to the predictions of the second-order self-consistent (SOSC) model of Ponte-Castaneda [1]. To implement the SBF representation, we express the orientation distribution function (ODF) $f(\mathbf{g})$ of the polycrystal approximately as a linear superposition of SBFs, viz.,

$$f(\mathbf{g}, t) = f_0 \left(1 + \sum_{s=1}^{3} C_s(t) \mathcal{F}_s \right), \tag{1}$$

where C_s are undetermined weighting coefficients and f_0 is the ODF for a random orientation distribution. Substituting (1) into the general evolution equation for $f(\mathbf{g}, t)$ and minimizing the residual error, we find that the coefficients $C_s(t)$ satisfy evolution equations of the form

$$\alpha_{ij} \dot{C}_j + \beta_{ij} C_j + \gamma_i = 0, \tag{2}$$

where the coefficients α_{ij}, β_{ij} and γ_i can be calculated in advance from the expressions for the SBFs. Equations (2) are solved numerically for different values of p_{12} and p_{23}, yielding numerical values of $C_s(r_{12}, r_{23}, p_{12}, p_{23})$ that can be fit using simple analytical functions. Our new parameterization allows CPO to be calculated some 10^7 times faster than full self-consistent methods such as SOSC.

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Water in geodynamical models of mantle convection and plate tectonics

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The presence of water in the the mantle has a significant effect in the dynamical and thermal evolution of Earth, which partially explains the differences with other planets and is a key factor for the presence of life on Earth. First, a small amount of water can decrease the mantle viscosity by a several orders of magnitude [1,2], thereby changing the convection regime and affecting the thermal evolution. Second, the presence of water significantly changes the solidus curve, with crucial implications for melting. Third, water in the mantle can change the Clapeyron slope of mantle materials [3], which changes the depth at which phase transitions take place. The thermal and dynamical evolution of Earth under the presence of water in the mantle has been the focus of recent studies, but many questions remain unanswered.

In this project we intend to investigate how the maximum water capacity of different mantle regions affects water transport and Earth's convective regime. We will study the effect phase transitions under the presence of water, which can change the buoyancy of slabs in the transition zone.

We will use the numerical geodynamics software tool StagYY [4] to run numerical models of global mantle convection for the whole history of Earth. We will use a new parametrisation of dehydration processes, obtained from high-resolution numerical simulations [5], to implement a more accurate description of the water released from the slab as it travels through the mantle. We will integrate recent experimental results of the water capacity of deep mantle minerals to study the water circulation and the total water budget. We will use data from the most recent experiments and ab- inito calculations to implement a realistic rheology.

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[2] Mei & Kohlstedt, Journal of Geophysical Research: Solid Earth, 105(B9), p21471-21481, 2000.
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Inferences on the uniform sampling of Earth's latitudes and paleomagnetic inclinations from spherical mantle convection models with continental drift

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Paleomagnetism is a key method for reconstructing Earth's paleogeography and thus important for our understanding of the Earth's tectonic evolution. However, it relies on the assumption of a geomagnetic field, persistently dominated by a Geocentric Axial Dipole (GAD). The validity of the GAD hypothesis can in principle be tested by inverting the globally accumulated frequency distribution of paleomagnetic inclinations at present-day, but only if that record is generated from uniform sampling all latitude bands by Earths continents. No consensus has been achieved yet whether this latter condition is fulfilled or not.

Here, we provide new insight into the possibility and time scales of uniform latitude and inclination sampling by employing 3D spherical mantle convection models that feature the self-consistent evolution of plate tectonics and continental drift over time scales of 2 Gyr or more. Statistical analysis of our modelling results suggests that the continents unlikely sampled Earth's latitudes uniformly throughout the Phanerozoic (i.e. during 600 Myr or less): only 5-30% of tested conditions allow for it. Uniform sampling of latitudes may be more confidently achieved on a Gyr-timescale though, in cases it becomes very likely on time scales of 1.5 Gyr. This is potentially shorter than the interval spanned by combined paleomagnetic record from the Phanerozoic and the Precambrian. Quantitative estimates depend on the viscosity structure of the mantle and lithosphere: time scales tend to be shorter with (i) reduced upper mantle viscosity because of a reduced resistive drag at the base of the continents that allows them to drift faster, and (ii) with lower plastic yield strength of the lithosphere, which promotes more dispersed configurations of continental drift. Above findings are obtained assuming the absence of significant true polar wander (TPW). However, TPW may affect the time scales of uniform sampling and our current efforts aim to estimate its potential role in more detail.

Dynamic modelling of Venus interior evolution and implications for mantle viscosity structure and surface observables

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Earth and Venus are often referred to as twin planets because of their bulk similarities. However, their tectonic evolution has been clearly different - with plate tectonics operating on Earth, but not on Venus. Rather little is known about Venus interior, but combining surface observables (such as the gravity field, the number of thermal emissivity anomalies and Venus uniform surface age) with models of the dynamic interior evolution can add relevant insight. Using the code StagYY, we incorporate secular cooling, core-mantle coupling and magmatic activity in our 3D spherical model and investigate the evolution of Venus mantle and lithosphere through time in stagnant and episodic lid modes of convection. To make inferences on Venus interior, we test the ability of different parameter sets to match the previously mentioned surface constraints.

In stagnant lid cases, the observed spectrum of surface gravity and its relation to topography as well as the number of mantle plumes is matched rather well if sublithospheric mantle viscosity is $\sim 2 \times 10^{20}$ Pa-s and the deep mantle is $\sim 100\times$ more viscous. No strong viscosity discontinuity across the transition zone is favoured. Such a smaller discontinuity than inferred for Earth could be linked to different water contents of Earths and Venus upper mantles: the latter may be drier so that its viscosity is not reduced. The stagnant lid scenario always generates very thick basaltic crust that leads to very high lithospheric stresses. This is avoided in the episodic lid regime, but then overturns strongly perturb the predicted spectra and number of hotspots in Venus mantle. Recovery to a reasonable number of plumes in line with thermal emissivity observations requires a long time, but predicted gravity spectra relax much faster (within < 200 Myr) following an overturn. Venus present gravity spectrum should thus represent the stagnant-lid state and is probably not contaminated by remains of the latest overturn - unless it ended only very recently. Our current efforts focus on analysing the distribution of model-predicted surface ages with regards to its mean age and its spatial uniformity.

The effect of regularisation in global tomography on mantle density models

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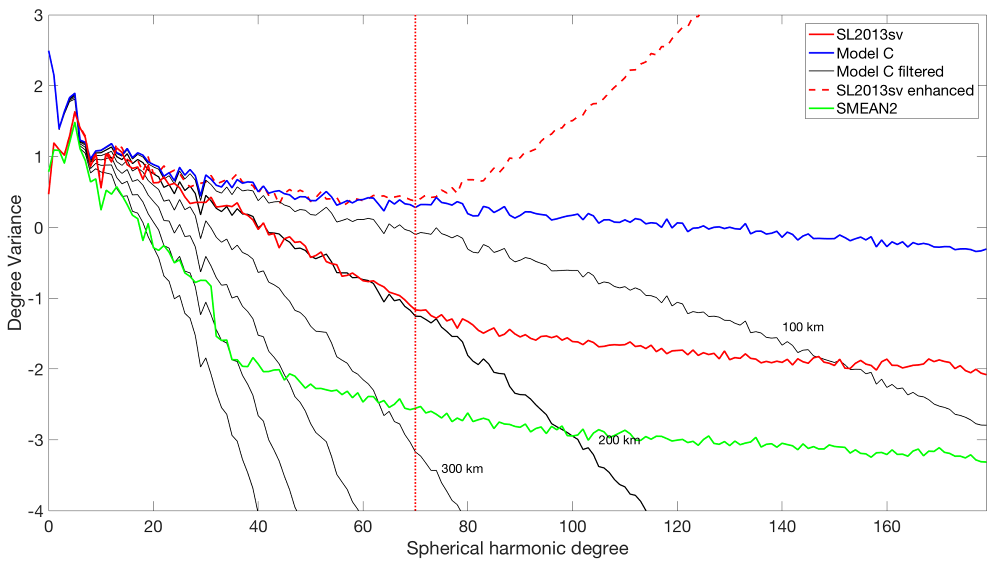
Global tomography models of the shear-wave velocity distribution give information about mass anomalies. But, there are some difficulties in construction of a global density model of the deep mantle from tomography. Seismic data coverage is not homogeneous, which result in the use of regularisation. This smoothens the image of the mantle anomalies. Also, the shear-wave anomalies need to be converted to density anomalies with uncertain conversion factors that relates to temperature and composition.

We study the reduction in magnitude of the density anomalies due to the regularisation of the global tomography models. The reduced magnitude of the anomalies cannot be fixed by increasing the conversion factor from VS-to-density transformation. The reduction of the tomographic results seems to resemble more like the effect of a spatial Gaussian filter. By determining the spectral difference between the models a reverse filter can be constructed to reproduce correct density variations in the complete mantle. The low degree region of the density estimates is less affected by the regularisation and can be used to fix the mean conversion factor of the mantle. This allows to fix a mean value for the conversion factor to transform shear wave velocity to density. Future study will examine depth dependent conversion factors.

This study is part of ESA's Support to Science project - 3D Earth. The goal of this study is to understand the effect of the deep Earth on the gravity field to facilitate global lithosphere modelling.



Degree Variance of different lithospheric density models: (solid red) converted SL2013sv (p=0.18), (blue) gravity-based model from Root et al. (2017), (black) filtered Root et al. model with different halfwidth Gaussian filters, (dashed red) enhanced SL2013sv with reverse Gaussian filter (200km), and (green) converted SMEAN2 (p=0.18).

Generation of proto-continental crust in the Archean: numerical simulations of global convection

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We study the formation of primordial continental crust (TTG rocks) using fully self-consistent numerical models of thermo-compositional convection on global scale at the archean. We solve the equations of compressible convection, employing realistic rheological parameters [1] using the convection code StagYY [2] in 2D spherical annulus geometry for a period of one billion years.

Starting from a pyrolytic bulk composition and an initially warm core, our simulations first generate basaltic crust and depleted mantle in the upper mantle when the temperature exceeds the solidus temperature. In our model, the basaltic material can be both erupted (cold) and intruded (warm) at the base of the crust according to a predefined partitioning. At all times, water concentration is considered saturated in the top 10 km of the domain, and it is advected with the deforming material elsewhere.

We track the P-T conditions of the newly formed hydrated basalt and check if it matches the conditions for the production of primordial continental crust [3]. We test the influence of volcanism (eruption, also called heat pipe) and plutonism (intrusive magmatism) on the lithosphere geotherm.

We show that the heat-pipe model (which assumes 100% eruption [4]) is not able to produce continental crust since it forms a too cold lithosphere. We test various friction coefficients. In all cases, we show that an intrusion fraction higher than 60% (in agreement with [5]) together with a friction coefficient larger than 0.1 can product the expected amount of the three main TTG compositions previously reported [3].

This result seems robust as the amount of TTG rocks produced vary over orders of magnitude. A large eruption over intrusion ratio can result in up to 100 times less TTG felsic crust production than a case where plutonism dominates. This study has been recently published [6].

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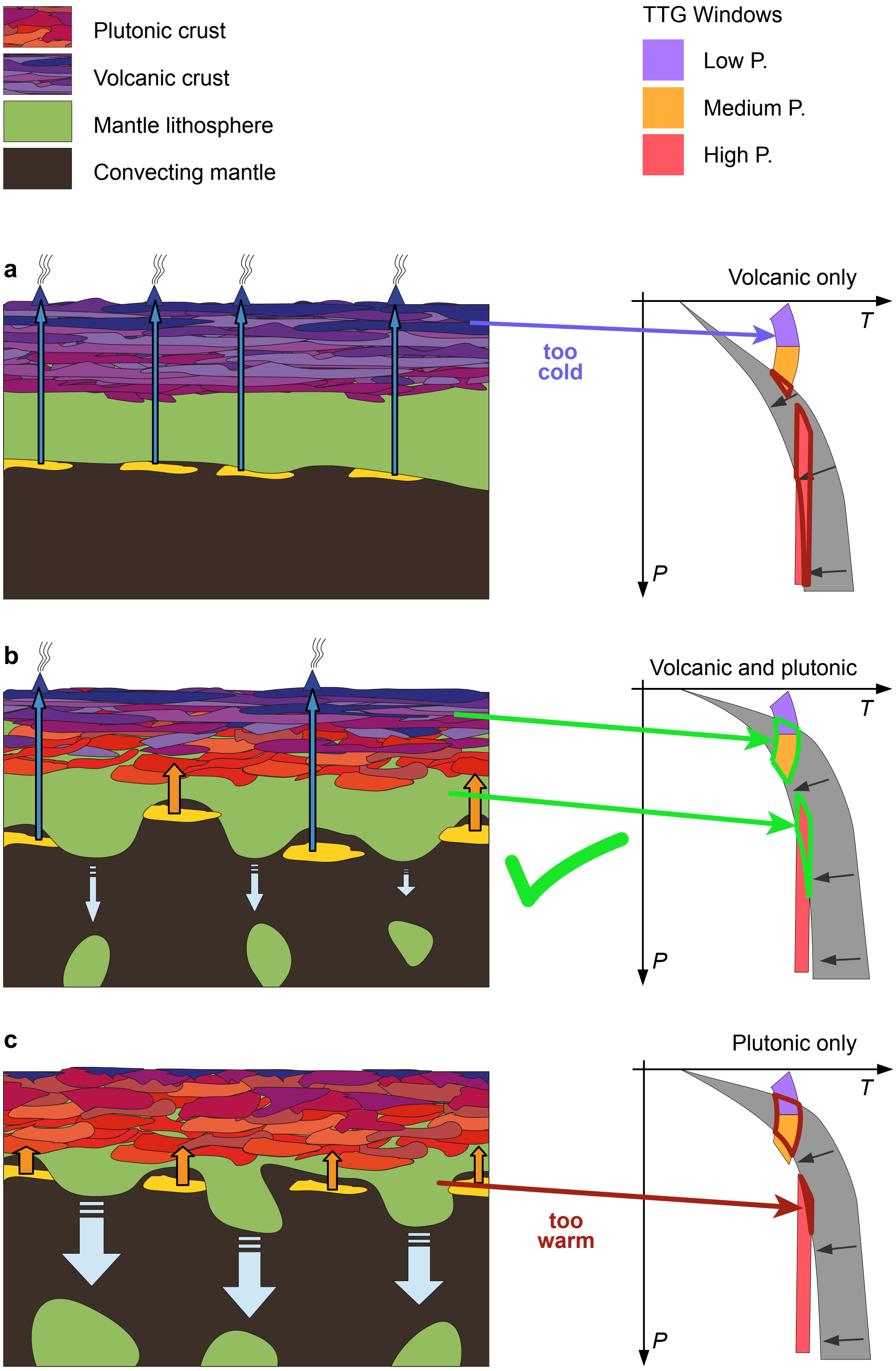

An important amount of intrusive magmatism is necessary to reach the appropriate pressure-temperature windows in which TTG rocks are produced (reproduction from [6]) .

From viscous plume to dikes and fractures

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The target of this project is to determine the influence and the importance of rheology on the nature (flow or fracturation) and morphology of intrusions in a deformable matrix. In numerical simulations, the lithosphere is often treated as a Non-Newtonian yield stress fluid, with a purely viscoplastic rheology. This implies that deformation occurs only if local stresses are larger than the yield stress, but the transition from static-solid to flowing behaviour remains ill-described. We explore here if and how thermo-elastic stresses can help reaching the yield stress.

We developed a numerical simulation model in order to investigate the development of thermo-elastic stresses in two different experimental situations: (1) the classical Rayleigh-Benard geometry where a steady-state linear temperature gradient is established between two horizontal boundaries heated from below and cooled from above, and (2) a localized source heating with a prescribed temperature history the fluid from below. Both situations were studied with a no-slip boundary condition, first in 2D Cartesian coordinates and then in axisymmetric geometry.

The system governing equations are the conservation of momentum, the constitutive relationships for a linear elastic material subjected to plane strain conditions and the heat diffusion. In this way, we are able to get the temperature and corresponding stress distribution as a function of time, for different layer thicknesses and for different elastic properties.

The preliminary results show that thermo-elastic stresses can increase with time, and become of the same order of magnitude as the yield stress. Therefore, the onset of convective motions is predicted for a certain range of thermo-elastic properties and temperature gradient, in agreement with experimental observations. That suggests the importance of the first deformation stage (i.e. the elastic response) for an elasto-viscoplastic fluid subject to a temperature difference.

Deformation, fluid flow and mantle serpentinization at oceanic transform faults

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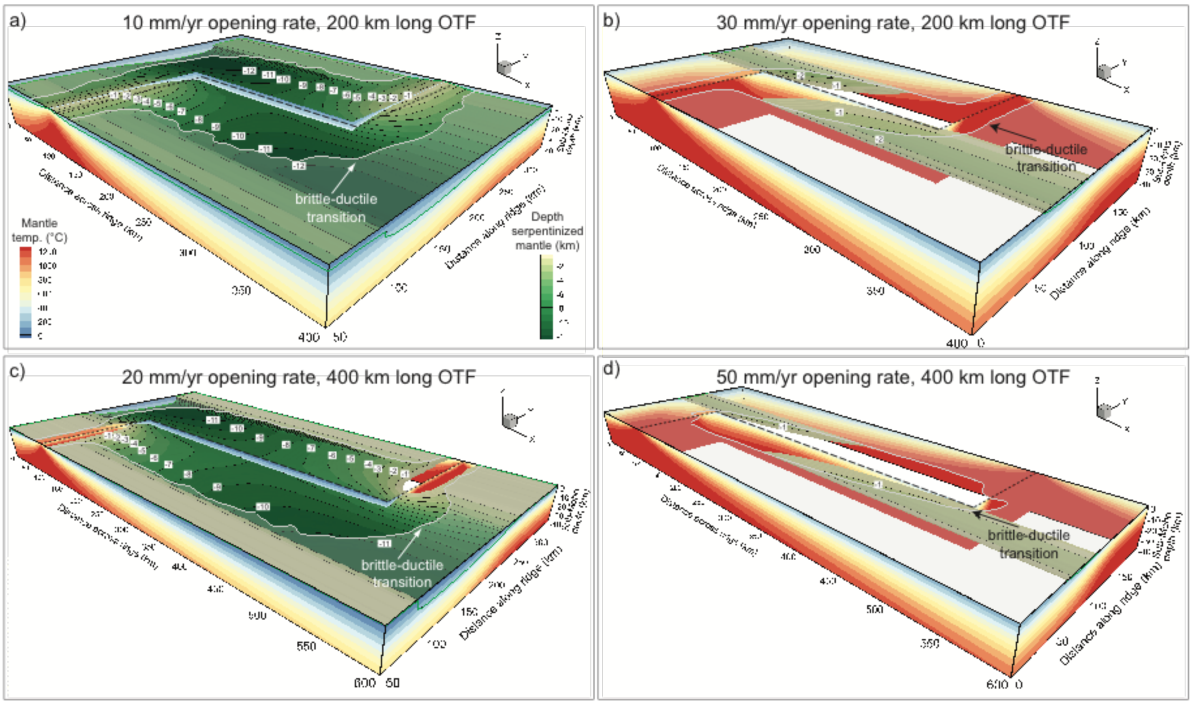
Oceanic transform faults (OTF) and fracture zones have long been hypothesized to be sites of enhanced fluid flow and biogeochemical exchange. In this context, the serpentine forming interaction between seawater and cold lithospheric mantle rocks is particularly interesting. The transformation of peridotite to serpentinite not only leads to hydration of oceanic plates and is thereby an important agent of the geological water cycle, it is also a mechanism of abiotic hydrogen and methane formation, which can support archeal and bacterial communities at the seafloor. Inferring the likely amount of mantle undergoing serpentinization reactions therefore allows estimating the amount of biomass that may be autotrophically produced at and around oceanic transform faults and mid-ocean ridges

Here we present results of 3D geodynamic model simulations that explore the interrelations between deformation, fluid flow, and mantle serpentinization at oceanic transform faults. We investigate how slip rate and fault offset affect the predicted patterns of mantle serpentinization around oceanic transform faults. Global rates of mantle serpentinization and associated H2 production are calculated by integrating the modeling results with plate boundary data. The global additional OTF-related production of H2 is found to be between 6.1 and 10.7×10^{11} mol per year, which is comparable to the predicted background mid-ocean ridge rate of $4.1 - 15.0 \times 10^{11}$ mol H2/yr. This points to oceanic transform faults as potential sites of intense fluid-rock interaction, where chemosynthetic life could be sustained by serpentinization reactions.



Mantle serpentinization around oceanic transform faults with different slip rates and offsets.
Figure taken from Rüpke & Hasenclever, GRL, 2017.

A coupled petrological-geodynamical model to investigate the evolution of crustal magmatic systems

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The evolution of crustal magmatic systems can be analyzed from different physical and chemical perspectives. Most previous work focus either on the petrological side (considering thermal effects and ignoring mechanics), or on the mechanical evolution (assuming a fixed melt chemistry). Here, we consider both by combining a 2D finite element code, MVEP2, with a thermodynamic modelling approach (Perple_X). Density, melt fraction and the chemical composition of the liquid and solid phase are computed for different starting rock compositions and the evolving chemistry is tracked on markers via 10 main oxides (SiO2-TiO2-Al2O3-Cr2O3-MgO-FeO-CaO-Na2O-K2O-H2O). As soon as the local chemistry changes due to melt extraction, new phase diagrams are computed based on the residual solid chemistry for the deflated magma chamber or on the liquid chemistry for newly generated magma filled fractures. To investigate the chemical evolution in magma chambers and magma filled fractures, we inject mafic sills periodically at varying depth levels into the continental crust. The initial sill injections are focused in either one or two main zones in the crust and may interact with each other. The formation of magma filled fractures from this partially molten zone is tracked with a semi analytical dike initiation algorithm that forms new dikes as a function of the local stress field above the partially molten region and subsequently depletes and compacts the magma source region. Dike generation is thus affected by the background strain rate, amount and depth of melt accumulations as well as parameters that control the plastic and viscous behaviour of the crust (e.g. cohesion, viscous creep flow low etc.). Results show that magma filled fractures triggered by sill injections preferentially form under extensional conditions, particularly within the middle crust (in ca. 25 km depth). Magma chambers in the lower continental crust, on the other hand, are stable over a longer period of time due a smaller cooling rate and less tensile fractures that could transport magma into shallower crustal levels. Magma mixing between mafic melts and more evolved melts of previously formed dikes/sills or surrounded crustal host rocks, quantify the effect of temperature-driven contamination in basaltic melts.

Upper mantle anisotropy in western Iran: shear-wave splitting and Love-to-Rayleigh scattering

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The Iranian plateau as a part of the Alpine-Himalayan system is made up of various tectonic and structural provinces such as the Zagros and Alborz orogenic belts, the Sanandaj-Sirjan and Urumieh-Dokhtar magmatic arcs, and the active subduction zone of Makran. Understanding the pattern of past and present-day deformation plays a key role in putting constraints on the evolution of the collisional boundary in the Iran region. Seismic anisotropy is among the efficient proxies for detecting the pattern of deformation in the lithospheric and asthenospheric upper mantle.

We use data from a temporary seismic network in western Iran deployed in 2013 and 2014; 63 broadband seismometers installed along three parallel profiles that crossed the Zagros Mountains, central Iran and the Alborz Mountains. The shear-wave splitting parameters of the SKS and SKKS core-refracted phases are calculated. Abrupt and gradual changes in one of the anisotropic parameters, the fast direction, are observed along the profiles, while the delay-time is not significantly changing, being in the range of more than 1s testifying the presence of significant deformation in the Iranian lithosphere-asthenosphere . The principal observed patterns are:

a) The mountain sub-parallel trend in Zagros (NW-SE)

b) The NE-SW trend beneath Alborz which is perpendicular to the strike of the mountain range.

The latter direction is sub-parallel to the plate motion in the absolute reference frame suggesting that the asthenospheric flow might be the source of the observed anisotropy.

We also quantitatively analyzed the relative presence or absence of coupled Love and Rayleigh (quasi-Love) waves recorded by the seismic stations. Existence of the lateral change in the anisotropic structure is known as a contributing factor in the generation of the quasi-Love waves. We used our coherent observations of SKS measurements and Love-to-Rayleigh scattering to put new constraints on the geodynamics of the Iranian plateau.

Investigating characteristics of detected thermochemical piles

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Seismic studies show two antipodal regions of low shear velocity at the core-mantle boundary (CMB), one beneath the Pacific and one beneath Africa. These regions, called Large Low Shear Velocity Provinces (LLSVPs), are thought to be thermally and chemically distinct and thus have a different density and viscosity. Whereas there is some general consensus about the density of the LLSVPs the viscosity is still a very debated topic.

So far, in numerical studies the viscosity is treated as either depth- and/or temperature- dependent but the potential grain size- dependence of the viscosity is neglected most of the time. In this study we use a self-consistent convection model which includes a grain size- dependent rheology based on the approach by Rozel et al. (2011) and Rozel (2012). Further, we consider a primordial layer and a time-dependent basalt production at the surface to dynamically form the present-day chemical heterogeneities, similar to earlier studies, e.g by Nakagawa & Tackley (2014).

With this model we perform a parameter study which includes different densities and viscosities of the imposed primordial layer. We detect possible thermochemical piles based on different criterions, compute their average effective viscosity, density, rheology and grain size and investigate which detecting criterion yields the most realistic results.

Our preliminary results show that a higher density and/or viscosity of the piles is needed to keep them at the core-mantle boundary (CMB). Relatively to the ambient mantle grain size is high in the piles but due to the temperature at the CMB the viscosity is not remarkably different than the one of ordinary plumes. We observe that grain size is lower if the density of the LLSVP is lower than the one of our MORB material. In that case the average temperature of the LLSVP is also reduced. Interestingly, changing the reference viscosity is responsible for a change in the average viscosity of the LLSVP but not for a different average grain size.

Thermo-mechanical two-phase flow models of magma ascent in the continental crust: effect of heat flow and extension

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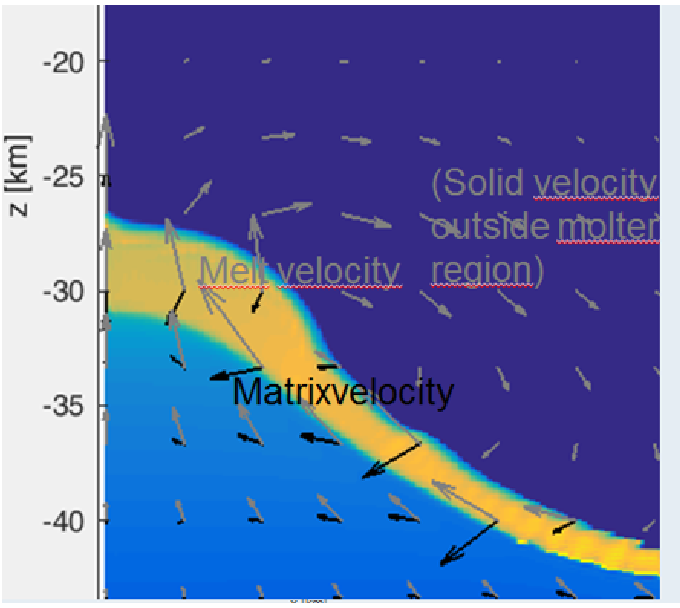
Melting within the lower continental crust with and without extension and subsequent ascent of silicic melts is modelled by a thermo-mechanical two-phase flow approach. The approach is based on the conservation equations of mass, momentum, and energy for melt and solid, respectively, and includes a simplified binary melting model, as well as compaction / decompaction of the solid matrix. The rheology is based on dislocation creep of quartzite or granite, and includes plasticity. 2D models are carried out for cases without and with differential melt-matrix flow. As control parameter the heat flow is varied between 75 and 90 mW/m^2 at the base of a thickened continental crust. In the case of no differential flow (batch melting) the model predicts episodic melting, rise and freezing of partially molten magmatic bodies. The recurrence time inversely scales with the bottom heat flux. In the case of allowing for melt migration, no such episodicity is observed anymore. Melt accumulates within melt rich layers and bodies, which subsequently rise through the crust by a combination of diapirism and decompaction related sinking of solid material through the melt rich layer. Final emplacement depths are between 30 and 15 km, shapes of the resulting plutons are visualized by the evolved enrichment and depletion fields. Models with extension show indications for melt channeling.



Snapshot of a rising magma volume. The color represents the melt fraction, reaching about 80%. Magma ascent by high melt fraction diapiric rise is combined with compaction related sinking of ambient solid rock

3D dynamics of crustal deformation along the western Andean margin

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Along the roughly 7000km-long South American subduction zone, the plate convergence obliquity angle, subduction dip angle and strength of the continental crust vary. These factors all influence the dynamics of deformation in the continental crust and how convergence is partitioned onto various fault systems in the overriding plate. Where convergence is oblique, partitioning of strain into margin-normal slip on the plate-bounding fault and horizontal shearing on a strike-slip system parallel to the margin is mainly controlled by the margin-parallel shear forces on the plate interface and the strength of the continental crust. While the plate interface forces are influenced by the dip angle of the subducting plate (i.e. the length of plate interface in the frictional domain) and the obliquity angle between the converging plates, the strength of the continental crust is strongly affected by the presence or absence of weak zones (e.g., arc volcanism or pre-existing fault systems). In order to investigate which of these factors have the greatest influence on continental deformation, this study compares results of lithospheric-scale 3D numerical geodynamic experiments from two regions in the north-central Andes: the Northern Volcanic Zone (NVZ; 5°N - 3°S) and adjacent Peruvian Flat Slab Segment (PFSS; 3°S -14°S).

Our experiments show that the obliquity angle has the largest effect on the initiation of strain partitioning, but margin-parallel movement of a coherent crustal sliver is clearly enhanced by the presence of a continental weakness. Movement of a continental sliver occurs at similar rates to those observed in the NVZ in nature when a pre-existing crustal weak zone is present, but without a continental weakness sliver movement velocities are half as fast. In addition, a shallower subduction angle results in formation of a wider continental sliver, as expected. These results (summarized in the Figure) and numerical experiments based on the PFSS suggest that the lack of strain partitioning in the PFSS is due to a low convergence obliquity and absence of a weak zone in the continent, even though shallow subduction should make strain partitioning more favorable. Results from thermomechanical numerical experiments agree well with the aforementioned purely mechanical reference experiments representing the NVZ and PFSS. We thus conclude that, despite their simplicity, purely mechanical models are well suited for studying lithospheric-scale subduction zone dynamics and yield results that are in very good agreement with observations in nature both in the study areas of this work as well as global subduction zones.

	obliquity angle ↗	continental crustal weakness ✓	subduction dip angle ↗
obliquity angle ↗ NVZ: high; PFSS: low	+	++	+
continental crustal weakness ✓ NVZ: present; PFSS: not present	++	+	+
subduction dip angle ↗ NVZ: large; PFSS: small	+	+	−

strain partitioning or sliver formation:
- \+ enhance
- ++ strongly enhance
- − restrict
- ✓ present
- ↗ increase

Comparison of main subduction zone characteristics: obliquity angle, continental crustal weakness and subduction dip angle with respect to strain partitioning (sliver formation).

Distribution of magmatism in numerical models after delamination during continental collision

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Magmatism in continental collision zones is still poorly understood due to the diversity of possible subduction dynamics and petrological processes. Particularly in continental collision zones, where small amounts of magma with a diverse composition are produced, magmatism might provide unique insight into the underlying dynamical and chemical processes. The buoyancy of the colliding continent, as well as the age of the subducting oceanic lithosphere are two of the key parameters influencing subduction dynamics. They can control the occurrence of delamination or slab breakoff, thus affecting the magmatic product. This scenario may be applied to the central Mediterranean subduction zone where the subducting plate seems to be delaminating beneath the younger and thinner Apennines or the Hellenic subduction system in the eastern Mediterranean.

In this study, we develop numerical models that can provide new insight into this topic, by combining previously developed 2D geodynamical models with thermodynamical databases and software. With this approach, we are able to trace the temporal and spatial evolution of various mantle and crustal magmas within arcs during subduction and the subsequent continental collision. We vary the continental buoyancy and the age of the subducting slab to study the effect on position and degree of melting. Preliminary results suggest the angle of the subducting slab at the point of delamination controls whether the delaminated crust is emplaced within the subduction channel or underplates the overriding plate. The amount of crustal melts is larger in the latter case and the melts are laterally emplaced up to 300 km away from the trench position where the crust is exposed to increased heat. Small amounts of melts are also created in the scenario with delamination into the subduction channel due to decompression melting.

Vote maps of the lower mantle linking seismology, tectonics and geodynamics

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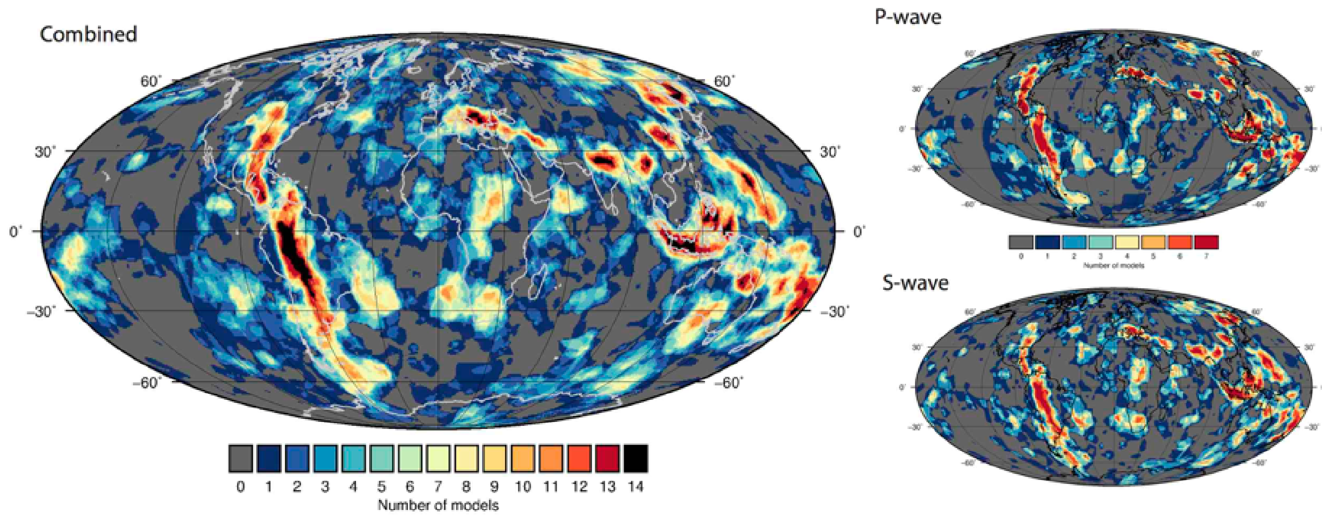
The broad geoscience community is increasingly utilizing seismic tomography to interpret mantle heterogeneity and its links to past tectonic and geodynamic processes. Although there exists an increasing number of individual tomography models that can be utilized for these ends, these models vary in their construction and resolving power. Differences between tomography models are manifest in seismic anomalies of variable magnitude, geometry, location, depth, and resolution. And yet several recent papers focusing on both relative and absolute plate motions, and on global and regional scales, use tomography to validate/test/refine the reconstructions. A measure of the consistency of identified slab features across seismically-derived models would therefore greatly aid in the identification and evaluation of the robustness of prominent features and permit a broader discussion of subduction flux.

To assess the robustness and distribution of positive seismic anomalies, inferred as subducted slabs, we create a set of vote maps for the lower mantle with 14 global P-wave or S-wavespeed tomography models. Based on a depth-dependent threshold metric, around 20% of a given tomography model depth is identified as a potential slab. However, upon combining the 14 models (or 7 S-wave and and 7 P-wave models separately), the most robust slabs are identified by an increasing vote count (i.e. 14 out of 14 models agree at that depth/location). We find an overall peak in the most robust anomalies between 1000-1400 km and a decline to a minimum around 2000 km. Whilst this may reflect an overall decrease in mid-mantle tomographic resolution it is notable that the depth dependent trend matches independent trends from subduction proxies with globally averaged mantle-sinking rates. Alternatively, the slab changes may also reflect a mid lower mantle viscosity increase. An apparent secondary peak in agreement below 2500 km may reflect the degree-two lower mantle slow seismic structures. A preliminary comparison to the depth dependent changes in slab volumes from forward mantle convection models will be provided.



Vote map at 800 km depth for the 14 combined models (left), and the 7 P-wave and 7 S-wave models separately (right).

Role of axial strength of the lithosphere on the accretion mode of mid-ocean ridges

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Oceanic ridges exhibit significant changes in their structural, morphological, and volcanic characteristics with changes in spreading velocity, mantle temperature and the balance of tectonic and magmatic axial accretion. However, the role of each process on the overall shape of oceanic ridges is unclear. We present a series of analogue experiments using colloidal silica dispersions as an Earth analogue. Saline water solutions placed in contact with these fluids, cause formation of a skin through salt diffusion, whose rheology evolves from purely viscous to elastic and brittle with increasing salinity. Ridge geometry becomes increasingly linear with spreading rate until reaching a critical value. This behavior is predicted by the axial failure parameter, a new dimensionless number, which compares the maximum fracture length attainable without plasticity to the axial strength. Slow spreading, fault-dominated ridges and fast spreading, dike-dominated ridges in the laboratory and on Earth are separated by the same critical value of the axial failure parameter. This result indicates that segmentation patterns for weaker axial lithosphere are governed by dike-induced fracturing and that segmentation patterns in strong axial lithosphere are governed by along-axis brittle faulting. Furthermore, higher mantle temperatures during the Archean preclude the formation of large tectonic plates at high spreading rate.

Numerical modeling of the formation of the Continental Rift of Southeastern Brazil

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The Continental Rift of Southeastern Brazil is characterized by several Cenozoic sedimentary basins occurring in a long, narrow valley between the escarpments formed by the Serra do Mar and the Serra da Mantiqueira at the Brazilian continental margin [1]. The explanation for the origin of this rift was related to factors including the reactivation of preexisting Precambrian shear zones as normal faults, processes involving a regional uplift due to the influence of a thermal anomaly in the mantle, and far-field stresses related with the Andean orogeny. These models, however, are essentially qualitative and there is a lack of quantitative models that consider the viability of the proposed mechanisms to explain the rift formation. In this work, we aimed to study the genesis of the rift and how different geological factors can affect its formation in a quantitative basis. We used a two-dimensional, viscoelastic numerical model to simulate the evolution of the Brazilian southeastern continental margin. The model permits the analysis of the lithospheric state of stress throughout time. The numerical experiments involved the simulation of the continental erosion, sedimentation, regional uplift induced by a thermal mantle anomaly and plate-wide tectonic stresses. We tested these factors both separately and superimposed in the numerical experiments. We used the Mohr-Coulomb criterion to evaluate the failure condition of rocks. The results of the models in which erosion and sedimentation were considered separately was compatible with a normal faulting tectonic setting near the stretched continental margin. For the model of a regional uplift, the deviatoric stresses in the upper crust was not expressively affected. However, the superimposed effect of erosion and sedimentation produced a favorable condition for the formation of deep normal faulting, up to the base of upper crust, in the vicinity of the continental margin, due the greater stresses magnitudes cause by the load balance on the lithosphere. The effect of compressive stresses diminished the rupture limit of the upper crust. Our results suggests that the load balance on the lithosphere caused by onshore denudation near the margin and the sedimentation in the adjacent marginal basin produced a state of stress in the lithosphere consistent with the formation of deep normal faulting in the upper crust. Both regional uplift and compressive horizontal stresses did not significantly influenced the state of stress to change the rupture condition of rocks along the continental margin.

[1] Riccomini et al., Evoluão geológica do Rift Continental do Sudeste do Brasil, *in* Mantesso-Neto, V., Bartorelli, A., Carneiro, C.D.R., Neves, B.B.B., eds., Geologia do continente Sul-Americano: Evolução da Obra de Fernando Flávio Marques de Almeida: Beca, São Paulo, p. 383-405, 2004.

Fault reactivation due to glacially induced stresses

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Melting glaciers worldwide have an effect on sea level but also on the stability of pre-existing faults. The load due to continental ice sheets or glaciers depresses the Earth's surface, leading to changes in the lithospheric stresses. The accumulation of ice mass increases the vertical stress, and the horizontal stresses increase due to the accompanying flexure of the lithosphere. During deglaciation, ice-mass loss causes a simultaneous decrease in vertical stress; however, horizontal stresses decrease more slowly due to the slow readjustment of the Earth. After the end of deglaciation, only the induced horizontal stresses remain as the process of glacial isostatic adjustment (GIA) proceeds visco-elastically. The modelling of the GIA process and the estimation of fault slip has been implemented in a finite element model capable of combining the two phenomena. The model has several input parameters, such as ice history, rheology of the Earth, frictional properties, pore-fluid pressure, which affect the activation time of faults and their resulting slip. We will present the setup of the model and results of a 3D model, and show the sensitivity of faults with respect to modelling parameters. The 3D model will be based on a 4-layer Earth model (crust, lithosphere, upper mantle, lower mantle) having a circular ice sheet on top. A thrusting background regime will be assumed with maximum stresses in the horizontal direction and minimum stresses in the vertical. This background stress regime is similar to what is known for previously glaciated areas (e.g. northern Europe, eastern North America).

The presence of dense material in the deep mantle: implications for plate motion

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The dense material in the deep mantle strongly interacts with the convective flow in the mantle. On the one hand, it has a restoring effect on rising plumes. On the other hand, the dense material is swept about by the flow forming dense piles. Consequently this affects the plate motion and, in particular, the onset time and the style of plate tectonics varies considerably for different model scenarios.

In this study we apply a thermochemical mantle convection model combined with a rheological model (temperature- and stress-dependent viscosity) that allows for plate formation according to the convective flow. The models starting condition is the post-magma ocean period. We analyse a large number of model scenarios ranging from variations in thickness, density and depth of a layer of dense material to different initial temperatures.

Furthermore, we present a mechanism in which the dense layer at the core-mantle boundary forms without prescribing the thickness or the density contrast. Due to advection-assisted diffusion, long-lived piles can be established that act on the style of convection and therefore on plate motion. We distinguish between the subduction-triggered regime with early plate tectonics and the plume-triggered regime with a late onset of plate tectonics. The formation of piles by advection-assisted diffusion is a typical phenomenon that appears not only at the lower boundary, but also at internal boundaries that form in the layering phase during the evolution of the system.

A computational framework to optimise global absolute plate motion models

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Plate tectonic reconstructions are an essential component in the understanding Earth's paleogeography, the configuration and behaviour of continents through time, and the link between surface motions and the Earth's interior dynamics on both global and regional scales. Tectonic reconstructions are relatively well constrained back to ∼200 Ma via the seafloor spreading record, but constraining motions for older times represents a significant challenge. Typically, models derived from seafloor spreading histories constrain only the relative motions between plates, representing the how of plate motion evolution, which for example could include how fast two plates separated by rifts or a mid-ocean ridge move apart, or how plates converge at subduction zones. This, however, represents only part the information, as these data contain limited information of the absolute location of plates on the Earth's surface, the where of plate motion evolution. Due to this limitation, relative plate motion (RPM) models are often coupled with absolute plate motion (APM) models to provide the missing information and insight into the relationship that exists between surface motions and the underlying mantle. Traditionally, APM models are derived from a single absolute observational constraint including (among others) palaeomagnetic data, hotspot trails, and seismic tomography. APM models derived in this way produce a wide variety of predictions, but are susceptible to biasing the constraining quantity through unintentional over-fitting. Significant issues exist in solving the problem of APM, including data variability and consistency, data and model uncertainty, and the validity of the included assumptions. To address this, we present a numerical approach combining constraints from multiple, diverse data sources into a suite of unified geodynamically reasonable models of absolute plate motions from 220-0 Ma. Models are constrained using any combination and weighting of hotspot data (for times younger than 80 Ma), net lithospheric rotation minimisation, and optimal global trench migration behaviours. The method employs an inverse approach to iteratively optimise the motion path of a given reference plate through time to converge on the solution that most closely conforms to selected constraint parameters. The method also provides a new way to more efficiently and accurately evaluate various kinematic, geological, and geodynamic properties of a given tectonic reconstruction, providing a way forward towards quantifying uncertainties in plate models.

Long-term coupling and feedbacks between surface processes and tectonics during rifting

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Whereas significant efforts have been made to understand the relationship between mountain building and surface processes, limited research has been done on the relationship between surface processes and extensional tectonics. Here we present high-resolution 2D coupled tectonic-surface processes modeling of extensional basin formation. The main aim is to find out how erosion and deposition affect the deformation in extensional systems. We test the combined effects of crustal rheology and varying surface process efficiency (erodibility, sea level) on structural style of rift and passive margin formation. The results show that both erosion of rift flank areas and basin deposition enhance localization of crustal deformation. Frictional-plastic extensional shear zones accumulate more deformation during a longer period of time, and loading of offshore basins can generate crustal ductile flow. Synthetic normal faults system in the proximal domain are enhanced by both erosion of footwall and deposition on the hangingwall. Feedbacks with distal margin formation are more contrasted. In case of wide margin, sediment export is limited as a results of absent rift flank topography. Sediment export to the distal margin is enhanced by a low sea level. In extreme cases sediment deposition delays lithospheric rupture. These mechanisms are enhanced when fluvial erosion, transport and deposition are efficient. We show that removal of mass from rift flanks and sedimentary loading in the basin area provide a first order feedback with tectonic deformation and control on rifted margin tectonic-morphology. However, surface processes do not change the first order structural style of rifting, which is largely controlled by crustal rheology. Rift escarpment morphology is function of paleo-topography and sea level. Variation of strain localization in natural rift systems correlates with the observed behavior and suggests similar feedbacks as demonstrated by the forward numerical models.

Towards modeling of magma mixing and mingling due to particle/bubble segregation

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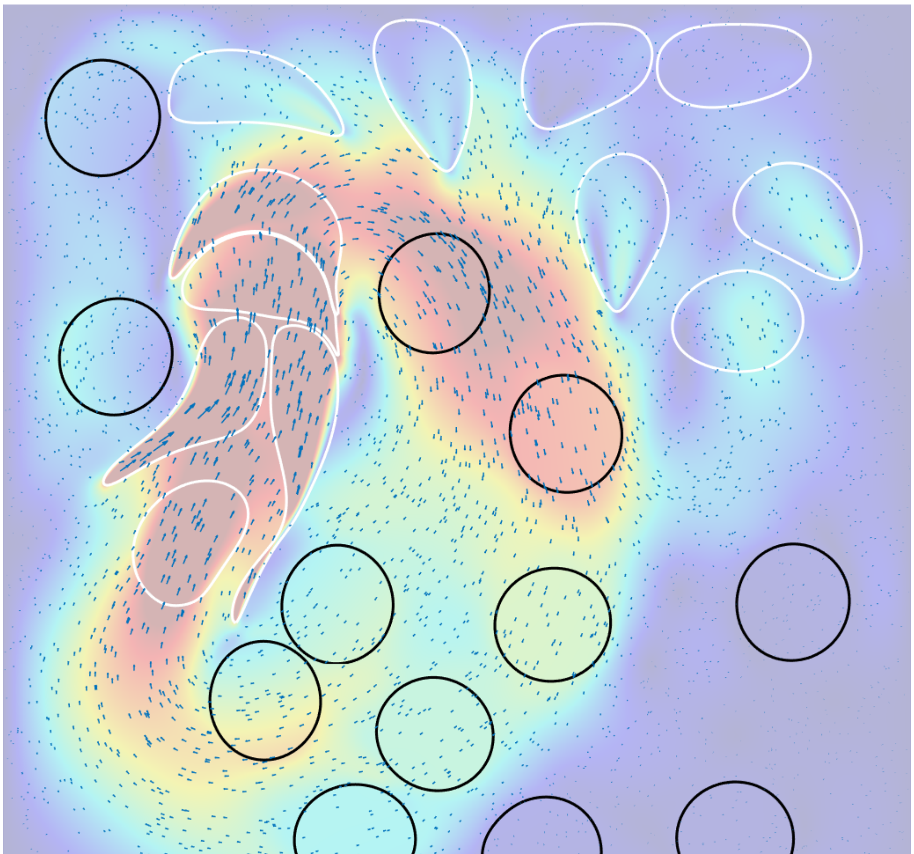
The process of magma mixing has been recognized to strongly affect the compositional variability of igneous rocks. It has also been associated with explosive volcanic eruptions. Recent experiments [1,2] have shown that in addition to chemical diffusion and thermal convection, both bubbles and particles have a significant effect on mixing properties and thus also on chemical heterogeneities.

The numerical solution of the magma/bubble/particle system poses several numerical challenges, such as curvature computation, stability issues and mass conservation of bubbles and particles during remeshing. Here we use numerical models employing the finite element method to simulate particle and bubble segregation in a magma chamber. We directly resolve bubble/magma and particle/magma interfaces using body fitted meshes which consist of triangular elements. Surface tension is implemented using the implicit approach described in Hysing [3]. Here, he impact of different numerical treatments of material interface reconstruction as well as time integration on model results is investigated. Simple resampling of material interfaces results in severe mass loss during simulations such that more sophisticated methods have to be used to circumvent this issue.

[1] Wiesmaier et al., Solid Earth, 6(3), p1007-1023, 2015.
[2] Renggli et al., Contrib. Mineral. Petrol., 171(11), p96, 2006.
[3] Hysing, International Journal for Numerical Methods in Fluids, 51(6), p659-672, 2006.



Bubble/particle segregation. Colors show absolute velocity, with arrows denoting velocity directions. Bubbles and particles are outlined with white and black lines respectively.

The rheology of the lithospheric mantle revisited: recent experimental data, crystal-scale models, and observations of natural systems

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In this poster, we summarize recent experimental data on olivine single crystals and polycrystals at moderate temperatures, crystal-scale models, and observations of natural systems by our groups, which indicate that the lithospheric mantle, although mostly 'dry' (that is, mainly composed by olivine containing low concentrations of hydrogenated defects), may deform by dislocation creep at geological strain rates (10^{-13} - 10^{-16} s^{-1}) in response to stress levels consistent with those produced by mantle convection (200 MPa). New flow laws derived from these data are presented and their geodynamical consequences, such as less effective strain localization processes like shear heating or grain size reduction or a decreased possibility of brittle deformation, discussed.

We also present petrostructural observations in the pargasite and phlogopite-bearing Finero peridotite massif (Italian Western Alps), which constrain the rheology of the lithospheric mantle under the pargasite stability field conditions, that is, below 1100°C and 2.8 GPa. These data show that percolation of hydrous melts in the lithospheric mantle in pargasite stability weakens in a transient way the lithospheric mantle, by favoring strain accommodation by stress-controlled dissolution-precipitation and advective transport of matter by the melts and in fast grain boundary migration in olivine, but that it has no long-lasting effect on the upper mantle rheology, as very little water is incorporated in the olivine structure and the crystallization of pargasite or phlogopite, even at concentrations of 25% vol. does not produces any weakening of the peridotites.

Deformation, crystal preferred orientations, and seismic anisotropy in the Earths D" layer

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We use a forward multiscale model that couples ab-initio modelling of dislocation-accommodated deformation in MgSiO3 post-perovskite (PPv) and magnesiowustite (MgO) at lower mantle pressures and temperatures to polycrystal plasticity simulations to predict crystal preferred orientations development and seismic anisotropy in D". We model the evolution of CPO in aggregates of 70% PPV and 30% MgO composed by 2000 crystals with random initial preferred orientations submitted to simple shear or axial shortening, as well as along two corner-flow streamlines, which simulate the flow pattern associated to the transition between a downwelling slab and flow parallel to the core-mantle boundary (CMB) within D" or between CMB-parallel flow to upwelling at the borders of the African or the Pacific large low shear wave velocity provinces (LLSVP). Simple shear produces monoclinic PPv CPO that progressively rotates towards parallelism between the dominant [100](010) slip system and the macroscopic shear. For shear strains 2, [010] axes align dominantly normal to the shear plane, whereas [100] and [001] axes form weak girdles at low angle to the shear plane, with the [100] maximum aligned with the shear direction. These patterns are in good agreement with experimental data in simple shear for CaIrSiO3 post-perovskite. These CPO result in marked anisotropy for both P- and S-waves propagating through D", with faster P-waves propagating and faster S-waves polarized parallel to the shear direction, that is horizontally for shear parallel to the CMB as well as a strong variation in delay times as a function of the propagation direction for ScS and Sdiff waves. Axial compression results in development of a PPv CPO characterized by a strong maximum of [010] parallel to the compression direction. This CPO differs from those formed in diamond-anvil cell experiments on MgSiO3 PPv, which display a concentration of [001] parallel to the compression. This suggests dominant activation of [100](001) instead of [100](010), maybe due to high stresses, in the experiments. Downwelling corner flow paths result in inclined (relatively to the CMB) fast polarizations for both Sdiff and ScS waves, with anisotropies varying from null to up to 3% as a function of the backazimuth. The CPO evolution is delayed relative to the flow reorientation and, hence, this pattern is preserved up to 50-75 km after the corner. The CPO is then reoriented by the horizontal shearing, with an initial weakening of the anisotropy. Typical simple shear patterns are observed 200 km away from the corner. Upwelling streamlines are also characterized by inclined fast polarization directions, which start to develop within ca. 100 km from the LLSVP, but they do not show decrease in anisotropy associated with CPO dispersion at the corner.

3D lithospheric mapping of the Iberian Peninsula and surrounding Atlantic and Mediterranean margins from 3D joint inversion of elevation and potential field data (gravity and geoid)

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We investigate the present day lithospheric density structure of the Iberian Peninsula and the surrounding Atlantic and Mediterranean margins from a 3D joint inversion of elevation, free-air and geoid data, based on a Bayesian approach. The crustal structure has been constrained by incorporating available sedimentary thickness and about 750 Moho values from DSS investigations and RF analysis covering the entire region. Our preliminary results show a significant lithospheric deformation in the northern (Bay of Biscay-Pyrenees) and southern (Gulf of Cadiz - Gibraltar Arc system) boundaries, where the CMB and LAB are at depths more than 45 and 150 km, respectively. Noteworthy is the arcuate lithospheric thickening observed at the westernmost end of the Gibraltar Arc showing the presence of the NW-to-Westward retreated Gibraltar Arc slab that has given rise to the formation of the Betics-Rif Alpine belt system and the back arc Alboran basin. To the west, the stable-slightly Alpine deformed Iberian massif shows a quasi-flat CMB and LAB topography (30 to 32 km and 100 to 120 km, respectively). The crust and mantle lithosphere thin towards the Mediterranean and Atlantic margins, with the exception of the northern margin where lithospheric thickening extends offshore to the Gulf of Biscay. In the western Mediterranean the SE-Neogene slab retreat has resulted in a significant thinning of the crust and mantle lithosphere. Thin lithosphere is also observed in the Tagus-Horseshoe abyssal plain region, where the LAB shallows to less than 90 km.

This work has been partially funded by MITE Spanish project (CGL2014-59516-P). Firs author has benefited from a short stay at GEOPS (Universit Paris-Sud).

The role of elasticity and plasticity in crustal shortening and topography evolution, insights from two-dimensional mechanical model

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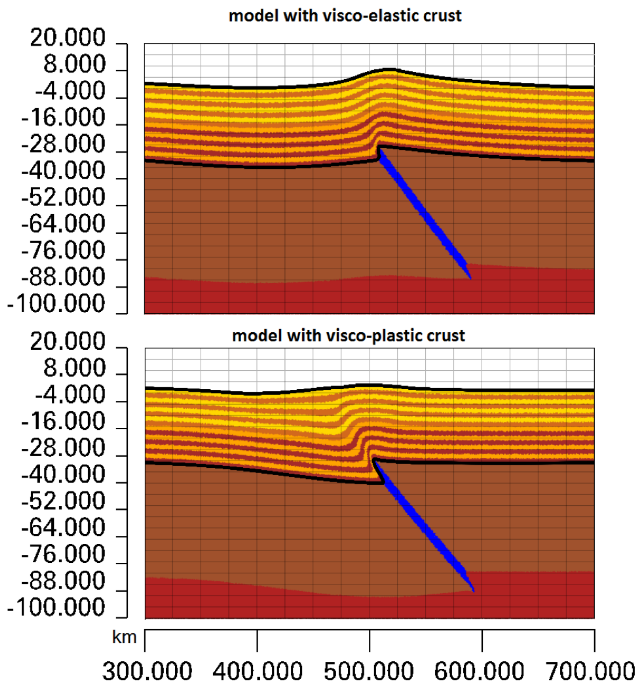
The rheology of the crust plays a fundamental role in the topographical evolution of orogens. Many authors have proposed thermo-mechanical visco-plastic models to explain the formation of orogeny produced by continental collision but not including elasticity. Some topographic features as foreland basins have been explained by flexural processes. Here we propose a series of two-dimensional mechanical models to evaluate the effect on topography by including elasticity in the cortical rheology in a continental-continental collision scenario in which deformation is driven by constant velocity. To that purpose, we use the numerical code Underworld2, which has implemented the Maxwell model for viscoelastic materials. In addition, for plasticity we use the depth-dependent Von Mises criterion along with the Byerlee law. Since the viscoelastic model of Maxwell does not take into account the elastic instantaneous part, we compare the results with a 1D flexural model incorporating pure elastic and viscoelastic thin-plate rheology. In agreement with other studies, depending on visco-elastic, visco-plastic or visco-elasto-plastic rheologies continental collision may form double vergent orogens and/or result in continental subduction and lithosphere thickening. Variables related to elasticity such as Young Modulus and plasticity like cohesion change the mode of crustal deformation; elasticity results in a higher orogeny and a smooth topography. Localization and formation of basins strongly depends on the rheology of the upper plate.



Sequential data assimilation for solid Earth sciences: Probabilistic estimation and forecasting of fault stresses

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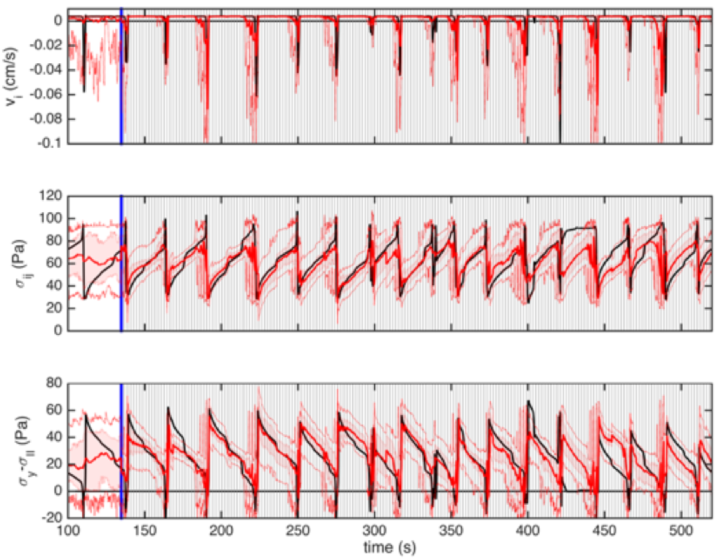
Integrating near-surface geological and indirect geophysical observations, laboratory results and physics-based numerical modeling is crucial to estimate the evolution of dynamic variables in solid earth systems. How to do this integration is not obvious in light of the scarcity and uncertainty of natural and laboratory data and the difficulty of modelling the physics governing dynamical system in general and earthquakes in particular. We adopt the statistical framework of sequential data assimilation - extensively developed for weather forecasting - to efficiently integrate observations and prior physical knowledge in the form of a forward model, while acknowledging errors in both sources of information. We prove this concept for seismicity purposes by estimating the unknown current and future state of stress and strength on faults.

To do so we sequentially assimilate noised, synthetic velocity and stress data and their errors from a single location in a simplified subduction setup. Using an Ensemble Kalman Filter we update 150 ensemble members of a Partial Differential Equation-driven seismic cycle model. This visco-elasto-plastic continuum forward model solves Navier-Stokes equations with a rate-dependent friction coefficient.

We quantitatively and qualitatively show that probabilistic estimates of fault stress and dynamic strength evolution capture the truth exceptionally well (Figure). This is possible, since the sampled error covariance matrix contains prior information from the physics that relates velocities, stresses and pressure at the surface to those at the fault. During the analysis step, stress and strength distributions are thus reconstructed so that fault coupling can be updated to either inhibit or trigger events. In the subsequent forecast step the physical equations are solved to propagate the updated states forward in time and thus provide probabilistic information on the occurrence of the next event. At subsequent assimilation steps, the systems forecasting ability turns out to be significantly better that of a periodic recurrence model to forecast the large events in this quasi-periodic sequence (requiring an alarm ∼17% vs. ∼68% of the time to forecast 70% of 21 events). Statistically combining our prior knowledge of physical laws with observations thus seems to be a powerful tool, which provides distinct added value with respect to using observations or numerical models separately. Although several challenges for applications to a natural setting remain, these first results indicate the large potential of data assimilation techniques for probabilistic seismic hazard assessment and other challenges in dynamic solid earth systems.



Ensemble Kalman Filter estimates capture fault state evolution, in terms of horizontal velocity, shear stress and strength excess, very well. Ensemble statistics in red are given in various percentiles P, while the true solution is black. Grey lines indicate times when data is assimilated with blue one showing the first step.

Formation, evolution, and extinction of pull-apart basins

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We present a model for the origin, evolution, and extinction of pull-apart basins based on elastic upper crustal numerical models, field observations, and fault theory. In our model, geometric differences between pull-apart basins are inherited from the initial geometry of the strike-slip fault step-over, which results from the forming phase of the strike-slip fault system. As strike-slip motion accumulates, pull-apart basins are stationary with respect to underlying basement, and the fault tips propagate beyond the rift basin, increasing the distance between the fault tips and pull-apart basin center. Because uplift is concentrated near the fault tips, the sediment source areas may rejuvenate and migrate over time. Rift flank uplift results from compression along the flank of the basin. With increasing strike-slip movement the basins deepen and lengthen. Field studies predict that pull-apart basins become extinct when an active basin-crossing fault forms; this is the most likely fate of pull-apart basins, because basin-bounding strike-slip systems tend to straighten and connect as they evolve. The models show that larger length-to-width ratios with overlapping faults are least likely to form basin-crossing faults, and pull-apart basins with this geometry are thus most likely to progress to continental rupture. The Gulf of California illustrates our model predictions well: larger length-to-width ratios are found in the southern Gulf, which is the region where continental breakup occurred rapidly. In the northern Gulf of California and Salton Trough lower length-to-width ratios were present, which our models suggest inhibits continental breakup and favours straightening of the strike-slip system. This may explain why the northern Gulf of California has not ruptured yet.

The influence of tectonics and wave propagation on splay fault activation

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To accurately study the seismic cycle in subduction zones, we need numerical methods that span a large range of spatial and temporal scales. The stresses on a fault need hundreds to thousands of years to build up on a tectonic time scale. The consequent earthquake rupture propagation, on a time scale of a couple of seconds to minutes, is influenced by these initial fault conditions as well as dynamic triggering due to emitted seismic waves. Spatial scales are also challenging, because the stress state of the fault can be affected by the subducting slab on scales of tens to hundreds of kilometers, while reflecting waves can influence dynamic rupture propagation in the hundred-meter-scale close to the tip of the wedge. To accurately model the physics involved over all temporal and spatial scales, we couple a geodynamic seismic cycle (SC) model [1,2,3] to a dynamic rupture (DR) model (`www.seissol.org`). The SC models have the advantage of modelling earthquake cycles in a self-consistent manner concerning stress, strength, and fault geometry, but lack a high enough spatial and temporal resolution to resolve co-seismic processes, such as seismic wave propagation. In contrast, dynamic rupture models solve for frictional sliding on a prescribed fault surface and the subsequent seismic wave propagation, but their initial conditions are not self-consistently constrained. By coupling these two codes, the advantages of both can be exploited.

The initial stresses and geometry from both a megathrust and splay fault rupture from the SC model are used as input in the DR model, resulting in the spontaneous nucleation and propagation of a dynamic rupture. The earthquakes of both modelling approaches are qualitatively comparable in terms of stress drop and propagation direction.

We exploit the advantages of our coupled method by studying when and how often a dynamic rupture favours propagation on the splay fault instead of on the megathrust. This is of importance when assessing a region's tsunami hazard. We find in the SC models that subduction zones with a larger sediment thickness and with relatively weaker sediments favour splay fault formation with corresponding splay fault ruptures. Then, the coupled method allows us to verify whether splay fault rupture selection is influenced by seismic waves reflecting strongly within the confined accretionary prism.

[1] Dinther et al., Journal of Geophysical Research: Solid Earth, 118(4):1502-1525, 2013.
[2] Dinther et al., Journal of Geophysical Research: Solid Earth, 118(12):6183-6202, 2013.
[3] Dinther et al., Geophysical Research Letters, 41(4), p1194-1201, 2014.

Geochemical cycling of greenhouse gases between interior and atmosphere

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Although geochemical cycling is of fundamental importance to processes such as climate variability, the history of volatile fluxes between interior and atmosphere remain controversial. Therefore, we examine in this study the geophysical factors that regulate the atmospheric abundances of H_2O, CO_2, and N_2. Our modelling approach includes a fully dynamical convection simulation, the transport of volatiles into and out of the convecting mantle, and a varying surface temperature due to infrared absorption in the atmosphere. We have linked these processes to compute simultaneously the thermal evolution of atmosphere and mantle. Depending on model parameters (e.g., critical yield stress), the evolving planet passes through episodic and plate tectonic regimes.

Planets with plate tectonics possess a mobile surface over extended periods of time. With respect to our simulations, we find an average plate speed ranging between few to several tens of cm/yr, which is slightly higher than what is observed on present-day Earth. Plate tectonics leads to efficient cooling of the interior and a well mixed mantle. Melt production and volcanism ensure the release of volatiles from the interior into the atmosphere at a constant rate. The excess amount of greenhouse gases is continuously removed from the atmosphere by weathering processes of the geochemical cycles, thus keeping variations in surface temperature under control. Furthermore, the formation of cratons on planets with plate tectonics stabilises the amount of rocks exposed to chemical weathering and dampens short-term fluctuations in the surface temperature.

Planets with episodic tectonics show periods of quiescence punctuated with rapid episodes of surface overturn. Our simulations suggest that catastrophic resurfacing occurs randomly and takes place over about 50 Myr. During such global-scale overturn events, the average plate speed reaches high values of a few hundreds of cm/yr. In comparison to the plate tectonic regime, planets with episodic resurfacing show a different cooling history and mantle mixing. Because of elevated melt production and volcanism, catastrophic resurfacing causes strong variations in surface temperature on the order of a few tens of Kelvin, which could be enough to push a planet into greenhouse runaway. The characteristic differences between the two tectonic regimes may explain the divergent evolution of Venus and Earth as suggested by previous studies (e.g. [1,2]).

[1] Noack et al., Icarus, 217, p484-498, 2012.
[2] Gillmann & Tackley, J. Geophys. Res. Planets, 119, p1189-1217, 2014.

Melting and melt flow under continental crust conditions: numerical exploration of flow rheologies of melt and rock

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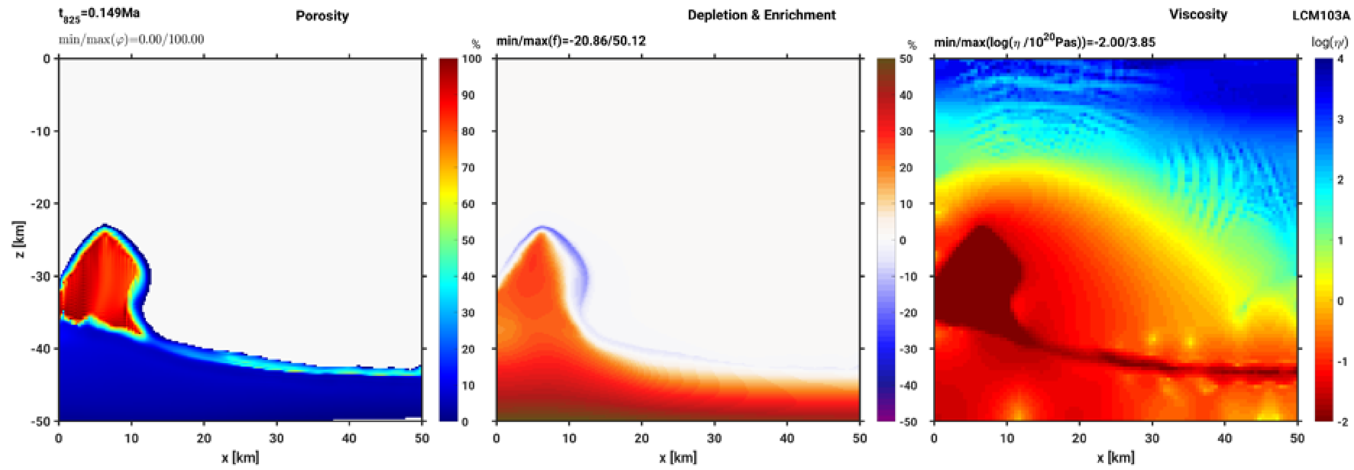
We try to improve physics and modelling of magmatic processes in the crust. Essential features are melting and freezing accompanied by depletion and enrichment with a feedback to a controlling melt law and melt curves. Segregation of fractional melt from the source rock to an emplacment where it solidifies leads to compaction and dilatation of the rock matrix and generats stresses. The transport properties of melt as well as of rock dominate the temporal dynamics and the evolving structures; they are objective of the study.

The mobility of the melt relative to the deformable rock matrix is determined - besides the porosity-permeability relation - by the retention number Rt which is varied from 0.1 to 100. The resulting behaviour spans from fast uprising local magma chambers freezing in shallow cold regions to a low degree molten band advected by the moving rock.

The rock or solid matrix follows a temperature and stress dependent power law. At Rt = 1 we tested two extrem crustal parameter sets: weak with values of dry quartzite and strong with dry Westerly granite data. In shallow cold levels Byerlee-like placticity dominates the effective viscosity. The weak rheology develops one peak event, a fast magma ascent and then cooling and freesing. The other, strong rheology, is more viscous and therefore slower but reveals a much more vivid dynamics over a longer time span. The higher viscous rock generates higher stresses with stonger feedback on the nonlinear viscosity. Various structural patterns emerge: weak channels leading the melt flow, lumpy localizations of accumulated melt, migrating stiff cores, shear zones and conjugated slip lines systems. They need deeper interpretation.

Other retention numbers or additional extension again may expand the scope of behaviour patterns.

For more theoretical background and model setup see the related poster Thermo-mechanical two-phase flow models of magma ascent in the continental crust: effect of heat flow and extension by Schmeling et al. .



Melt fraction/porosity, depletion and effective viscosity of the rheologically strong model at time of maximum velocity. Segregating melt heats and weakens the solid matrix. Magma forms an asending pluton. Freezing melt in the uprising front enriches the rock matrix. Accompanied stresses feedback with the viscosity.

Mountain building in Taiwan: insights from 3D numerical modeling

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The orogeny of Taiwan bracketed by two sub-orthogonal subduction systems is one of the world's foremost natural laboratories for studies of mountain building. It has formed by oblique arc-continent collision between the Eurasian continental passive margin, and the Luzon Arc of the Philippine Sea plate over a time span of approximately 6.5 Ma. The high rate of convergence and rock uplift, and the wet, stormy climate of the subtropical typhoon belt combine to produce erosion and sediment yield rates amongst the highest in the world.

However, the key processes involved in the building of the island remain under discussion. The Manila trench and Ryukyu trench subduction systems are an untenable plate tectonic situations and must result in either a change in the relative motion of the two plates or the formation of a new plate boundary in order to accommodate continued convergence. Lallemand et al. [1] argue that the Eurasian plate is presently tearing along a fault roughly parallel to the Ryukyu arc in order to permit the westward motion of the Philippine Sea plate. Alternatively, Teng et al. [2] argue that the South China Sea slab has broken off beneath Central and Northern Taiwan and thus is absent in the North where the space problem would otherwise arise with the subducting Ryukyu slab.

Here, we employ the parallel 3D code LaMEM (Lithosphere and Mantle Evolution Model), using staggered grid differences and simultaneously taking mantle flow and an internal free surface into account. We investigate crustal exhumation, mantle circulation, lithospheric deformation, and the double subduction collision zone in Taiwan region. We further study the geodynamic process that formed Taiwan to evaluate the hypothesized models.

[1] Lallemand et al., Tectonophysics, 335, p229-253, 2001.
[2] Teng et al., Geology, 28, p155-158, 2000.

The energetics of evolving convective systems: Internal heating, mixing, and Earth's evolution

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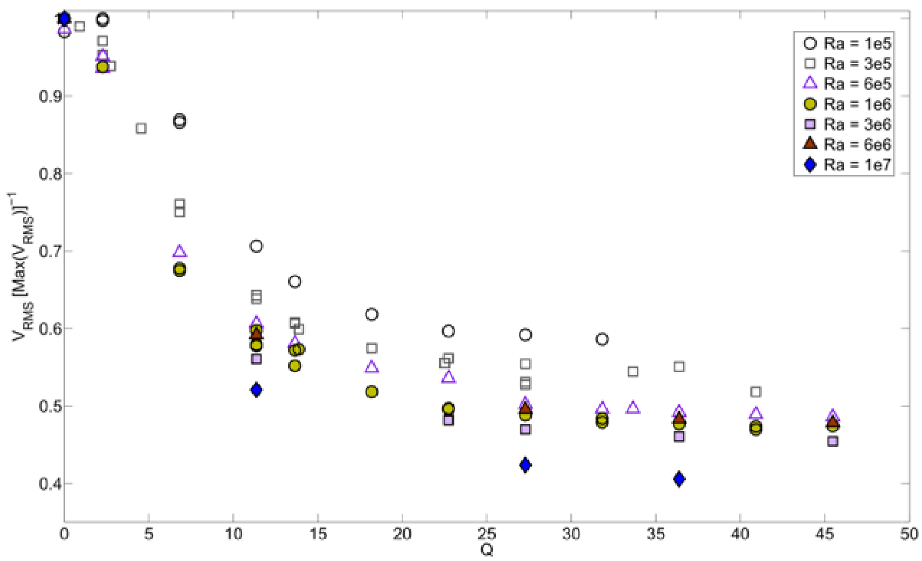
The Earth's mantle is heated by a combination of internal heating, from the decay of radioactive nuclei, and basal heating associated with core cooling. Convective velocities, energy, and heat loss depends on the combination of these heating modes. Yet, canonical models explicitly assume that endmember heating relationships either pure basal or pure internal, that are relevant for either radiogenically depleted mantles or for mantle temperatures equal to that of the core, respectively are valid for mixed heating systems. The key assumption implicit in such models is that a rapid increase in convective velocities, and consequently chemical mixing within the mantle, follows with increasing convective vigor (and surface heat flux) from increasing internal temperatures. This leads to the canonical prediction that younger, or hotter planets will have increased internal and surface velocities in order to balance higher heatflow. It then follows that early/hotter planets mix their interiors efficiently, such that inhomogeneities (e.g., primordial chemical reservoirs) would be difficult to retain, an inference apparently at odds with observations of the Earth.

In this work, we examine the underlying dynamics and energetics of convection using both isoviscous and temperature-dependant viscosity formulations under mixed heating conditions. We find convective velocities are decoupled from internal temperature and surface heat loss over much of the relevant radiogenic range. In pure isoviscous systems velocity decreases asymptotically with increasing internal heating rates (Figure), while temperature-dependant viscosity systems show only weak dependency. These results show a significant break with canonical endmember scaling behaviors for mixed heating systems. This suggests that in early planetary systems (with high internal heating rates) velocities may plateau, and that increasing heating (or temperature) will not necessarily result in increasing velocities, or mixing ability despite the increasing surface heat flux and convective vigor. Mixed heating results show that canonical thermal evolution and mixing models for the Earth, and indeed our understanding of Earth's evolution, needs to - and indeed shall - be revisited.

[1] Weller & Lenardic, Geophys. Res. Lett., 43, doi:10.1002/2016GL069927, 2016.



Normalized isoviscous internal velocities (VRMS) vs. the Internal heating rate (Q). Ra are the Rayleigh numbers defined at the base of the mantle [1].

Strain partitioning in arcuate orogens: Analytical predictions and numerical experiments based on the Himalayan arc

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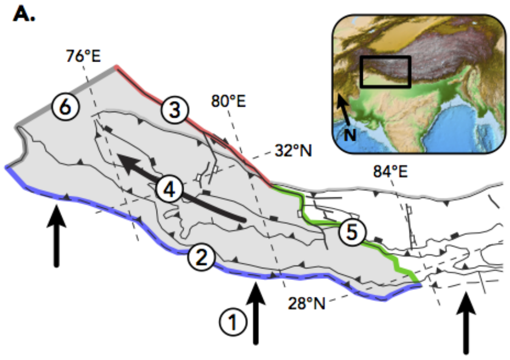
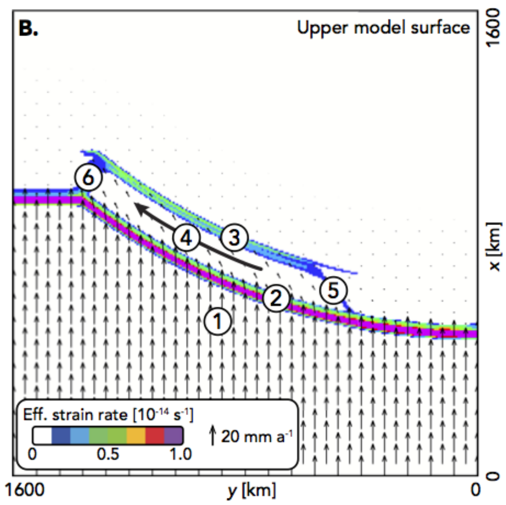
In regions where tectonic plate convergence is oblique, strain is often partitioned onto margin-normal thrust and margin-parallel strike-slip faults. In arcuate orogens such as the Himalaya, the obliquity angle between the plate convergence vector and the normal to the thrust front varies along strike, suggesting strain will be partitioned in the parts of the orogen with relatively high obliquity while oblique thrusting will occur in other regions. Strain partitioning along part of such an orogen will result in the orogenic wedge being translated along strike, but also in the development of structures at the lateral ends of the translating wedge that accommodate the transitions to and from the partitioned region. We hypothesize that a number of such features observed in the western Himalaya are related to strain partitioning along strike, including the Western Nepal Fault System, Karakoram fault, and shortening structures in the western Himalayan syntaxis (Figure A).

We combine a new analytical solution for determining the conditions under which strain partitioning will occur with numerical experiments of oblique plate collision to demonstrate that strain partitioning is a process that can feed crustal mass along strike into the western syntaxis to compensate extreme rates of erosion (Figure B). The analytical solution balances the horizontal shear driving forces acting on the base of the orogenic wedge with those resisting strain partitioning at the rear of the wedge and at its lateral ends. It predicts that strain partitioning should occur along much of the western Himalayan arc provided the strength of the orogenic wedge or material at its rear is relatively low (friction angle $\phi \leq 5°$). Results from numerical experiments are generally agree with the analytical predictions, though the region at the rear of the orogenic wedge or the wedge itself must be stronger in the numerical experiments than predicted. We attribute this discrepancy to partial partitioning of the orogen-parallel component of oblique convergence in the numerical experiments and some predicted frictional parameters that push the orogenic wedge out of a critical state. When partitioned, our purely mechanical numerical experiments show that along-strike mass transport in an arcuate orogen of Himalayan scale can produce local zones of uplift in the syntaxis region with uplift rates of $5-6$ mm a^{-1} (Figure B). This is slightly below the observed Quaternary rate of rock exhumation in the western syntaxis region, but may be enhanced by erosional thermal weakening of the crust.

[1] Silver et al., Tectonics, 34(12), p2494-2513.





Features related to strain partitioning in an arcuate orogen. (A) Tectonic map of the western Himalaya, simplified from [1]. Features related to strain partitioning in this region include: (1) oblique convergence across (2) the orogen thrust front, (3) a strike-slip shear zone at the rear of the orogenic wedge that facilitates (4) along-strike translation of the wedge, and (5) extensional/strike-slip and (6) shortening structures at the lateral ends of the partitioned region (light gray). (B) Calculated velocity vectors and contoured strain rates for a numerical experiment of continental collision with an arcuate plate boundary based on the western Himalaya. The numerical experiment reproduces the features labeled in (A) as a result of strain partitioning across the thrust front with uplift rates at (6) that exceed 5 mm a^{-1}*. Feature labels as in (A).*

Fractional crystallization in a terrestrial magma ocean

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The thermochemical evolution of the magma ocean has profoundly influenced the differentiation of the planet, the core-formation process, the structure and dynamics of the mantle, and the time history of the magnetic field. A magma ocean is a very complex system at extreme conditions. Though there is little hope to realistically simulate the full dynamics of a magma ocean, a well-balanced model approach to the magma ocean phenomenon will help us better understand key features of transport phenomena in the magma ocean and their importance.

So far, numerical simulations of magma oceans have mostly used one-dimensional parameterizations for the progressing solidification. As already mentioned, a direct numerical simulation of the magma ocean at the level of individual crystals would go far beyond the capabilities of todays computer systems. For this reason, we use a single-continuum model based on classical mixture theory [1] with a hybrid approach [2] to model the processes in the mush region. For simplicity, we assume that the core has already formed and we start with a pure silicate composition neglecting metal segregation.

An important question is whether equilibrium or fractional crystallization is favoured and which density distribution would result from fractional crystallization. In a first step, we have investigated fractional crystallization by melt percolation, i.e. after the rheological transition. We are currently extending the model to allow for crystal settling/flotation.

[1] Bennon & Incropera, Int. J. Heat Mass Transfer, 30, p2161-2170, 1987.
[2] Oldenburg & Spera, Numer. Heat Transfer, 21B, p217-229, 1992.

The Altyn Tagh fault: quantifying the contribution of strain-weakening on lithospheric rheology

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The Global Strain Rate Model (GSRM) shows strain variation by a factor of 16 across the Tibetan Plateau region with developed high strain linear regions associated with major faults and suture zones. The Altyn Tagh Fault (ATF), which forms the boundary between the Tibetan Plateau and the Tarim basin, is one such high strain region and is the surface expression of localised strain that extends into the lithosphere. The ATF partially accommodates strain arising from the India-Asia collision, has undergone up to 475 km left-lateral displacement since the late Oligocene ($\sim$25 Ma) and presently accommodates an effective total relative motion of $\sim$10 mm/yr.

Where strength contrasts exist in a deforming medium, a concentration of shear strain is typically observed in the adjoining weaker medium. Thin viscous sheet models, which assume a continuous viscous deformation, show that the strength contrast alone between the Tarim Basin and Tibetan plateau is insufficient to produce the apparent strain localisation on the ATF unless the effective strain-rate vs stress exponent n is of order 10 or 20. While such large exponents might be explained by low-temperature plasticity laws for smaller values of n, more typical of dislocation creep ($n \sim 3$ to 5), including a damage based strain-weakening mechanism in the model can also result in formation of a high strain region at the Tarim Basin boundary that progressively narrows with an increase in the total strain. We show how variations in this strain-weakening parameter influence the development of the high strain region which is analogous to the ATF in these thin sheet models.

We represent the strain-weakening mechanism by a viscosity coefficient that is proportional to the accumulated viscous work (with proportionality constant Γ), as expected for a mechanism such as shear heating or grain size reduction. To avoid run-away weakening in the model, we also include a healing mechanism (which could represent cooling or annealing) in which the viscosity coefficient recovers at a rate proportional to the accumulated damage, with proportionality constant β. At a given strain-rate the balance between weakening (Γ) and healing (β) mechanisms allows the viscosity coefficient to reach a stable value that decreases with strain rate. We discuss the influence of the damage parameters (Γ, β) on the formation of the high strain rate region that represents the ATF.

Previous thin viscous sheet models have used a geometrically simplified approach to represent the India-Asia collision and development of the ATF. Here we use calculated paleo co-ordinates of India and the Tarim Basin at 47 Ma, the time of initial collision with Asia. We rotate India forward to its present day position and observe the localisation of strain developing as the collision proceeds.

From back-arc extension to orogenic plateau formation a numerical modeling study of ocean-continent subduction systems

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The crustal structures of overriding plates in subduction settings around the world can vary between a wide range of deformation styles, ranging from extensional structures and back arc opening induced by slab roll back as in the Tonga or Hellenic subduction zone to large, plateau-like orogens such as the central Andes. Both end member types have been intensively studied over the last decades and a range of hypotheses has been proposed to explain their characteristics. Here we model ocean-continent collision using high resolution, upper mantle scale plane-strain thermo-mechanical models, which also account for phase changes of rocks that enter the eclogite stability field and the phase transition at the 660 km mantle discontinuity. We consider varying plate velocities, continental crustal rheology and back-arc lithospheric strength as the main variables affecting the strain regime of the overriding plate in subduction zones and conducted a sensibility study with those parameters. Our results show that the back arc lithospheric strength plays a pivotal role in determining whether and when the overriding plate will deform, and the combination of subduction and overriding plate velocity determines the type of strain regime in the overriding plate. To verify and discuss our modeling results, we also present a comparison of the models with natural subduction systems.

Lithospheric stresses on Europa's icy shell: Can subduction initiate on Europa?

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Europa presents an exciting area of research to understand processes occurring on icy satellites and their astrobiological potential. Despite its small size, Europa is a dynamic world. Surface features indicate a young age and extensive tectonic activity. The widespread extensional features create extra surface that needs to be accommodated to preserve the strain balance on Europa. Previous modeling have proposed that this could be achieved by folding or passive thickening [1,2]. Another mechanism of balancing this extra surface area is subduction on the icy shell, suggested by the mapping analysis of Kattenhorn and Prockter [3]. This gives rise to the notion of plate tectonics on the icy shell, and this has important implications for the satellite's evolution, surface environment, and thus habitability. Therefore it is of great interest to explore the conditions favorable for plate tectonics to operate on Europa.

The dynamics for subduction initiation, which is considered the key factor for plate tectonics initiation, has been widely studied but is not yet well understood. For planetary lithospheres without pre-existing faults or weak zones, subduction initiation is difficult due to the high strength of the lithosphere. Sublithospheric convection has been proposed as a mechanism for subduction initiation for these planetary bodies. The stresses induced in the lithosphere from convection, caused by the dipping slope of the base of the lithosphere, may be large enough to overcome the yield stress of the lithosphere such that it can subduct. If Europa's icy shell can develop a sufficiently wide convective cell, the stresses in the lithosphere will be higher and thus more easily exceed the yield stress to initiate subduction. The relationship between the yield stress and the time of subduction initiation can be derived from the simple model of Rayleigh-Taylor instability. Considering the range of possible conditions on Europa, we use scaling relations to constrain the yield stress of the icy lithosphere so that plate tectonics can initiate within the lifetime of Europa's icy shell.

[1] Bland & McKinnon, Icarus, 221, p694-709, 2012.
[2] Bland & McKinnon, Geophys. Res. Lett., 40, p2534-2538, 2013.
[3] Kattenhorn & Prockter, Nature Geoscience, 7, p762, 2014.

The participation of ilmenite-bearing cumulates in lunar mantle overturn

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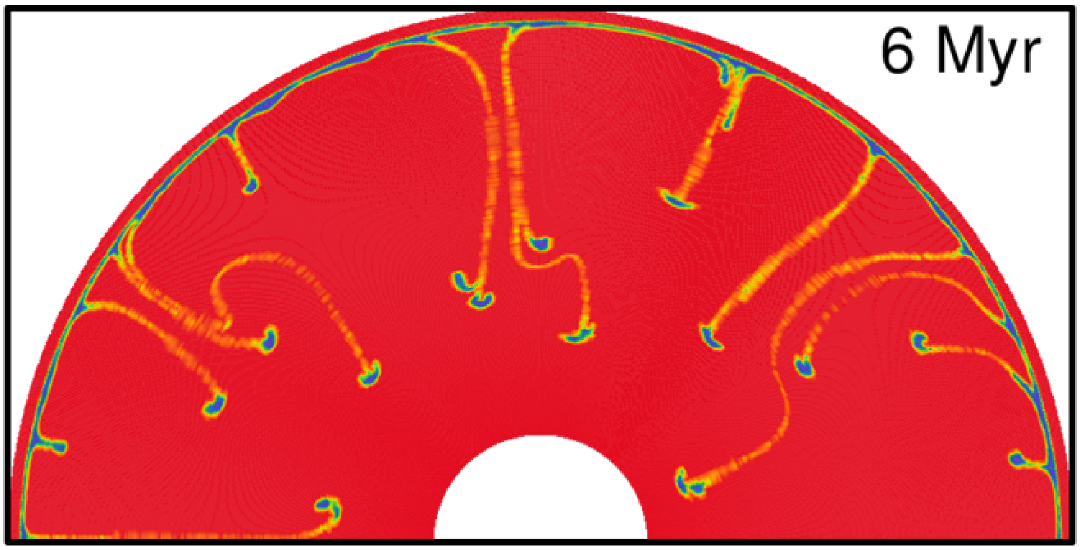
The Moon is considered to have solidified from a global magma ocean. As the magma ocean cools, it goes through fractional crystallization. Experimental results of the crystallization sequence of the magma ocean suggest that dense minerals, with high iron content and including the mineral ilmenite, formed when about 90% of the magma ocean had solidified. In the final stages of solidification, materials enriched in KREEP (potassium, rare earth elements, and phosphorus) were formed between the crust and the mantle cumulates. This layer is termed urKREEP. The crystallized mantle cumulates underlying the urKREEP layer are denser towards the crust, and are therefore gravitationally unstable. This instability is considered to facilitate a global mantle overturn event, where mantle convection is additionally driven by the ilmenite-bearing cumulates (IBC).

This study investigates the quantity of IBC that participate in the mantle overturn after magma ocean crystallisation, and its dependence on a range of parameters. We test the effect of viscosity by varying initial temperature, temperature dependence of viscosity, and weakening by simulation of a partially molten urKREEP layer. The effect of different density contrasts is also tested.

Modelling experiments are performed on a 2D cylindrical finite element model. Convection equations are solved using the extended Boussinesq approximation assuming an infinite Prandtl number. Our models start with stratified cumulates from the crystallized magma ocean, with varying density and distribution of heat-producing elements among the layers.

We find that participation of IBC in mantle overturn is highly sensitive to their viscosity and the viscosity of the surrounding layers. Parameters that have a first-order influence on IBC sinking are initial temperature and temperature-dependence of viscosity in the region of IBC, and the presence of a partially molten urKREEP layer. Second-order influences come from parameterization of the partially molten urKREEP, and density contrast between IBC and the layer below. IBC overturn most likely happened when the urKREEP layer is still partially molten, with 50-70% of the original IBC layer sinking down. Participation of urKREEP in IBC sinking is unlikely. Some of the IBC would always remain in the original region, making it possible for rising partial melt to assimilate the Ti-rich composition. Foundered IBC would likely form a stable layer at the core-mantle boundary. This could explain the presence of present-day partially molten lower lunar mantle, but leave it difficult to explain the duration and intensity of the lunar dynamo.



Normalised concentration of IBC in the mantle at 6 Myr in a representative model. Diapirs are formed at distances of a few hundred kilometers.

Subduction initiation propagates along the transform fault: 3D numerical modeling

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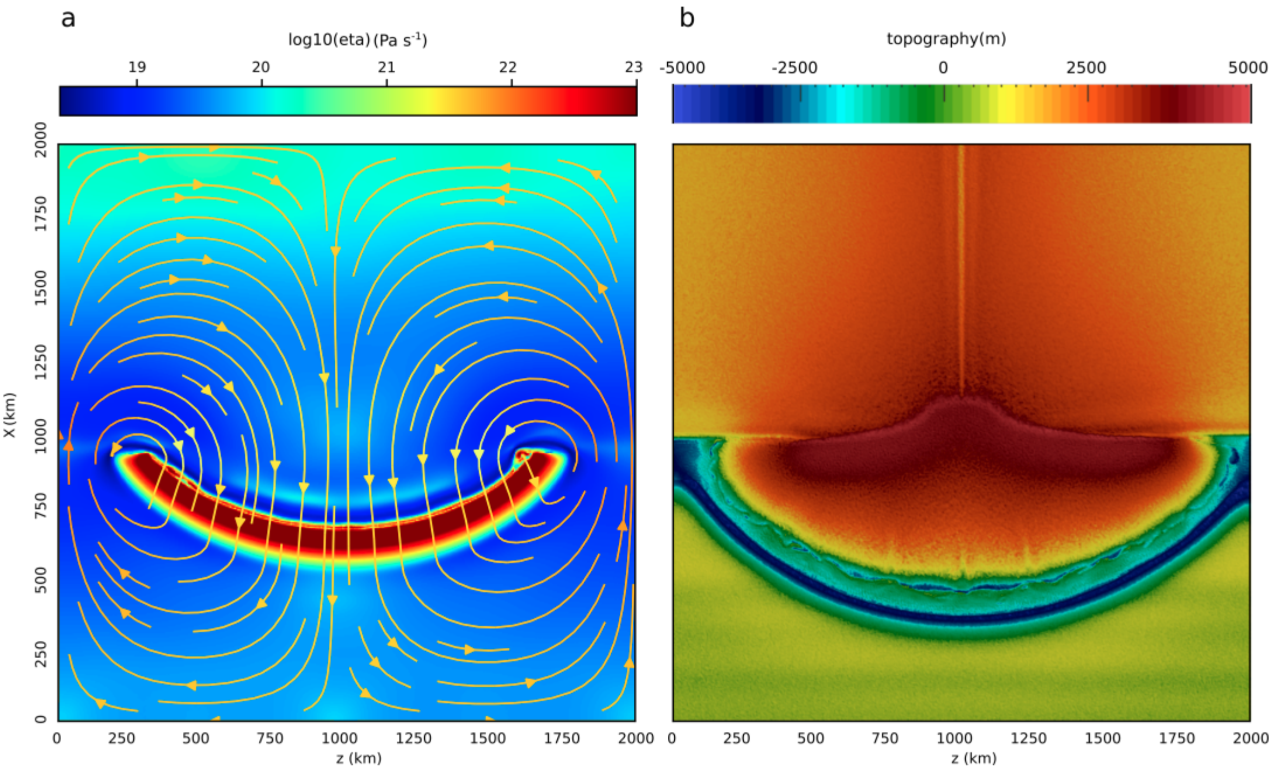
Initiation of new subduction zones along oceanic transform faults has been suggested on the basis of natural observations and is essential for understanding the origin and dynamics of intraoceanic subduction systems. To date, this process has been only investigated with two-dimensional (2D) numerical models, which thus ignored its intrinsic three-dimentional (3D) geometry and dynamics. Here, we investigate the 3D thermo-mechanical visco-plastic model, in which and old and thick oceanic plate is separated by a transform from a thinner and younger oceanic plate containing a transform-orthogonal mid-ocean ridge. Our numerical experiments suggest that the older plate starts to subduct spontaneously at the transform-ridge junction, thereby forming an arcuate gradually widening and retreating subduction zone (Fig. 1). Our models thus demonstrate that the subduction initiation processes strongly depends on the age contrast of the overriding and subducting plate and is happening faster when this contrast is larger (as e.g. at the ridge-transform junction. Consequently, the distribution of plate ages (symmetric or asymmetric) across the mid-ocean ridge should strongly affect subduction geometry and dynamics. On the other hand, the age of the subducting plate controls the slab dynamics and thus the retreating trench motion. Based on these results we propose that two key factors control the 3D subduction initiation dynamics in nature: (1) the age of subducting plate which influence the negative buoyancy of the subducting slab and (2) the thermal structure of the overriding plate, which reflects the spreading history of the mid-ocean ridge. Results of our numerical experiments can be applied for the tectonic evolution of Neotethyan ophiolites along Bitlis-Zagros suture zone, which has strong regularity in the age distribution of SSZ type ophiolite. The modeled trench evolution also contributes to our understanding of the formation of curved oceanic subduction zones worldwide.



The basic characteristics of the 3D SI model at 3.95 Ma. (a) shows the subduction induced mantle flow and the subducted slab which is on depth slice (y=200 km); (b) shows the formation the curved trench.