2019 Ada Lovelace Workshop on Modelling Mantle and Lithosphere Dynamics

CIG COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

EGU

ROMA TRE UNIVERSITÀ DEGLI STUDI

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 Putten, The Netherlands (2017), Oleron, France (2015), in Hønefoss, Norway (2013) and in Gross Doelln, Germany (2011).

This workshop is part of the EGU conference series.

Scientific committee & organisers

The scientific committee consists of:

- Thorsten Becker (University of Texas at Austin, USA)
- Fabio Capitanio (Monash University, Australia)
- Manuele Faccenda (Università di Padova, Italy)
- Claudio Faccenna (Università di Roma Tre, Italy)
- Francesca Funiciello (Università di Roma Tre, Italy)
- Carmen Gaina (University of Oslo, CEED, Norway)
- Takashi Nakagawa (University of Hong Kong, China)

This meeting is organised by Manuele Faccenda (main convener), Claudio Faccenna, and Francesca Funiciello.

Sessions and invited speakers

Session 1: Planetary Geodynamics (Monday 26th, 8:30 - 10:30)

- K. Kalousova (Charles University, Czech Republic)
- T. Rückriemen (TU Berlin, Germany; Department of Extrasolar Planets and Atmospheres, DLR, Germany)

Session 2: Plate-mantle dynamics in the Early Earth (Monday 26th, 8:30 - 10:30)

- A. Webb (University of Hong Kong, China)
- C. O'Neill (Macquarie University, Australia)

Session 3: The emergence of plate tectonics (Tuesday 27th, 8:30 - 10:30)

- N. Coltice (Ecole Normale Supérieure, France)
- S. Zhong (University of Colorado, USA)

Session 4: Global mantle convection (Tuesday 27th, 11:30 - 13:00)

- J. Dannberg (University of California, Davis, USA)
- G. Shephard (University of Oslo, CEED, Norway)

Session 5: Plate-mantle dynamics in the Cenozoic (Wednesday 28th, 8:30 - 10:30)

- E. Bredow (Kiel University, Germany)
- T. Gerya (ETH Zurich, Switzerland)

Session 6: Modelling deep surface process connection (Wednesday 28th, 11:30 - 13:00)

- B. Steinberger (GFZ, Germany; University of Oslo, CEED, Norway)
- V. Magni (University of Oslo, CEED, Norway)

Session 7: Data assimilation and Inverse geodynamic modelling (Thursday 29th, 8:30 - 10:30)

- G. Reuber (JGU Mainz, Germany)
- G. Stadler (New York University, USA)

Session 8: Geodynamics across the scales (Thursday 29th, 11:30 - 13:00)

- F. Crameri (University of Oslo, CEED, Norway)
- Y. van Dinther (Utrecht University, Netherlands)

Keynote abstracts

How plume-ridge interaction shapes large areas of the Earth's surface

- Eva Bredow
  Institute of Geosciences, Kiel University, Germany
  eva.bredow@ifg.uni-kiel.de

- Bernhard Steinberger
  GFZ German Research Centre for Geosciences, Potsdam, Germany

- Rene Gassmöller
  Department of Earth and Planetary Sciences, University of California, Davis, USA

- Juliane Dannberg
  Department of Earth and Planetary Sciences, University of California, Davis, USA

- Folker Pappa
  Institute of Geosciences, Kiel University, Germany

The classical plume hypothesis associates the impingement of a large spherical plume head on the base of the lithosphere with the formation of voluminous flood basalts (a Large Igneous Province), while the narrow plume tail is expected to generate a linear, age-progressive chain of volcanic edifices (a hotspot track) as the tectonic plate migrates over the relatively stationary plume. Thus, both plume heads and tails reshape enormous areas of the Earth's surface over many tens of millions of years. However, many plumes have left volcanic records that appear to be much more complicated than these straightforward predictions.

Using the mantle convection code ASPECT to set up three-dimensional regional models, we investigate how specific hotspots have created the crustal thickness pattern attributed to their volcanic activities. Our models consider the local surroundings of a certain plume by combining reconstructed plate boundaries and plate motions, large-scale global flow velocities and an inhomogeneous lithosphere thickness distribution together with a dehydration rheology. So far, we have modelled the individual geodynamic histories of the Tristan, Réunion, Iceland, Kerguelen and Hawaii hotspots, showing that the model setup is primarily suitable for oceanic hotspots.

Altogether, the modelled plume-related crustal thickness patterns agree well with present-day topographic structures, crustal thickness estimates and age determinations of volcanic provinces associated with hotspot activity. Regionally, the dynamic development of the plumes in the models provide explanations for the generation of smaller, yet characteristic volcanic features that remained previously unexplained by the classical plume hypothesis. And, presumably most important, it became evident that the interaction between the respective plume and nearby spreading ridges is one of the essential factors for reconstructing the geodynamic history of a specific plume. If these dynamic effects are considered, it may become unnecessary to attribute complicated properties to a specific plume in order to account for complex observations – as often assumed in previous studies.

Apart from the hotspots typically assumed to be fed by deeply rooted plumes, we also investigate a much less constrained candidate: a mantle plume located beneath West Antarctica. Strengthened by recent evidence that the ice cover in Marie Byrd Land conceals one of the largest volcanically active provinces in the world, a distinctively elevated surface heat flux, volcanic rock samples with a geochemical signature similar to that of ocean island basalts, and seismic tomography revealing distinct zones of slow seismic velocities extending at least down to the transition zone, a debate on the existence of a West Antarctic plume has been kept alive over the past 30 years. Integrating a three-dimensional lithosphere scale model of the Antarctic continent that combines satellite gravity gradients and seismological data in instantaneous ASPECT models, our study addresses this long-standing hypothesis – for the first time from a geodynamic point of view.

When geodynamic models fill the gaps of plate tectonics theory: from the emergence of modern tectonics to plate boundary dynamics

- Nicolas Coltice
  Ecole Normale Supérieure, Paris, France
  nicolas.coltice@ens.fr

In this presentation, I will review modelling approaches to go beyond the limitations of plate tectonics, which are essentially linked to both the absence of dynamics in the theory, and the sparsity of observations. I will focus on two topics:

When did plate tectonics start? How do plate boundaries evolve over tens of million years? Sometimes observations are lacking or not precise enough to answer. From the observational point of view, evidence of the onset of plate tectonics can only be found on continents, whereas plate tectonic theory has been defined for oceans. Fortunately, modelling can provide a mechanistic and energetic framework, able to fill observational gaps. Is buoyancy, rheology, or the thermal "initial" state of the mantle the main driver the onset of plate tectonics?

Concerning the dynamical mysteries underlying modern global tectonics, we now have about 20 years of modelling efforts that have led to the development of effective physical theories, numerical models and experiments with complex fluids. For plate boundaries, difficulties lie mostly in building models at the global scale, running for a sufficient amount of time, and analysing the structure of their products automatically to extract statistical descriptions of how the complex system works.

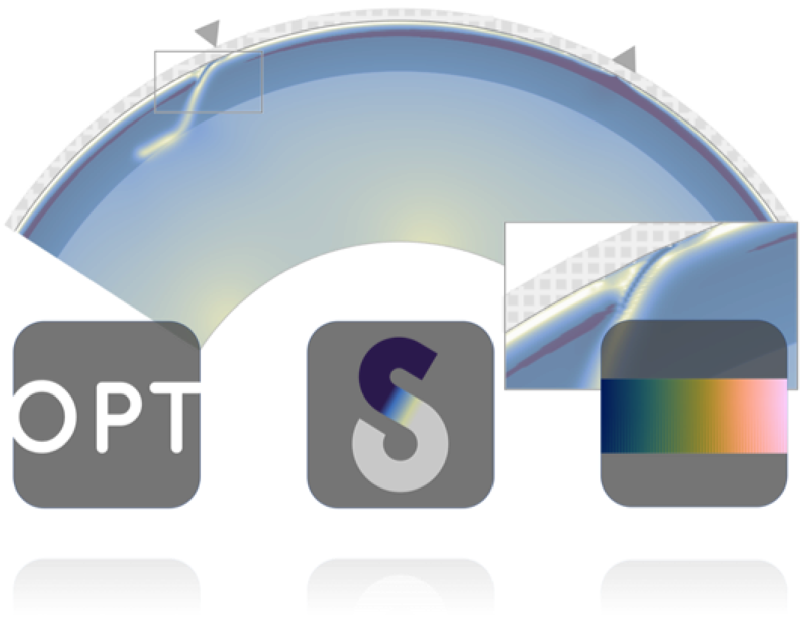
Modelstanding Ocean-Plate Tectonics

- Fabio Crameri
  The Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway
  fabio.crameri@geo.uio.no

Modelling leads to a better understanding; a better understanding leads to a better model. Improving models as well as generating new understanding is therefore generally an iterative process, going back and forth between improving the modelling and furthering the understanding.

Our understanding of the global plate-mantel dynamics has evolved significantly, even over the past 10 or so years. We are about to incorporate original concepts like plate tectonics, which describes pure surface dynamics, into its complete framework of the convecting mantle. This so-called 4th revolution of the Earth Sciences is well underway, not the least thanks to global modelling: Recent modelling helped us to better understand the strongly interlinked dynamics between a planet's mantle and its surface plates. I will present an overview over my current modelstanding of Ocean-Plate Tectonics, the dynamics of the oceanic plate as part of its bigger framework of mantle convection. I will outline some of the recent progress with focus on the dynamic interplay between the sinking oceanic plate, mantle flow and its upper most part, the directly observable plate surface.

In symphony with the advancing knowledge, modelling needs to keep improving too to remain the useful tool it came to be in recent years. The modelling not only needs to adjust to the changing knowledge, but crucially also to the changing computational infrastructure, the changing research environment, and the changing publishing conditions. I will therefore also outline key methodological steps forward that we, as a modelling community, could take now to advance the whole scientific procedure behind modelling itself and thereby enable and significantly speed up the completion of our 4th revolution.



Advancing the key aspects of modelling ocean-plate tectonics.

Modelling mantle convection with chemical and rheological heterogeneities

- Juliane Dannberg
  University of Florida, USA
  University of California, Davis, USA
  juliane.dannberg@ufl.edu

- Rene Gassmoeller
  University of California, Davis, USA

Many observations have shown that the lowermost mantle has a heterogeneous thermal and chemical structure. Seismic models show distinct regions with sharp boundaries, and some of them have been interpreted as thermo-chemical piles, plume clusters, superplumes, and partially molten regions. Additionally, geochemical data from ocean islands indicate the presence of primordial and/or recycled material at the base of the mantle, which suggests this heterogeneity is sampled when buoyant plumes rise from the core-mantle boundary and carry material towards the surface. Accordingly, plumes can provide a window to the composition of the Earth's deep interior. This makes it important to understand the processes that allow mantle plumes to inherit lower-mantle geochemical signatures and transport material from the core-mantle boundary to the surface. On the other hand, chemical heterogeneities also actively affect mantle convection through their influence on density, viscosity and other material properties.

Here, I will give an overview over how chemical and rheological heterogeneities likely present in the lowermost mantle may influence plume dynamics. I will discuss a number of different processes:

Compositional and thermal density anomalies control the buoyancy of mantle plumes, determining the plume shape and the amount of chemically anomalous material they can carry. Subducted slabs arriving at the core-mantle boundary determine the lower mantle flow, displacing material and influencing how material from chemical reservoirs is entrained in plumes. The heterogeneous temperature distribution at the base of the mantle controls the rheology, both through the temperature-dependence of viscosity and through thermal effects on the evolution of the mineral grain size. The associated viscosity contrasts determine how much material plumes can entrain from chemical reservoirs and how fast they will rise. Furthermore, if temperatures at the core-mantle boundary exceed the solidus of mantle rocks, plume generation zones may be partially molten. Fractionation upon melting or freezing and the segregation of melt may introduce additional chemical heterogeneities into rising plumes.

Better understanding these processes through a combination of observations and geodynamic modelling will help us to map chemical anomalies at the surface to the deep mantle and illuminate the composition of one of the least well-understood regions of the Earth.

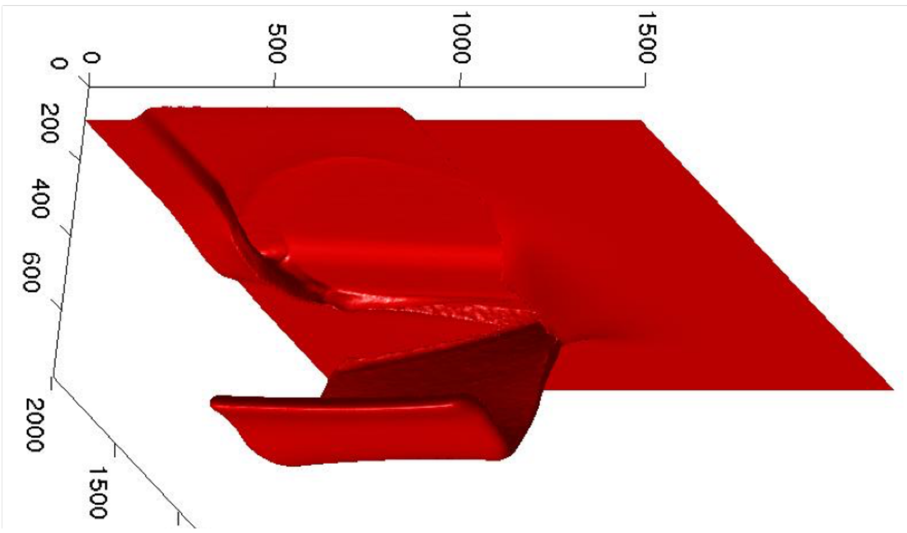
Slab tear propagation: numerical model and implications to Apennines

- Taras Gerya
  Institute of Geophysics, ETH Zurich, Switzerland
  taras.gerya@erdw.ethz.ch

- David Bercovici
  Department of Geology & Geophysics, Yale University, USA

- Claudio Faccenna
  Department of Geological Sciences, the University of Texas at Austin, USA

Retreating oceanic plate subduction is common in nature and can terminate by collision of the retreating arc with a passive continental margin. The collision is associated with rapid topographic changes and can result in partial or complete detachment of the oceanic slab by laterally propagating tear, which develops on the time scale of few Myr. Here we investigate this geodynamic transition by using 3D high-resolution thermomechanical models, in which a spontaneously retreating subduction zone limited by two STEP faults collides with a continental margin oriented at an angle to the retreating trench. Realistic visco-plastic plate rheology is used for the mantle and slab, which takes into account both brittle-plastic strain weakening and grain-size reduction assisted by Zenner pinning. Arc-margin collision results in the rapid growth of topography and trigger rotation of the retreating subduction arc toward the margin-parallel direction. Slab tear initiates at shallow depths at the part of the margin that collided earlier and rapidly propagates toward the other side of the forming arc-continent collision zone. The tearing process (Figure) is governed by a combination of plastic yielding and ductile strain localization caused by grain-size reduction. The lateral tear propagation rate Vt is mainly controlled by two parameters: (1) the slab retreat rate Vr and (2) the angle A of the passive margin obliquity relative to the retreating trench, such that Vt=Vr/sin(A). Slab tearing and subsequent detachment produces rapid uplift, which marks transition from compression to extension in the forming orogen. The detachment may also creates a new subduction zone from one of the STEP faults that start to retreat in the same direction as the previously active lateral tear. Numerical experiments reproduce some essential aspects of the recent evolution of the Apennines related to the formation and enlargement of a slab window and subduction rearrangement in this region in the past 2 Myr.



3D numerical thermomechanical model of the lateral tear propagation.

Generation and transport of liquid water in the high-pressure ice layers of Ganymede and Titan

- Klara Kalousova
  Department of Geophysics, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
  kalous@karel.troja.mff.cuni.cz

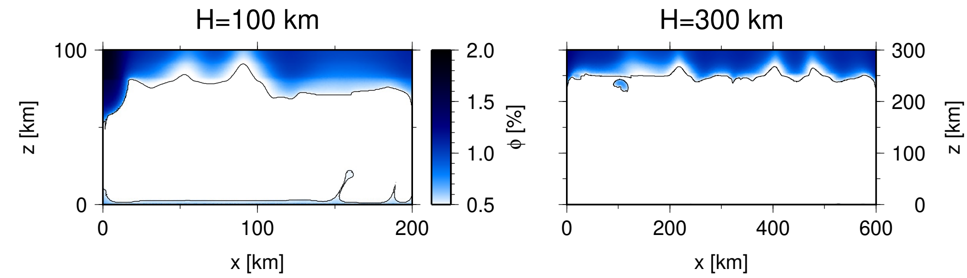
- Christophe Sotin
  Jet Propulsion Laboratory-California Institute of Technology, Pasadena, California, USA

The presence of deep oceans in the interiors of icy moons has been confirmed by the measurements performed by the Galileo and Cassini missions. A lot of attention is given to Europa and Enceladus where the deep ocean is likely in a direct contact with the silicate mantle - such conditions are similar to those at terrestrial sea floors where life develops. Ganymede and Titan, the largest icy moons in the solar system, possess larger amounts of H_2O so that a layer of high-pressure (HP) ice phases is predicted between the silicates and the ocean[1]. While the bulk of this HP ice layer prevents a direct contact between the ocean and the silicates, the exchange of heat and material may still be possible.

The two moons are similar in mass and radius but their radial mass distribution is different. Ganymede is likely the more differentiated with iron core, silicate mantle, HP ice layer, ocean and ice crust, while Titan is probably less differentiated with a core made of hydrated silicates. Titan is also the only known moon with a dense, methane-rich atmosphere. Since photochemistry would remove the present-day amount of methane in only a few millions of years[2], its presence indicates resupply from Titan's interior.

We study the dynamics of HP ice layers by performing 2D numerical simulations of two-phase convection that allow us to address meltwater generation and its transport. We find that melting can occur at the silicates interface and that melt is then transported through the layer by the upwelling plumes and extracted into the above lying ocean. This process may enable the transfer of volatiles that might have been leached from silicates but is only operating in thin HP ice layers (see figure below). Ganymede's HP ice layer is probably too thick and thus impermeable for transfer of volatiles [3,4]. On the other hand, Titan's HP ice layer is expected to be thinner which suggests that volatiles transport may have been occurring recently or even ongoing [5]. We also derive scaling laws that will be used in thermal evolution models to address the long term evolution of these moons.

[1] Hussmann, H., et al. (2015), *Treatise on Geophysics*, **10**, 605–635.
[2] Yung, Y. L., et al. (1984), *Astrophys. J.*, **55**, 465–506.
[3] Kalousova, K., et al. (2018), *Icarus*, **299**, 133–147.
[4] Kalousova, K., & C. Sotin (2018), *Geophys. Res. Lett.*, **45**, 8096–8103.
[5] Kalousova, K., & C. Sotin, under review in *Earth Planet. Sci. Lett.*.



Water content for two different HP ice layer thicknesses. *Left*: H=100 km - water is generated at the silicates interface and transported upwards. *Right*: H=300 km - melting is not occurring at the silicates interface.

Linking mantle flow and volcanism at subduction zones

- Valentina Magni
  The Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway
  valentina.magni@geo.uio.no

Volcanic arcs are one of the most common features of subduction zones. However, they are not the only type of volcanism related to subduction. Volcanoes can form along Subduction Transform Edge Propagator (STEP) faults, at the edge of slabs, due to mantle upwelling. Moreover, if the back-arc region is under extension, rifting and eventually seafloor spreading can occur. Although distinct, these three types of magmatism belong to the same regional tectonic setting and they all respond and evolve accordingly to the dynamics of subduction. To fully understand them, it is therefore important to take into account the large spatial and temporal scales in which they operate. It is also crucial to investigate if and how they interact with each other and how they are affected by changes in subduction dynamics and associated mantle flow. Here, I use three-dimensional numerical models of back-arc basins formation during oceanic subduction to investigate how melt production evolves in different regions of a subduction zone. Results show that back-arc spreading can be responsible for changes in arc activity and magmatic composition as trench retreat produces a mantle flow that temporary brings depleted mantle material from the back-arc to the arc region. These models demonstrate the key role of mantle flow and changes in its pattern in subduction-related volcanic activity and composition.

Hadean mantle dynamics, tectono-volcanic regimes, and the role of impacts

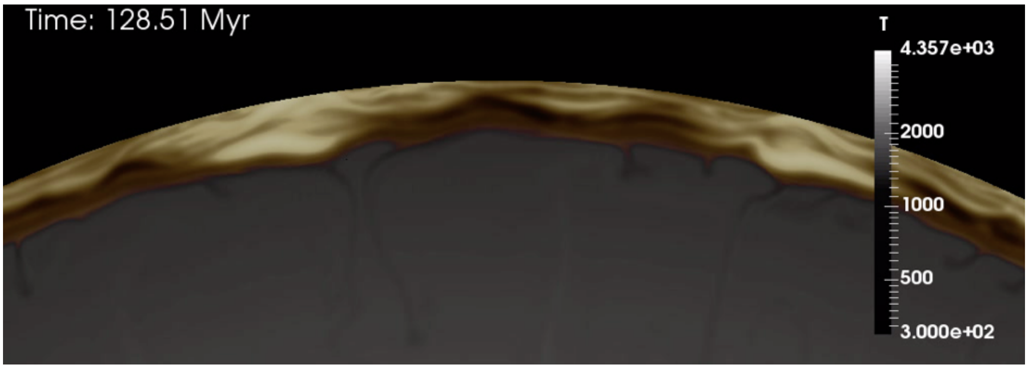
- Craig O'Neill
  Macquarie Planetary Research Centre, Macquarie University, Australia.
  craig.oneill@mq.edu.au

Simulations tectonic plates in mantle convection models under present-day conditions have generally demonstrated a largely thermal control on viscosity, and rheological weakening mechanisms such as yielding, exert first-order controls on system behaviour and evolution. In such models, conductive heat loss through plates (either in cooling oceanic plates, steady-state continental, or locally (/regionally) stagnant zones) dominates heat loss, and local non-conductive contributes, such as through volcanism at mid-ocean ridges, is generally neglected. Plate dynamics tend to be coupled solely to the mechanical interaction of the lithosphere with the solid-state convecting interior.

However, early in Earth's history workers have shown that magmatic transport may dominate conductive components, and the system may enter into a volcano-tectonic regime, such as a heat-pipe regime, or a plutonic-squishy lid. In these systems advection of heat due to volcanic transport dominates heat loss, and effective melt removal keeps these systems close to the solidus. The eventually emplacement of the melt is a critical factor the system's tectonics: full extraction to the surface, in a heat-pipe model, can cool the mantle and lithosphere and result in (volcanically-loaded) thick stagnant lid. If a significant amount of the melt is emplaced in the mid crust, the lid is heated and weakened, and may exhibit widespread non-localised deformation.

The tectonic forcing factors likewise evolved significantly over the Hadean. Impacting was a first-order geological process during this epoch, large impacts can directly instigate tectonic responses, including localised subduction. Smaller impacts during the tail-end of accretion, into the Archaean, can trigger tectonics in lids that are primed to subduct, particularly in the presence of large lithospheric gradients.

The history-dependence of tectonic systems demonstrate the critical need to understand the Earth during this period. Here we present new advances in modelling volcano-tectonic systems, core evolution, and exogenous factors such as impacts, to constrain dynamic end-members, and make geological predictions of Hadean geodynamics.



Development of a thick mafic crust due to voluminous mantle melting in a Hadean mantle convection simulation, using a modified version of the geodynamics code Aspect.

Adjoint based inversion in gedynamic modelling: A guide

- Georg Reuber
  JGU Mainz, Germany
  reuber@uni-mainz.de

- Boris Kaus
  JGU Mainz, Germany

- Anton Popov
  JGU Mainz, Germany

Most problems in geophysics can be formulated as an inverse problem, since measured data has to be fit with a model. In geodynamics the misfit function (e.g. the difference between observation and model result) that is sought to be minimized is subject to the Stokes equations that describe the flow for high viscous fluids. As a result one obtains the velocity distribution which can be compared to actual velocity measurements. There are different ways of tackling inverse problems, namely statistic or deterministic approaches. Special cases of deterministic inversions are gradient based methods, in which one computes the gradient of the model parameters with respect to a misfit function. Besides the straightforward finite difference approach to compute these gradients, where the numerical cost grows with the amount of model parameters, there exists the adjoint method which presents a more efficient way of compute these gradients. The material gradients can not only be used to solve the inverse problem but also to get some general insight into the underlying system of equations, such as sensitivity kernels or scaling laws. The method has proven its applicability to the wave equation in geophysics, e.g. full waveform inversions, as well as in other fields of science, such as optimal control or automatic shape optimization in engineering and has also already been applied to geodynamics [1,2].

In this talk the general inverse problem will be defined and different solution techniques briefly explained. Some background to the adjoint method will be introduced. It will be shown how to compute sensitivity kernels or scaling laws using the gradients derived from the adjoint method. Furthermore, some inversion examples will be presented.

[1] Ratnaswamy, Vishagan, Georg Stadler, and Michael Gurnis. "Adjoint-based estimation of plate coupling in a non-linear mantle flow model: theory and examples." Geophysical Journal International 202.2 (2015): 768-786.

[2] Horbach, André, Hans-Peter Bunge, and Jens Oeser. "The adjoint method in geodynamics: derivation from a general operator formulation and application to the initial condition problem in a high resolution mantle circulation model." GEM-International Journal on Geomathematics 5.2 (2014): 163-194.

Top-down versus Bottom-up Core Freezing: Modes of Core Crystallization and Implications for Dynamos in Terrestrial Planets and Satellites

- Tina Rückriemen
  Zentrum für Astronomie und Astrophysik, TU Berlin, Berlin, Germany; Department of extrasolar planets and atmospheres, DLR, Berlin, Germany
  tina.rueckriemen@dlr.de

- Doris Breuer
  Department of planetary physics, DLR, Berlin, Germany

- Tilman Spohn
  International Space Science Institute, Bern, Switzerland

A fundamental question in planetary science is to explain the remarkable variability in the intensity and spatio-temporal properties exhibited by the magnetic fields of terrestrial bodies. These fields are generated in metallic cores, and hence the observed variability is likely tied to differences in the structure, dynamics and evolution of planetary interiors. Earth's liquid core is slowly freezing from the bottom upwards as the planet cools, releasing the heat and light material that power the geomagnetic field. In contrast, recent studies on low pressure Fe-FeS alloys suggest that core crystallization in small planetary bodies such as Mars, Mercury, Ganymede, Moon, and planetesimals likely works very differently from what is expected for Earth's core.

Instead of freezing from the inside out, the metal cores of those small bodies likely solidify from the top to the bottom. Different top-down freezing scenarios can be envisioned depending on the type of solid material and its density compared to that of the liquid. If solid iron (Fe) forms, it may evolve as free crystals and "snows" down into the deeper, entirely liquid core. If solid iron sulfide (FeS) crystallizes at the top of the core it likely creates a solid FeS layer above the deeper core. We develop a one-dimensional thermo-chemical evolution model of the core and find that the evolution and dynamics of bodies in the "Fe snow" and "FeS layer" regime are profoundly different to those of Earth. The model is applied to study the evolution of Ganymede's magnetic field in order to investigate the viability of Ganymede's present-day dynamo generated by a top-down freezing core.

The talk will discuss the recent insights on core dynamics and magnetic field generation gained from studying top-down freezing in metallic cores. In particular, we focus on our findings for top-down freezing in the cores of Ganymede, the Moon, and Mars. Finally, we want to look ahead towards even more complex core freezing scenarios that are still waiting to be discovered.

Bayesian parameter inference in global instantaneous mantle flow

- Georg Stadler
  Courant Institute of Mathematical Sciences, New York University

Seismic detection of iron spin pairing in ferropericlase and the structure of the lower mantle

- Grace E. Shephard
  Center for Earth Evolution and Dynamics (CEED), Department of Geosciences, University of Oslo, Norway
  grace.shephard@geo.uio.no

- Christine Houser
  Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo, Japan

- John Hernlund
  Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo, Japan

- Reidar Trønnes
  Center for Earth Evolution and Dynamics (CEED), Department of Geosciences, University of Oslo, Norway
  Natural History Museum, University of Oslo, Norway

- Renata Wentzcovitch
  Department of Earth and Environmental Sciences, Columbia University, Lamont-Doherty Earth Observatory, Palisades, USA
  Department of Applied Physics and Applied Mathematics, Columbia University, New York City, USA

The spin-pairing transition in iron-bearing ferropericlase ((Mg,Fe)O; herein Fp) is an example of a material behaviour being predicted in advance of a corresponding geophysical observation. Fp may constitute 15-20 % of the Earth's lower mantle and experimental and theoretical work has shown that constituent Fe^{2+} cations undergo a transition from high to low spin states (e.g. Badro et al., 2003) across the lower half of the lower mantle. The associated change in spin affects density, viscosity, elasticity, thermal conductivity and elemental partitioning and thus is important to constrain for geodynamic modelling. For example, the spin transition might reduce the viscosity of the mantle materials and has been related to the nature of LLSVPs, upwellings and sinking slabs (e.g. Li et al., 2018).

The spin state is dependent on pressure, temperature and composition, thus estimates for the depth and distribution of the mixed spin state vary. Along a geotherm 500 K below the ambient adiabat, the transition is onset predicted in the 1250-2000 and 1450-2200 km depth ranges for harzburgitic and pyrolitic compositions, respectively. However, partly due to the gradual nature of such a transition, the expected seismic signature of this transition is weak or absent in globally averaged seismological profiles (e.g. Koelemeijer et al., 2018). This possibly suggests that the seismic resolution is insufficient or that the lower mantle is Fp-poor relative to the shallow mantle in spite of whole mantle convection.

We compare multiple global seismic velocity tomography models based on a 'vote map' methodology (Shephard et al., 2017). We show a decoupling of shear (S-wave) and compressional (P-wave) wavespeed anomalies in the lower mantle for both fast wavespeed anomalies (>+1sigma) at depths greater than ∼1400 km and for slow anomalies (<−1sigma) greater than ∼1750 km. This provides observational evidence consistent with the occurrence of a spin transition in Fp. The absence of an equivalent signal in the ambient (±0.5sigma) seismic domain suggests that these are Fp-poor, consistent with models involving rheologically strong bridgmanite-rich domain (e.g. Ballmer et al., 2017).

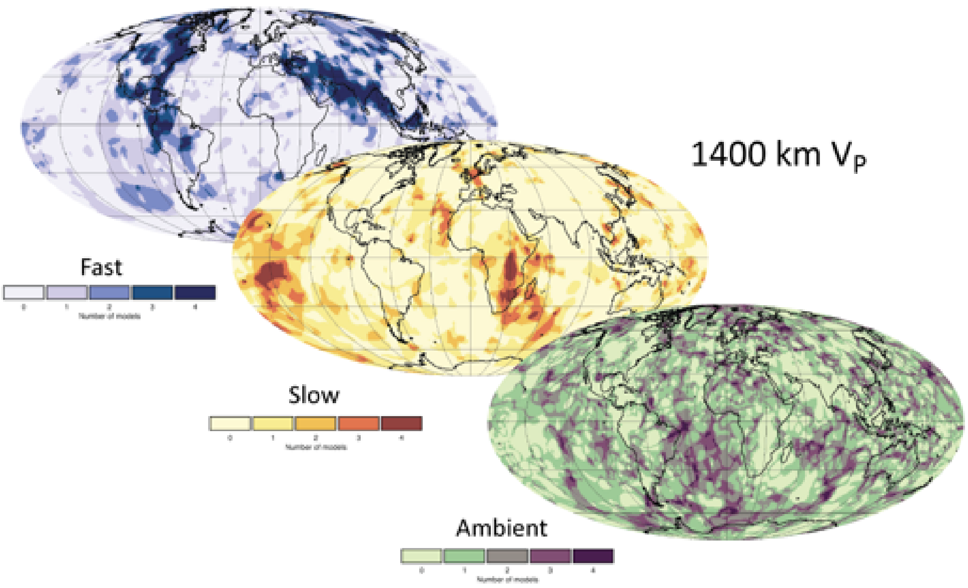
[1] Badro, J., G. Fiquet, F. Guyot, J-P. Rueff, V.V. Struzhkin, G. Vanko, and G. Monaco (2003). Iron Partitioning in Earth's Mantle: Toward a Deep Lower Mantle Discontinuity. Science.

[2] Ballmer, M.D., C. Houser, J. W. Hernlund, R. M. Wentzcovitch and K. Hirose (2017). Persistence of Strong Silica-Enriched Domains in the Earth's Lower Mantle. Nature Geoscience.

[3] Li, T., K. Vilella, F. Deschamps, L. Zhao and P. J. Tackley (2018). Effects of Iron Spin Transition on the Structure and Stability of Large Primordial Reservoirs in Earth's Lower Mantle, Geophysical Research Letters.

[4]Koelemeijer, P., B.S.A. Schuberth, D.R. Davies, A. Deusse and J.Ritsema (2018). Constraints on the presence of post-perovskite in Earth's lowermost mantle from tomographic-geodynamic model comparisons. EPSL.

[5] Shephard, G.E., K.J. Matthews, K. Hosseini and M. Domeier (2017). On the consistency of seismically imaged lower mantle slabs. Scientific Reports.



Vote map method as applied to four P-wave tomography models for fast (>+1 sigma), slow (<−1 sigma) and ambient (±0.5 sigma) wavespeed domains at 1400 km depth.

How Long Does a Plume Head Take to Rise Through the Mantle?

- Bernhard Steinberger
  GFZ German Research Centre for Geosciences, Potsdam, Germany and Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway
  bstein@gfz-potsdam.de

- Peter L. Nelson
  The University of Texas at Austin, USA

- Trond H. Torsvik
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway
  University of Witwatersrand, Johannesburg, South Africa

Mantle plumes are likely initiated by large plume heads. Because mantle viscosity and its dependence on temperature and stress is poorly known, it is uncertain how long plumes take to rise through the mantle. Knowing this is important for constraining the total time until subducted material may resurface in mantle plume heads. Here we apply observational constraints to narrow down plume rise times. Firstly, the margins of Large Low Shear Velocity Provinces (LLSVPs) which probably represent piles of hot chemically dense material in the lowermost mantle are likely locations for plume generation. Here we model, as a function of rise time, the locations where plume heads start rising, such that plumes reach the surface at the observed hotspots. We find that these source locations agree well with LLSVP margins only for rise times of about 30 Myr or less. Different from other hotspots with likely deep source, Yellowstone is close to subduction zones and far from LLSVPs. Yet a recent tomography model shows a tilted plume conduit beneath, rising from the lowermost mantle. Here we compare modelled plume conduit shape, as a function of rise time, with tomography and find the best agreement for rise times of about 90 Myr or more. Comparatively slow rising could be due to a small plume head (corresponding to Columbia River Basalts being smaller than other Large Igneous Provinces). Faster rising of plumes near LLSVPs could also be due to hotter mantle, causing upward ambient mantle flow and reduced viscosity.

How Tectonics Affects Seismicity

- Ylona van Dinther
  University of Utrecht

Heat-pipe tectonics

- Alexander Webb
  University of Hong Kong (Hong Kong S.A.R. China)
  aagwebb@hku.hk
- William Moore
  Hampton University & National Institute of Aerospace (USA)
- Jiawei Zuo
  University of Hong Kong (Hong Kong S.A.R. China)
- Jupiter Hiu Ching Cheng
  University of Hong Kong (Hong Kong S.A.R. China)
- Chunan Tang
  Dalian University of Technology (China)
  China University of Geosciences Wuhan (China)
- Thomas Müller
  University of Leeds (UK)
- Peter Haproff
  University of North Carolina, Wilmington (USA)
- Justin Simon
  Johnson Space Center (USA)

The role of volcanic heat-loss in guiding the early geodynamic evolution of terrestrial planets has been increasingly recognized in recent years. A young terrestrial planet should be hot, and therefore the volcanism-dominated "heat-pipe" tectonics of the solar system's hottest terrestrial body (in terms of heat-loss per unit area), Io, has received special attention. The essence of heat-pipe tectonics is as follows: large-volume melts of hot mantle rise buoyantly to the surface, where heat is lost to the atmosphere and volcanic material is deposited. The continuing rapid exhumation of material at depth and its emplacement at the surface produces a downwards advection of the lithosphere, which in turn refrigerates the lithosphere as cold surface temperatures are carried downwards. The base of the lithosphere corresponds to a sharp thermal transition where lithospheric materials are rapidly warmed and resorbed into the flowing mantle and/or melted.

This presentation will provide an overview of recent and on-going geodynamic and geologic explorations of heat-pipe tectonics. Io appears to be the only terrestrial body in the solar system experiencing active heat-pipe tectonics, but Earth's pre-3.2 Ga geological record appears consistent with the model predictions (i.e., rapid volcanic resurfacing, contraction in response to inwards advection of spherical shells, cold lithospheric thermal gradients). Similarly, the early records of Mars, Mercury, the Moon, and Venus are all consistent with an early heat-pipe cooling phase which transitioned directly into stagnant lid tectonics. Ongoing efforts to test this model on Earth include interrogation of detrital zircon patterns of various tectonic modes vs. the geological record, as well as integrated metamorphic and structural studies of the 3.85-3.55 Ga Isua supracrustal belt of southwestern Greenland. Our ongoing exploration of Venus is focused on the marginal relationships of elevated tessera plateaus, as these regions may reflect waning heat-pipe contractional systems preserved in the stagnant lid. The warming of the lithosphere inherent in the waning of heat-pipe cooling (as volcanic advection of heat wanes and conductive cooling comes to dominate the lithospheric geothermal gradient) leads to a new variety of possible plate breaking mechanisms to explain the onset of plate tectonics on Earth. In sum, heat-pipe tectonics may represent the missing link between magma oceans and plate / stagnant lid tectonics, and thus represent a universal feature of terrestrial planetary development.

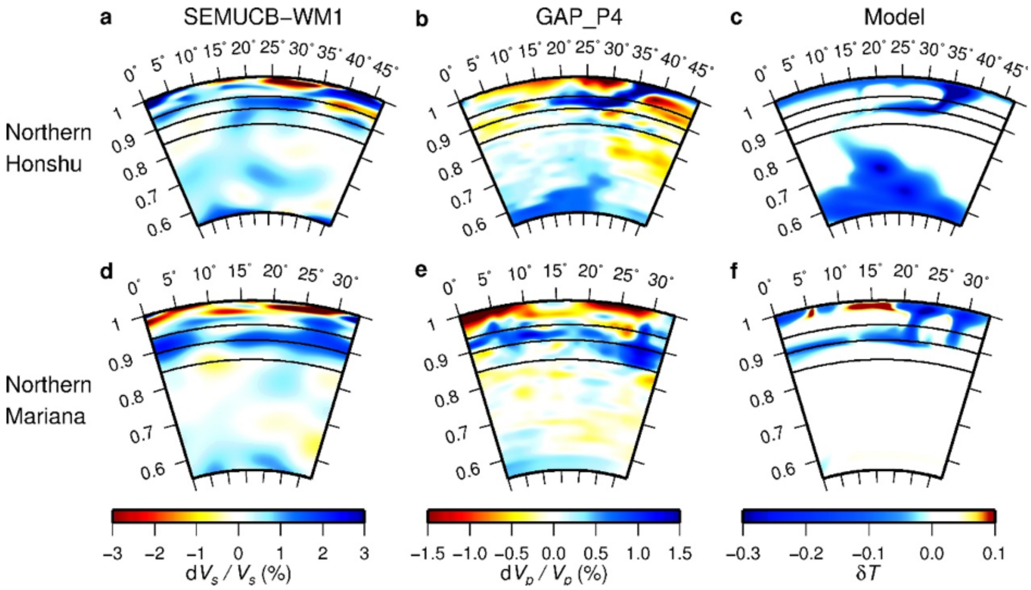
Comparison of Global Mantle Convection Models with Seismic Tomographic Models

- Wei Leng
  University of Colorado, Boulder, Colorado, USA
  wei.leng@colorado.edu

- Shijie Zhong
  University of Colorado, Boulder, Colorado, USA

Significant progress has been made in studies of seismic imaging of the Earth's mantle and of global mantle convection modeling. Seismic observations indicate significant accumulation of subducted slabs above the 670-km discontinuity in many subduction zones, suggest possible structure change at ∼1000 km depth, and support that the African and Pacific LLSVP be associated with chemical heterogeneity. Global mantle convection models with realistic mantle viscosity and plate motion history reproduce the LLSVP structures and slab stagnation in the mantle transition zone. However, it remains unclear how the convection models compare with seismic models at different spatial wavelengths and depths. This study has two objectives. The first is to explore the role of the weak layer below the transition zone in causing slab stagnation [Mao and Zhong, 2018]. The second is to perform a correlation study between convection and seismic models to examine to what extent the convection models explain the seismic structures. We found that the weak layer consistently produces slab stagnation in the western Pacific for different model parameters, leading to increased wavelength in the transition zone while having insignificant effects elsewhere. Mantle structure from global convection models shows significantly improved correlation with seismic structure at all depths and wavelengths, especially at immediate wavelengths (i.e., spherical harmonic degrees 4 and higher), compared with previously constructed mantle structures. However, the global correlation is weak at short wavelengths (for degrees 10 and higher), suggesting the challenges with global convection models. We will also discuss the model characteristics around 1000 km depth and near the CMB.

[1] Mao, W., and S.J. Zhong, Slab stagnation due to a reduced viscosity layer beneath the mantle transition zone, Nature-Geo, 11, 876-881, 2018.



Cross-sectional view of seismic anomalies and our model temperature anomalies for northern Honshu and Mariana subduction zones. Panels **a-c** and **d-f** are S-wave velocity anomalies from seismic model SEMUCB-WM1, P-wave velocity anomalies from seismic model GAP_P4 and our model dimensionless temperature anomalies at the northern Honshu and Mariana subduction zones, respectively. The three lines correspond to 410 km, 670 km and 1000 km depths, respectively. Both of the seismic tomography models show long horizontal distance of stagnant slabs over 1500 km at these two subduction zones that are well reproduced in our convection model with realistic spinel-post-spinel phase change (-2 MPa/K Clapeyron slope) and plate motion history and a weak layer below the phase change boundary.

Poster abstracts

Modeling rollback subduction dynamics on Venus

- Andrea Adams
  Scripps Institution of Oceanography, UCSD
  aca009@ucsd.edu

- Dave Stegman
  Scripps Institution of Oceanography, UCSD

The tectonic and convective histories of Venus are highly enigmatic. On Earth, plate tectonics continuously recycles the surface to cool the interior; however no such unifying conceptual framework for Venus exists. To explain the observed uniform surface age, it has been suggested that Venus has undergone an episodic style of resurfacing with intermittent stable periods of lithospheric thickening due to conductive cooling (Turcotte, 1993, 1995). The current paradigm favors this catastrophic-overturn hypothesis, in which episodes of lithospheric recycling occur on a global scale and are followed by a period of rapid resurfacing (Solomatov & Moresi, 1996; Strom et al., 1994). A competing theory, referred to as equilibrium resurfacing, suggests that smaller and more frequent volcanic resurfacing events may also explain Venus' uniform surface age and crater distribution (Bjonnes et al., 2012; Hauck et al., 1998). Recently, a study suggested that the center of mass and center of figure (CM-CF) offset for Venus is incompatible with a global catastrophic overturn event (King et al., 2018). In order to better understand how Venus may have evolved over time, we are creating a series of numerical experiments to analyze the dynamics of the equilibrium resurfacing regime. We utilize the finite volume code, StagYY, to solve equations of mass, momentum, and energy for highly viscous flow. The rheology of the model is strongly temperature-dependent. A pseudo-free surface "sticky-air" upper boundary condition is used to allow the development of topography. We will present a suite of 2D cartesian models with an initial condition containing a single downward lithospheric perturbation (Fig. 1). In order to evaluate the duration and extent of rollback subduction on Venus, we systematically vary the strength of the lithosphere primarily through variations in 3 parameters: lithospheric thickness, max lithosphere viscosity, and and upper mantle viscosity. By exploring for which mantle and lithosphere conditions the equilibrium resurfacing regime is viable, we can better constrain the state of Venus' interior and its dynamic history.

Northward drift of the Azores plume in the Earth's mantle

- Maëlis Arnould
  Laboratoire de Géologie, 24 rue Lhomond, 75005 Paris, France
  arnould@geologie.ens.fr

- Jérôme Ganne
  IRD, CNRS, GET, Université Toulouse III, 14 Avenue Edouard Belin, 31400 Toulouse, France

- Nicolas Coltice
  Laboratoire de Géologie, 24 rue Lhomond, 75005 Paris

- Xiaojun Feng
  School of Safety Engineering, University of Mining and Technology, Jiangsu, China

Mantle plume fixity has long been a cornerstone assumption to reconstruct past tectonic plate motions. However, precise geochronological and paleomagnetic data along Pacific continuous hotspot tracks have revealed substantial drift of the Hawaiian plume. The question remains for evidence of drift for other mantle plumes. Here, we use plume-derived basalts from the Mid-Atlantic ridge to confirm that the upper-mantle thermal anomaly associated with the Azores plume is asymmetric, spreading over ∼2,000 km southwards and ∼600 km northwards. Using for the first time a 3D-spherical mantle convection where plumes, ridges and plates interact in a fully dynamic way, we suggest that the extent, shape and asymmetry of this anomaly is a consequence of the Azores plume moving northwards by 1-2 cm/yr during the past 85 Ma, independently from other Atlantic plumes. Our findings suggest redefining the Azores hotspot track and open the way for identifying how plumes drift within the mantle.

Geodynamic causes of lateral motions of mantle plumes in whole-mantle convection

- Maëlis Arnould
  Laboratoire de Géologie, 24 rue Lhomond, 75005 Paris, France
  arnould@geologie.ens.fr

- Nicolas Coltice
  Laboratoire de Géologie, 24 rue Lhomond, 75005 Paris

- Nicolas Flament
  School of Earth and Environmental Sciences, University of Wollongong, Northfields Avenue, Wollongong, NSW 2522, Australia

- Claire Mallard
  EarthByte group, School of Geosciences, the University of Sydney, NSW 2006, Australia

Mantle plumes have been widely used as a fixed reference frame in order to reconstruct the absolute motions of tectonic plates. However, some paleomagnetic and geochronological observations suggest that substantial relative motions between hotspots or clusters of hotspots can occur. Mechanisms explaining substantial motions of mantle plumes include both a direct (plume capture by a spreading ridge) and an indirect role (plume deflection by mantle wind or plume push by a slab) of surface tectonics.

Here, we propose to quantify the properties and relative motions of mantle plumes, and identify the role of plate tectonics on their drift in a set of 3D-spherical models of mantle convection generating self-consistent surface dynamics, with Earth-like characteristics. In these models, fully-dynamic mantle plumes emerge with a temperature excess, a rising speed and a buoyancy flux comparable to Earth's observations, and drift due to interactions within the convective system. We investigate the role of mantle and lithosphere dynamics on the behavior of mantle plumes by varying the lithospheric yield stress, the depth-dependence of thermal expansivity and the presence of dense basal thermochemical provinces.

In a stagnant-lid model, 98% of plumes move by less than 1 cm/yr. In models with plate-like behavior, 58% to 72% of plumes move relatively to each other at speeds lower than 1 cm/yr, depending on model parameters. Such slow drifts are driven by slow entrainment by ambient lower mantle flow. 2% to 42% of model plumes drift at speeds between 2 and 15 cm/yr due to lateral pressure gradients exerted at their base, induced either by lower mantle slab push or by the proximity of another plume conduit leading to plume merging. Model plumes ascend almost quasi-vertically and are therefore insensitive to mantle wind.

Accelerating CPO calculations using neutral networks

- Suzanne Atkins
  ENS, France and Universite Claude Bernard Lyon 1, France
  suzanne.atkins@univ-lyon1.fr

- Thomas Bodin
  Universite Claude Bernard Lyon 1, France

- Navid Hedjazian
  Universite Claude Bernard Lyon 1, France

Geodynamic flows put rocks under stress. Under mantle conditions, crystalline rocks, such as pyroxene, respond to this stress by developing a crystallographic preferred orientation. The crystals orient themselves under stress by various processes, including recrystallisation, grain boundary sliding and diffusion creep. When a CPO has developed, the properties of the bulk rock will become anisotropic, because of the aligned crystals. Common anisotropic properties include the elastic tensor, which determines the seismic anisotropy, and the viscous tensor, which determines the rock's response to stress. Seismic anisotropy can therefore be used to give an indication of the CPO and its viscous anisotropy (e.g. Mameri et al. 2019). However, CPO is not the only contributor to seismic anisotropy, therefore ideally probabilistic methods to find CPO from anisotropy should be used to take into account other factors.

The crystallographic response of a rock to stress is a complex process. Various computer packages exist to calculate the CPO resulting from an applied stress. These go from atomic scale modelling (e.g. Keralavarma et al., 2012), through crystal scale modelling (e.g Kaminski et al. 2004) to parameterised approximations (e.g Ribe et al 2019). For each increase in scale, both accuracy and computational time is reduced. The choice of method is therefore always a trade-off. For a post-calculation analysis of a geodynamic simulation, this is not necessarily a problem. However, if we want to use the CPO to determine the evolution of subsequent time steps of a calculation (e.g. using viscous anisotropy), or as a sample in a probabilistic inversion of seismic anisotropy, both computational expense and accuracy are crucial.

We propose a machine learning method that accelerates CPO calculations by approximating expensive simulations. In this case, we approximate CPO evolution calculated by the D-rex package for olivine. The neural network has the potential to accelerate D-rex enough that the CPO can be analysed and recalculated for every time step within a geodynamic simulation, or to produce samples for a Monte Carlo probabilistic inversion of seismic anisotropy.

[1] Mameri et al. 2019. Predicting viscoplastic anisotropy in the upper mantle: a comparison between experiments and polycrystal plasticity models, Physics of the Earth and Planetary Interiors 286, 69-80

[2] Kaminski et al. 2004. D-Rex, a program for calculation of seismic anisotropy due to crystal lattice preferred orientation in the convective upper mantle, GJI, 158, 744–752

[3] Keralavarma et al. 2012 Power-Law Creep from Discrete Dislocation Dynamics, Phys. Rev. Lett. 109, 265504

[4] Ribe et al. 2019. An analytical finite-strain parametrization for texture evolution in deforming olivine polycrystals, GJI, 216, 486–514

The influence of obliquity on subduction zones and related topography: inferences from 3D numerical and analogue modelling

- Attila Balázs
  Universita Roma Tre, Rome, Italy
  abalazs@uniroma3.it

- Kosuke Ueda
  ETH Zürich, Department of Earth Sciences, Zürich, Switzerland

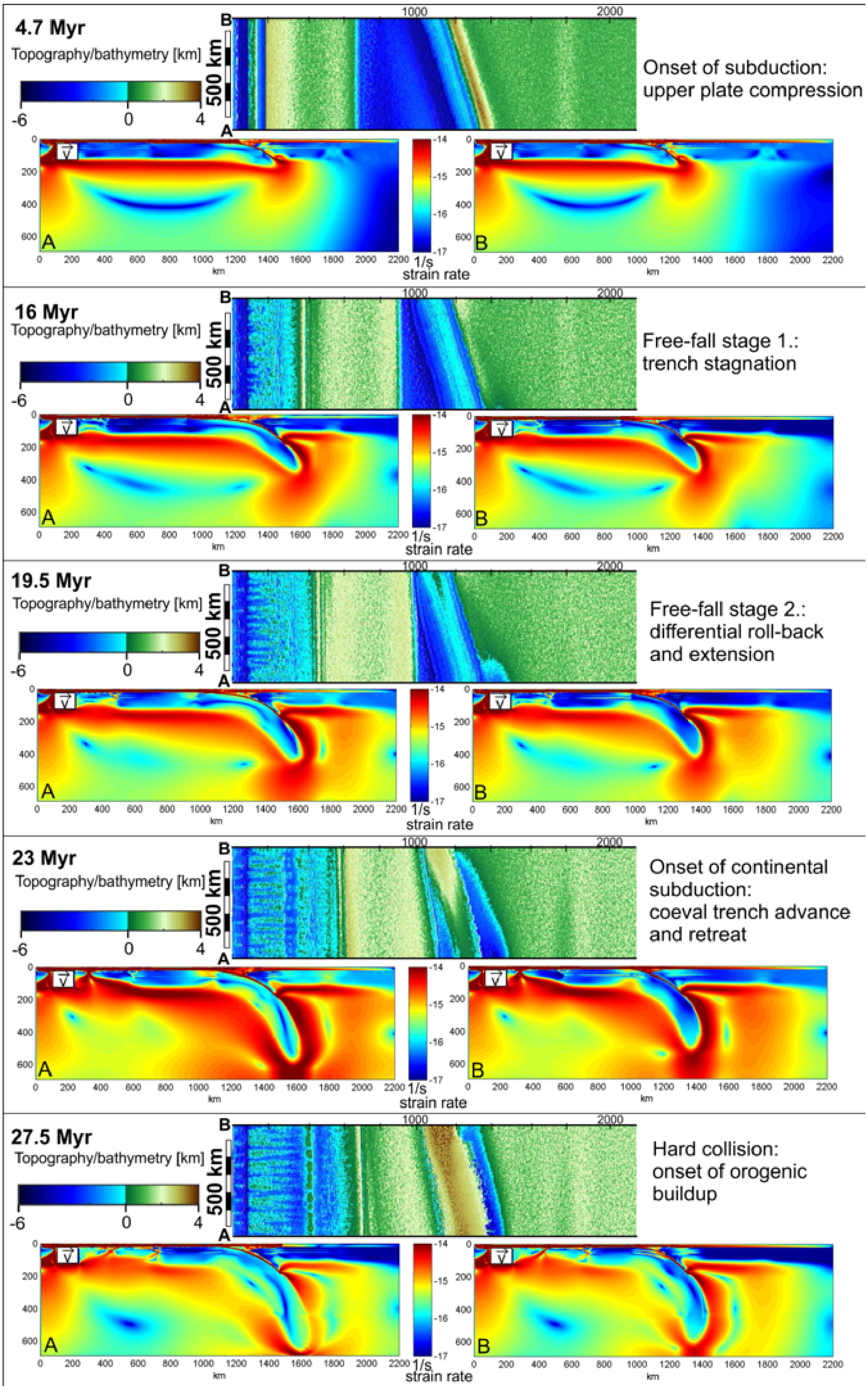
- Claudio Faccenna
  Universita Roma Tre, Rome, Italy

- Francesca Funiciello
  Universita Roma Tre, Rome, Italy

- Eric J.-P. Blanc
  Equinor, Oslo, Norway

- Taras Gerya
  ETH Zürich, Department of Earth Sciences, Zürich, Switzerland

We aim to contribute to the understanding of 3D surface topography and sedimentary basin evolution in the geodynamic context of oblique subduction systems. In this study we present a series of numerical experiments to analyze the evolution of oceanic and subsequent continental subduction prior to continental collision along an oblique continental margin. Numerical modelling is compared with analogue subduction experiments. We applied the thermo-mechanically coupled 3D finite-difference code I3ELVIS (Gerya, 2013). Simplified surface processes and phase changes are implemented in the simulations. Oceanic subduction is forced by an initial boundary velocity imposed on one model side for the first few million years. Subsequent subduction velocity varies in time as a function of the dynamics of the system, i.e. gradually increases during free-fall subduction and then starts to decrease at the onset of continental subduction. Oblique subduction creates a specific mantle flow pattern. Orientation of the convective cell beneath the downgoing plate is parallel with the subduction velocity direction, while the poloidal return flow is near perpendicular to the trench. The obliquity between the two convective cells creates an overall asymmetrical mantle flow pattern leading to the along-strike variation of slab roll-back and upper-plate deformation. Furthermore, vertical axis rotation is recorded in the upper plate. We model the formation of the accretionary wedge behind a 4-6 km deep trench. 1-3 km accommodation space is created in the wedge-top forearc basin area recording repeated extensional and contractional deformation. A 2-3 km deep dynamic forearc sag basin forms at ca. 250 km distance behind the trench, during the main phase of slab steepening and roll-back. Furthermore, back-arc extensional deformation is distributed or localized at heterogeneities in the upper plate. Onset of continental subduction is diachronous due to the oblique margin geometry. The transition from oceanic to continental subduction is manifested in the gradual decrease of the accommodation space in the basins and the extensional stress regime changes to compression. Following a few million years of soft collision and continental subduction a high topography orogen is gradually built up during hard collision before subduction ultimately slows down.



Topographic (upper panel) and strain rate (lower panel) evolution of the reference experiment (Mod20) shown by two sections from the two sides of the 3D model. Note the decreasing obliquity of the trench.

Compositional Differentiation of Terrestrial Planets due to Reactive Freezing the Basal Magma Ocean

- Maxim D. Ballmer
  Dept. Earth Sciences, University College London
  Institute of Geophysics, ETH Zurich
  Earth-Life Science Institute, Tokyo Insitute of Technology
  m.ballmer@ucl.ac.uk

- Rob Spaargaren
  Institute of Geophysics, ETH Zurich

- Daniela Bolrão
  Institute of Geophysics, ETH Zurich

- Adrien Morison
  Ecole Normale Superieure, Lyon

- Miki Nakajima
  Dept. Earth and Environmental Sciences, University of Rochester

Terrestrial planets evolve through several magma-ocean stages during accretion and differentiation [1]. Studying the crystallization and fractionation of magma oceans (MO) provides constraints on the initial condition and long-term evolution of solid-state mantle convection. The fractionation of the MO leads to progressively Fe-enriched cumulate layers in the proto-mantle upwards [2]. The final-stage cumulates near the surface, in addition to being Fe-enriched, are likely to be enhanced in SiO_2 (probably roughly near-basaltic), as being controlled by final-stage MO-related (partial) melting in the uppermost mantle. The Fe-enrichment of these Fe-enriched cumulates is thought to promote gravitational (incremental) overturn(s) of the mantle. Once the cumulates reach the CMB and equilibrate thermally, they stabilize a basal magma ocean (BMO) that is in chemical disequilibrium with the overlying mantle. Thus, for significant SiO_2-enrichment, the BMO reacts with the overlying mantle according to the lower-mantle phase diagram (Figure 1), and reactive cumulates are progressively entrained. Entrainment occurs because BMO-cumulates are only mildly enriched in FeO, hence not forming a long-lived deep dense layer. For Earth, this prediction can explain geophysical constraints, which suggest no layering or strong Fe-enrichment in the deep mantle. In turn, cumulates may survive as small-to-large sized blobs due to their expected very high modal bridgmanite content (see Figure 1), which tends to sustain high viscosity and prevent long-term mixing [6].

In turn, we rule out the alternative “classic” scenario, in which the Earth’s BMO was primarily stabilized due to a melt-mineral density crossover at near-CMB pressures [7,8]. For this scenario, we infer that the BMO would have frozen by fractional crystallization. Fractional crystallization of the BMO would have led to distillation of FeO and hence the long-term stabilization of a thick Fe-rich basal layer at the CMB, inconsistent with geophysical constraints for Earth. Combinations of both scenarios with mixing of melts in the BMO remain realistic, but the final BMO composition has to be on the SiO2-rich side of the bridgmanite thermal divide. For other terrestrial planets such as the Mars, both the “classical” and the reactive-freezing scenarios are viable. A better understanding of the present-day Martian mantle structure through geophysical exploration may constrain early differentiation, initial (B)MO composition, and (B)MO fractionation across the solar system.

[1] Nakajima, M., and Stevenson, D.: Melting and mixing states of the Earth’s mantle after the Moon-forming impact, Earth and Planetary Science Letters, Vol. 427, pp. 286-295, 2015.

[2]Elkins-Tanton, L. T.: Linked magma ocean solidification and atmospheric growth for Earth and Mars, Earth and Planetary Science Letters, Vol. 271, pp. 181-191, 2008.

[3] Ballmer, M. D., D. Lourenço, K. Hirose, R. Caracas, and R. Nomura: Reconciling Magma-Ocean Crystallization Models with the present-day Structure of the Earth’s mantle, Geochemistry Geophysics Geosystems, Vol. 18, doi:10.1002/2017GC006917, 2017.

[4] Maurice, M., N. Tosi, H. Samuel, A.-C. Plesa, C. Hüttig, and D. Breuer: Onset of solid-state mantle convection and mixing during magma ocean solidification, Journal of Geophysical Research: Planets, 122(3), 577-598, 2017.

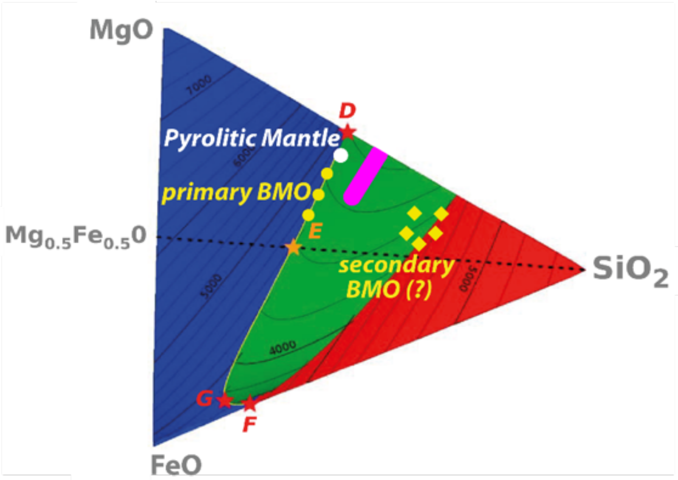
[5] Boukaré, C. E., Parmentier, E. M., and Parman, S. W.: Timing of mantle overturn during magma ocean solidification. Earth Planet. Sci. Lett., 491, 216-225, 2018.

[6] Ballmer, M. D., Houser, C., Hernlund, J. W., Wentzcovitch, R. M., and Hirose, K: Persistence of strong silica-enriched domains in the Earth’s lower mantle. Nature Geoscience, 10(3), 236, 2017.

[7] Labrosse, S., J. W. Hernlund, and N. Coltice (2007): A crystallizing dense magma ocean at the base of the Earth’s mantle, Nature, 450, 866–869, 2007.

[8] Caracas, R., Hirose, K., Nomura, R., and Ballmer, M. D: Melt–crystal density crossover in a deep magma ocean. Earth and Planetary Science Letters, 516, 202-211, 2019.

[9] Boukaré, C. E., Y. Ricard, and G. Fiquet: Thermodynamics of the MgO-FeO-SiO2 system up to 140GPa: Application to the crystallization of Earth's magma ocean, Journal of Geophysical Research-Solid Earth, 120(9), 6085-6101, 2015.



Ternary phase diagram in the MgO-FeO-SiO_2 system at 130 GPa. Contours show liquidus temperatures in K. Stability fields are color coded (ferropericlase: blue, bridgmanite: green, stishovite: red). Circles show range of compositions for primary BMOs that are stabilized due to a melt-mineral density crossover. Diamonds show range of compositions for secondary BMOs that are stabilized due to gravitational overturn of the "proto-crust" (also see ref. [3]). Pink bar denotes the possible range of reactive cumulates for secondary BMOs (i.e. within bridgmanite stability field). This figure is modified from ref. [9].

How does the interaction between mantle upwelling and lithosphere affect locally the thermochemical structure

- Walid Ben Mansour
  Macquarie University, Department of Earth and Planetary Science, Sydney
  walid.benmansour@mq.edu.au

- Juan Carlos Afonso
  Macquarie University, Department of Earth and Planetary Science, Sydney; CEED University of Oslo

- Guust Nolet
  Université Côte d'Azur/CNRS/OCA/IRD, Géoazur, Sophia Antipolis

- Beñat Oliveira Bravo
  Macquarie University, Department of Earth and Planetary Science, Sydney

Mantle plays an important role in the present-day topography and on the chemical and temperature homogenization of the deep Earth. Imaged from seismic tomography, mantle plumes are the extreme expression of this dynamism with the production of a large volume of magma at the surface (Deccan Traps, Siberian Traps, Ontong Java Plateau).

Here we show preliminary results of a 3D multi-observable inversion method based on a probabilistic (Bayesian) formalism [Afonso et al. 2016] using high-quality geophysical, geochemical and geological datasets for 3 geodynamic settings where mantle upwelling observed. This framework allows us to move beyond classic inversion schemes and jointly invert multiple seismic data (e.g. surface wave, receiver functions, etc.) and non-seismic data (geothermal, topography, potential fields, etc.) to retrieve estimates of the thermal and lithological structures. The goal of this study is to look at the local effect of the mantle upwelling on the thermochemical structure of the mantle (geotherm and major element composition) in the different geodynamic setting.

We first select Galapagos archipelagos, characterized by the interaction between the mantle plume and the spreading ridge. This region is characterized by two volcanic chains (Cocos and Carnegie ridges) and a low-velocity anomaly beneath the western archipelago. From geochemical observations, the Galapagos plume shows a chemical distinction of magma between the northern and the southern part of the archipelago [Gazel et al. 2018]

Then we look at the interaction of the mantle upwelling with cratonic areas. We select Africa where a superswell is observed from South Africa to East African Plateau. This interaction is responsible for the uplift of the topography along with this upwelling [Jones et al. 2017].

Finally, we select the Ontong Java Plateau located at the edge of the Solomon subduction zone. This large magmatic edifice, too large to subduct, is characterized by lower Qs anomaly, low Vs anomaly [Gomer and Okal, 2003] and a non-usual discontinuity at 280 km beneath oceanic plateau [Tharimena et al. 2016].

In this presentation, we will discuss the benefits and limitations of our approach to studying the interaction of the mantle upwelling with the lithosphere for different geodynamic setting. These new results could bring important information and implication of the current models of hot spots and their interactions with lithosphere.

[1] Afonso, J. C., N. Rawlinson, Y. Yang, D. L. Schutt, A. G. Jones, J. Fullea, and W. L. Griffin (2016), 3D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle, J. Geophys. Res. Solid Earth, 121, 7337-7370.

[2] Gazel, E., Trela, J., Bizimis, M., Sobolev, A.V., Batanova, V., Class, C. and Jicha, B. (2018), Long-lived source heterogeneities in the Galapagos mantle plume, Geochem, Geophys Geosyst.,19,8, 2764-2779

[3] Gomer, B.M., Okal., E.A. (2003). Multiple ScS probing of the Ontong Java plateau, Physics of the Earth and Planetary Interiors, 138, 317-331.

[4] Jones, A.G., Afonso, J.C., Fullea, J. (2017), Geochemical and geophysical constrains on the dynamic topography of the Southern African Plateau. Geochem, Geophys Geosyst.,18,10, 3556-3575.

[5] Tharimena, S., Rychert, C.m Harmon, N. (2016). Seismic imaging of a mid-lithospheric discontinuity beneath Ontong Java Plateau, Earth and Planetary Sciences Letters, 450, 62-70.

2D Numerical models for converging oppositely dipping subduction zones at upper mantle and whole mantle scale

- Anouk Beniest
  Department of Earth and Life Sciences, Faculty of Science, Vrije Universiteit Amsterdam
- Wouter P. Schellart
  Department of Earth and Life Sciences, Faculty of Science, Vrije Universiteit Amsterdam

We use the viscous-plastic numerical code 'Underworld2' to investigate the subduction initiation of two converging, oppositely dipping subducting slabs. Such a setting is comparable to the Scotia Plate that, during its early existing stage, was bounded by the east-ward subducting Nazca and Phoenix plates, that formed one continuous subduction zone along the western side of the South American and Antarctic continents, and the westward subducting South American plate. The South Sandwich trench formed much later in response to the westward dipping South American slab to the east of the Scotia Plate.

In a first attempt to simulate the dynamics of converging oppositely dipping subduction zones, we tested various parameters, such as slab thickness, lithosphere thickness, angle of subduction and width of the overriding plate with a simplified 2D numerical setup that includes the upper mantle down to the 660 km boundary of the transition zone. The results showed that by changing the suite of these parameters, we were not able to model double subduction. By increasing the density of the plate representing the South American slab, double subduction was possible, but only when the density was very high. One notable result was the apparent random slab geometry of the subducting plate that represents the Nazca-Phoenix subduction system, which differed between a concave backward bent geometry and a forward moving s-shaped geometry.

A follow-up study with whole-mantle scale models may provide more insights in the dynamics of converging oppositely dipping subduction systems because the simulated time-window can be prolonged significantly.

Core freezing, chemical segregation and mushy magnetohydrodynamics

- David Bercovici
  Department of Geology & Geophysics, Yale University
  david.bercovici@yale.edu

- Elvira Mulyukova
  Department of Geology & Geophysics, Yale University

The freezing of planetary and planetesimal cores and resultant compositional convection are likely important drivers for dynamo activity. The solidification of compositional mixtures, such as iron and sulfur, generates mush zones of partial melt at the freezing front, which can eject chemically buoyant or heavy liquid that then drives convection. Freezing in large planets can take billions of years, but small planets and planetesimals likely undergo complete freezing relatively rapidly, and their final stages of fluid motion during crystallization are probably dominated by mushy convection, compaction and percolative flow. However, dynamo models usually treat the solid core as static and electrically conducting, while models of partial melt mush zones assume the medium is mobile but electrically insulating. The magneto-hydrodynamic behavior of the deformable mush zone imposes a different boundary condition on dynamo activity than would a conducting solid, and conversely magnetism can impose extra forces on the phase separation in the mush zone. We extend our new two-phase magneto-hydrodynamic theory (Bercovici & Mulyukova, 2019) for percolation and compaction of a mush zone to include bulk mass, chemical and energy exchange during crystallization. Our model indicates that core freezing, partial crystallization and continuous compaction of the mush layer generates a well-magnetized chemically enriched liquid phase that is ejected into the pure-melted portion of the core.

[1] Bercovici D. and E. Mulyukova, Two-phase magnetohydrodynamics: Theory and applications to magneto-compaction and magnetoconvection in crystallizing planetary and planetesimal cores, under revision for *Phys. Earth Planet. Int.*, 2019.

Geodynamic constraints on the initiation of mélange diapirs from subducting slabs

- Nicolas Berlie
  Johannes Gutenberg University Mainz, Germany
  nberlie@uni-mainz.de

- Boris Kaus
  Johannes Gutenberg University Mainz, Germany

- Horst R. Marschall
  Goethe University, Frankfurt am Main, Germany

Subduction zones represent an important part of the general volcanic activity and magma production on earth. The numerous geochemical analyses performed over time on those magmas suggest a mixing between the crustal components of the subducting slab and the mantle. The mixing process likely takes place at the interface between the slab and the mantle wedge, where mélange rocks form comprising of crustal and mantle rocks and hydrous fluids extracted from the slab. This mélange layer would then evolve into diapirs and rise in the asthenosphere until it reaches melting conditions suitable for the creation of magmas. Here, we study the geodynamic feasibility of this process and the conditions that determine the ability of the mélange to peel off from the slab and form diapirs as well as the size of those diapirs. We perform 2D finite element calculations focusing on two different setups to observe the initiation and later the evolution of the diapirs with time. Results confirm that this mechanism is feasible under a specific range of condition and we show how the lateral extents of those diapirs along the slab depends on the geometry of the slab, the rheological and density parameters of the mélange layer and the overlying mantle. We also investigate the P-T paths followed by the diapirs and the implications on their mineralogical compositions.

Assimilation of observations into physical models of the seismic cycle at subduction thrusts.

- Marie Bocher
  Seismology and wave physics group, Institute of Geophysics, Earth Science Department, E.T.H. Zurich, Switzerland
  marie.bocher@erdw.ethz.ch

- Ylona van Dinther
  Tectonics, Department of Earth Sciences, Utrecht University, the Netherlands.

Seismo-thermo-mechanical (STM) models are physics-based numerical models able to reproduce the main characteristics of the seismic cycles observed at subduction zones. By combining these models with surface observations through an ensemble data assimilation technique, van Dinther et al. (GJI, 2019) found it is possible to estimate the evolution of the stress on and around a fault in a simple subduction setup, when physical parameters are perfectly known. However, one of the crucial steps inhibiting the application of this method to nature is precisely the uncertainty on physical parameters. Here, we explore the possibility to jointly estimate physical parameters and the evolution of the state of stress using ensemble data assimilation. Through appending parameters to the state vector in an Ensemble Kalman Filter, we test the estimation of the shear modulus and seismogenic zone width in the same synthetic setup of an analogue seismic cycle model.

[1] Ylona van Dinther, Hans R. Künsch, and Andreas Fichtner (2019). Ensemble Data Assimilation for Earthquake Sequences: Probabilistic Estimation and Forecasting of Fault Stresses. Geophysical Journal International, doi: 10.1093/gji/ggz063

Mechanisms enabling chemical interactions between core and mantle

- Irene Bonati
  Earth-Life Science Institute, Tokyo Institute of Technology, Japan
  irene.bonati@elsi.jp

- Lim Kang Wei
  Earth-Life Science Institute, Tokyo Institute of Technology, Japan

- Scott D. Hull
  Rutgers University, USA

- John W. Hernlund
  Earth-Life Science Institute, Tokyo Institute of Technology, Japan

Processes taking place at the core-mantle boundary (CMB) are topic of active research. While usually considered as two separate reservoirs, the mantle and the core might exchange mass, along with chemical signatures. Signs of core-mantle chemical interaction might have surficial manifestations in “ocean island basalt” (OIB) lavas derived from hot upwelling plumes generated near the CMB. Recent isotopic measurements of OIBs show negative ^{182}W, reduced D/H, and elevated ^{3}He/^{4}He, all of which could be expected signatures of the core. However, the difficulty of entraining dense core metal into the silicate mantle flows and the absence of a correlated increase in siderophile element abundances have instead motivated hypotheses that attribute such isotope variations to the mantle heterogeneity alone. In order to satisfy siderophile element abundances, only limited metal can be directly entrained from the core. We consider three separate mechanisms that can impart a core-like isotopic signature to the mantle and be transported to upwelling plumes rooted in the CMB region: (1) Interaction with deep mantle melts (i.e., basal magma ocean) in the early Earth, (2) upward sedimentation of solids precipitated from the core, and (2) grain-scale intrusion of liquid iron into mantle material that is depressed inside the top of the core as a result of downwellings. We focus on the latter scenario, which requires that metals at the CMB form an interconnected network at the grain boundaries even at low volume fractions. We present the velocity field in proximity of downwelling mantle material and provide first-order estimates for the residence time of core material within the mantle before draining back into the core, and the resulting isotopic signature left inside the mantle.

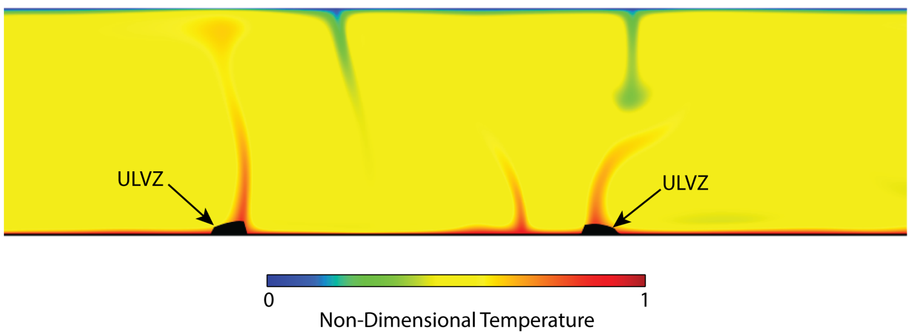
Modeling Utralow Velocity Zones as a global thin layer at the Core Mantle Boundary

- Irene Bonati
  Earth-Life Science Institute, Tokyo Institute of Technology, Japan
  irene.bonati@elsi.jp

- John W. Hernlund
  Earth-Life Science Institute, Tokyo Institute of Technology, Japan

Seismically detected ultralow velocity zones (ULVZs) at the core-mantle boundary (CMB) reflect the dynamical state and the geological evolution of the silicate-metal frontier of Earth's deep interior. Understanding the origin and long-term evolution of ULVZs is limited by a number of computational difficulties, such as the necessity of fine scale resolution and the treatment of large viscosity contrasts between the ULVZs and the overlying lower mantle. By using lubrication theory[1], we derive a simple advection-diffusion equation describing the evolution of ULVZs, and apply it to numerical and analytical models of mantle convection in the CMB region. The models feature an initially global thin low viscosity ULVZ layer embedded between an overlying convective viscous mantle and an underlying inviscid core. The evolution outcomes can explain features that are consistent with seismic inferences, such as the absence of ULVZs in some regions and an elongated shape where they are concentrated. The topography of ULVZs tends to saturate as they become thicker as a result of the feedback between viscous aggregation beneath upwelling mantle currents and gravitational relaxation. The implementation of the ULVZ equation in numerical models of mantle convection shows that ULVZs are preferentially concentrated beneath long-lived plumes roots, and may not exist below newly formed plumes (Figure 1). The presence or absence of ULVZs, as well as their shapes, can provide important insights into both the dynamics of the lowermost mantle and potential core-mantle interactions.

[1] Reynolds, O. (1886), IV. On the theory of lubrication and its application to Mr. Beauchamp tower's experiments, including an experimental determination of the viscosity of olive oil, Proceedings of the Royal Society of London, 40(242-245), 191–203, doi:10.1098/rspl.1886.0021.



Snapshot of a solution of Rayleigh-Bénard convection showing the non-dimensional temperature field and the ULVZ layer profile (black) at the CMB. The ULVZ thickness is vertically exaggerated for better visibility.

Topographic fingerprints of deep mantle subduction

- Arthur Briaud
  Università degli studi Roma Tre, Rome, Italy
  arthur.briaud@uniroma3.it

- Roberto Agrusta
  ENS Lyon, Lyon, France

- Francesca Funiciello
  Università degli studi Roma Tre, Rome, Italy

- Jeroen van Hunen
  Department of Earth Sciences, Durham University, United Kingdom

- Claudio Faccenna
  Università degli studi Roma Tre, Rome, Italy

The dynamic topography links with the mantle structures at various temporal and spatial scales. However, it is still unclear how it relates to the dynamics of subducting lithosphere when plates reach the mantle transition zone and lower mantle. Seismic tomography images show how slab morphologies vary from either sinking sub-vertically into the lower mantle, lying flat above the upper-lower mantle discontinuity, or thickening in the shallow lower mantle (e.g. Fukao & Obayashi, 2013; Van Der Meer et al., 2010). These slab shapes have been considered to be the results of variable interaction of the slab with the upper-lower mantle discontinuity at ∼670 km depth. Previous studies show that periodic deep slab dynamics can explain a variety of puzzling geological and geophysical observations such as periodic variations of the plate velocities, trench retreat and advance episodes and the scattered distribution of slab dip angle in the upper mantle (e.g. Cerpta et al., 2015; Lee & King, 2011). In this study, we use two dimensional subduction models to investigate the surface topography expression and its evolution during the slab transition zone interaction. Our models show that topography does not depend on slab morphology; indeed, the dynamic topography cannot distinguish between slab sinking straightly into the lower mantle and slab stagnation at the 670 km depth discontinuity. However, topographic oscillations are associated to episodes of the trench advance and retreat, which in turn are linked to the slab folding behaviour at transition zone depths. Our results suggest that surface transient signal observed by geological studies, could help to detect deep subduction dynamics.

[1] Cerpa, N. G., Araya, R., Gerbault, M., & Hassani, R. (2015). Relationship between slab dip and topography segmentation in an oblique subduction zone: Insights from numerical modeling. Geophysical Research Letters, 42(14), 5786–5795.

[2] Fukao, Y., & Obayashi, M. (2013). Subducted slabs stagnant above, penetrating through, and trapped below the 660 km discontinuity. Journal of Geophysical Research: Solid Earth, 118(11), 5920–5938.

[3] Lee, C., & King, S. D. (2011). Dynamic buckling of subducting slabs reconciles geological and geophysical observations. Earth and Planetary Science Letters, 312(3–4), 360–370.

[4] Van Der Meer, D. G., Spakman, W., Van Hinsbergen, D. J. J., Amaru, M. L., & Torsvik, T. H. (2010). Towards absolute plate motions constrained by lower-mantle slab remnants. Nature Geoscience, 3(1), 36–40.

Impact of convection in the mantle transition zone on long-term lithospheric deformation during the Alpine cycle

- Lorenzo G. Candioti
  Institut des sciences de la Terre, Université de Lausanne
  lorenzo.candioti@unil.ch
- Stefan M. Schmalholz
  Institut des sciences de la Terre, Université de Lausanne
- Thibault Duretz
  University of Rennes 1, UMR CNRS 6118, France

The geodynamic history of the Western Alpine orogeny comprises periods of distinct phases of lithospheric deformation. Ultra-slow to slow spreading during ca. 60 Myrs formed the ca. 300-400 km wide Piemonte-Liguria basin. This basin was bounded by magma-poor, hyper-extended continental margins of the European and Adriatic plate and consisted mainly of exhumed and partially serpentinized sub-continental mantle. Subsequently, post-extension cooling took place for ca. 70 Myrs with insignificant tectonic activity. Then, convergence of the basin-margin system started at ca. 90 Ma causing the closure of the basin during subduction and the formation of an orogenic wedge during continent-continent collision.

Modelling the long-term geodynamic history (>100 Myrs) of orogens such as the Alps, including the pre-orogenic extension and cooling stages, remains challenging. For example, significant heat loss due to thermal diffusion over large time scales leads to unrealistic temperature and viscosity fields in the models. Modelling mantle convection in the transition zone below the thermal lithosphere-asthenosphere boundary (LAB) provides a mechanism to decrease the heat loss and stabilize the LAB in depth. Thermal effects of convection can be modelled by either (1) directly modelling small-scale mantle convection, or by (2) artificially scaling the thermal parameters of the sub-lithospheric mantle without modelling convection.

We perform 2D high resolution thermo-mechanical numerical simulations of more than 200 Myrs of lithospheric deformation. The models include the mantle transition zone down to a depth of 660 km to model the Western Alpine cycle including three subsequent deformation phases: (1) formation of a ca. 350 km wide basin of exhumed mantle bounded by two hyper-extended passive margins during a 60 Myrs rifting period. (2) Thermal relaxation of the margin system for 70 Myrs with no far-field tectonic activity. (3) Convergence of the passive margin system leading to subduction initiation, basin closure and orogenic wedge formation.

We perform two types of simulations: (1) We resolve and model sub-lithospheric convection during lithospheric extension, cooling and convergence. (2) We scale the thermal conductivity of the sub-lithospheric mantle without modelling and resolving the convection. We discuss and quantify the general differences of the model results for the extension, cooling and subduction phase. We further quantify differences in effective viscosities in the models and their impact on the extension and subduction dynamics.

Mars with a parametrized giant impact: Numerical simulation

- Kar Wai Cheng
  ETH Zurich
  karwai.cheng@erdw.ethz.ch

- Antoine Rozel
  ETH Zurich

- Paul Tackley
  ETH Zurich

- Harry Ballantyne
  University of Bern

- Martin Jutzi
  University of Bern

- Gregor Golabek
  University of Bayreuth

The presence of the crustal dichotomy is one of the most prominent characteristics on Mars. It features a ∼5.5 km contrast in topography and a ∼25 km difference in crustal thickness between the northern lowlands and southern highlands [1], and is suggested to have formed early within the first 400-500 Myr in Mars' history [2]. However, the formation process of such dichotomy remains unclear. In this study, we examine the hypothesis where a giant impact induced regional melting and subsequent crust production, leading to a thicker crust of the southern hemisphere. We use the mantle convection code StagYY [3] to run sets of 2D numerical simulations.

By varying parameters related to a parametrized impact, melt and grain size evolution, we test the sensitivity of different mechanisms on our convection models. We show quantities including crustal thickness and topography that can be compared to observables available for Mars.

[1] Watters, T., McGovern, P., & Irwin III, R. (2007). Hemispheres Apart: The Crustal Dichotomy on Mars. Annual Review Of Earth And Planetary Sciences, 35(1), 621-652

[2] Taylor, S.,& McLennan, S. (2009). Planetary crusts. Cambridge, UK: Cambridge University Press.

[3] Tackley, P. (2008). Modelling compressible mantle convection with large viscosity contrasts in a three- dimensional spherical shell using the yin-yang grid. Physics Of The Earth And Planetary Interiors, 171(1-4), 7-18.

Tidal dissipation in Dione's interior: implication for past geological activity

- Mathilde Kervazo
  Laboratoire de Planétologie et Géodynamique, CNRS-Université de Nantes, France.

- Gaël Choblet
  LPG, CNRS-Université de Nantes, France.
  gael.choblet@univ-nantes.fr

- Gabriel Tobie
  LPG, CNRS-Université de Nantes, France.

- Christophe Sotin
  JPL, Caltech, USA.

- Julie Castillo-Rogez
  JPL, Caltech, USA.

The Cassini-Huygens mission revealed that Saturn's moon Dione exhibits convincing clues for past endogenic activity, suggestive of strong internal heating in the past. Studies of craters relaxation lead to heat flow estimates locally as high as 60 mW m^{-2} relatively late in Dione's history. Furthermore, contrasting terrains between heavily cratered surfaces (that supposedly underwent little relaxation) and lightly cratered (more relaxed) surfaces suggest long-lived planetary scale heterogeneity in the interior's thermal structure. This distribution suggests some similarity with Enceladus' pronounced north-south dichotomy. However, while the spectacular activity of Enceladus attests to powerful heat sources at present, their persistence is not obvious in the case of Dione.

Combined analysis of gravity and topography favors a differentiated interior and is consistent with the presence of a subsurface ocean estimated between 80 and 120 km below the surface. Maintaining such an ocean would require a sufficient amount of energy coming from the interior in order to prevent crystallization. Even if the ocean is deeper in Dione, as in the case of Enceladus, additional heat sources most probably related to tidal dissipation, have to be envisioned besides the modest radiogenic content residing in the rocky materials (the rock fraction is similar for the two moons). This raises the question of the origin of an enhanced dissipative state, at least in the past.

The mechanisms leading to tidal dissipation in a differentiated body such as Dione are explored in detail. A promising scenario proposed for Enceladus locates most tidal heating in the unconsolidated rock core saturated with interstitial liquid water: we adapt this model to Dione. In addition, while Enceladus' thin ice shell is presumably in a conductive state and that little dissipation occurs there, Dione's ice crust is potentially much thicker and prone to convection. This favors tidal dissipation in the ice so that this second ingredient is also considered for Dione. Both heat sources (dissipative porous rock core, dissipative ice crust) are naturally expected to vary throughout the satellite's history in conjunction with its orbital evolution and possible core compaction. We confront our results to observational constraints.

Subduction zone initiation (SZI) database 1.0: Ready, set, model!

- Fabio Crameri
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Oslo, Norway
  fabio.crameri@geo.uio.no
- Valentina Magni
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Oslo, Norway
- Mathew Domeier
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Oslo, Norway
- Grace Shephard
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Oslo, Norway
- Kiran Chotalia
  Department of Earth Sciences, University College London, London, United Kingdom
- George Cooper
  Department of Earth Sciences, Durham University, Durham, United Kingdom
- Caroline Eakin
  Research School of Earth Sciences, Australian National University, Canberra, Australia
- Antoniette Greta Grima
  Department of Earth Sciences, University College London, London, United Kingdom
- Derya Gürer
  School of Earth and Environmental Sciences, University of Queensland, Brisbane,
- Ágnes Király
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Oslo, Norway
- Elvira Mulyukova
  Department of Geology and Geophysics, Yale University, New Haven, USA
- Kalijn Peters
  Department of Earth Sciences, Utrecht University, Utrecht, Netherlands
- Boris Robert
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Oslo, Norway
- Marcel Thielmann
  Bavarian Geoinstitute, University of Bayreuth, Bayreuth, Germany

The initiation of new subduction zones is likely the key to maintaining ocean-plate tectonics on the Earth until present day. Despite its importance in maintaining plate tectonics, the process to form new subduction zones on a planet with ongoing plate tectonics remains enigmatic. This is possibly due to the incomplete or missing and geographically discontinuous geologic evidence, as well as the long timescales and the numerous physical processes involved in forming new plate boundaries, thus requiring strongly inter-disciplinary studies to understand this phenomenon.

Moreover, the initiation of a new subduction zone is literally poorly defined. The discussion within and especially across different Earth Science communities is often confusing. Extracting observational data from the current literature is difficult and the data extracted is often very specific to individual subduction zone initiation (SZI) events. Constraining general geodynamic SZI models is therefore still challenging.

In a dedicated and collaborative effort, we gathered experts in different fields across the Earth Sciences to provide and collect presently available data on recent subduction zone initiation (SZI) events and build a cross-disciplinary Subduction Zone Initiation Database. This novel database, which is based on an unambiguous definition of SZI, covers many recent SZI events currently back to 100 Ma and will be made openly available. The database is, amongst other things, a significant step forward to better constrain subduction zone initiation models, which will foster new insights into this key outstanding problem of the Earth Sciences.

The SZI Database is a product of the YoungCEED initiative, which aims to bridge the various subfields of the Earth Sciences and foster new ideas by supporting young scientists. The evidence collected within the SZI Database provides new insight to the long-standing questions about where, when and how new subduction zones have initiated on the Earth in the past 100 Myr.

On the cause of enhanced landward motion of the overriding plate after a major subduction earthquake

- Mario D'Acquisto
  University of Utrecht
  m.dacquisto@uu.nl

- Rob Govers
  University of Utrecht

- Matthew W. Herman
  University of Utrecht

We focus on the overriding plate at along-trench distances of hundreds of kilometers from the rupture area of a megathrust earthquake, where geodetic observations show increased landward velocities following the 2003 Tokachi, 2010 Maule, and 2011 Tohoku earthquakes. Is increased coupling or faster slab sinking required, or are these observations a consequence of common earthquake cycle-related processes? We use kinematically driven finite element simulations to understand how velocity changes similar to the observed ones can be produced in the context of viscous relaxation and afterslip, without changes in interseismic locking or slab sinking. The 3D model has repeated, periodic seismic cycles, a uniform cross-section and predefined, fully coupled asperities. The interface properties are based on parameterizations of slip weakening and strengthening, and viscoelastic rheology. During postseismic relaxation, increased landward as well as trench-parallel velocities are produced on either side of the area of coseismic slip surrounding the ruptured asperity. Displacement during the initial relaxation driven by primary afterslip is sensitive to the assumed distribution and size of asperities. The subsequent 3D viscoelastic relaxation of the mantle wedge produces similar velocities but is not sensitive to the presence and location of other asperities. All relaxation-induced velocities in the overriding plate are independent of velocity changes in the slab. Overall, the models indicate that postseismic deformation driven by slip-induced stress changes produce landward velocity changes over similar lateral distances from the megathrust earthquake source as observed and with comparable amplitude. This suggests that transient changes in interplate coupling and slab velocity might not be required to explain the observed enhanced landward motion. The models also make testable predictions that landward displacements will occur simultaneously and thus over the same timescales as viscous relaxation and afterslip, and that earthquakes with long-lived afterslip will have landward velocity changes only above unlocked portions of the plate interface.

Influence of dislocations jamming on Plumes and Slabs in a Bridgmanite Lower Mantle

- Anne Davaille
  FAST, CNRS / Univ. Paris-Sud, Orsay, France
  davaille@fast.u-psud.fr

- Anna Massmeyer
  FAST, CNRS / Univ. Paris-Sud, Orsay, France
  Institute of Heat and Mass Transfer, RWTH Aachen Univ., Germany.

- Patrick Cordier
  UMET, Univ. Lille / CNRS / INRA / ENSCL, France

- Philippe Carrez
  UMET, Univ. Lille / CNRS / INRA / ENSCL, France

Numerical calculations recently showed that $MgSiO_3$ Bridgmanite, the most common phase of the lower mantle, was probably preferentially deforming in pure dislocation climb creep under lower mantle conditions. The resulting rheology presents two key elements : i) the existence of a yield stress which depends on the dislocations density, and ii) shear-thinning with an stress exponent ~ 3. So irreversible deformation (i.e. creep) will occur only if the deviatoric stress exceeds a critical "yield stress" value. In such a viscous-elasto-plastic fluid, laboratory experiments show that only convective features with a sufficient thermal buoyancy can develop. Moreover, plumes'morphology is greatly altered, changing from the classical mushroom-shape morphology for no or very weak yield stress, to fat fingers for significant yield stress. So the existence of the fat plumes recently imaged in the lower mantle by seismic tomography would indeed be consistent with a pure climb creep rheology of bridgmanite in the lower mantle for yield stresses between $\sim$1 and 10 MPa.

Such values can seem low, but they still are significant compared to the thermal stresses produced by mantle convection. Hence they can have major consequences for mantle flow characteristics. Besides fat plumes, scaling laws derived from the laboratory experiments suggest that the buoyancy force of a subducting plate would not be sufficient to enter a yield-stress lower mantle, but the buoyancy force of a pile of folded slabs would be. Moreover, entire regions of the mantle could remain stagnant while upwelling and downwelling regions would be more localized than in a newtonian mantle.

Extrinsic viscous anisotropy of Newtonian two-phase aggregates

- Albert de Montserrat
  Università degli Studi di Padova
  albert.demontserratnavarro@unipd.it

- Manuele Faccenda
  Università degli Studi di Padova

Earth's mantle rocks are poly-aggregates where different mineral phases coexist. These rocks may often be approximated as two-phase aggregates with a dominant phase (e.g. olivine in the upper mantle, olivine polymorphs in the transition zone) and less abundant one (e.g. pyroxene in the upper mantle, garnet in the transition zone). Severe shearing of these rocks leads to a non-homogeneous partitioning of the strain between the different phases. The resulting bulk rock is not isotropic, and the elastic and viscous tensor depend on the volume fraction and viscosity contrast between the mineral phases, and the fabric.

Here we employ three-dimensional mechanical models to reproduce fabrics typical of mantle rocks and quantify the evolution of the viscous tensor. These fabrics are produced by shearing a mechanically heterogeneous medium comprised by randomly distributed isotropic inclusions embedded in a isotropic matrix: i) a weak inclusion-strong matrix aggregate where strain is mainly accommodated by the weak phase, that flattens and yields a penetrative foliation; and, ii) a strong inclusion-weak matrix where strain is mainly accommodated by the matrix, in this case the strong phase deforms primarily parallel to the direction of the flow, producing cigar-shaped inclusions. The evolution of the viscous tensor is computed by shearing and compressing the models in different directions at different stages of deformation.

The anisotropic tensors of poly-aggregates with non-interactive mineral grains may also be calculated employing effective medium theories. We further explore the capability of the Differential Effective Medium (DEM) to predict the viscous tensor of two-phase aggregates with fabrics representative of mantle rocks. Our results show that there is a good match between the viscous tensor computed from the 3D numerical experiments and the DEM.

Transport of volatiles and trace elements in solitary porosity waves using a two-phase flow approach including disequilibrium melting

- Janik Dohmen
  Institute of Geosciences, Goethe University Frankfurt, Germany
  dohmen@geophysik.uni-frankfurt.de

- Harro Schmeling
  Institute of Geosciences, Goethe University Frankfurt, Germany

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 (1984) 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.

Using these two-phase flow equations the transport of volatiles and trace elements in ascending magmas is investigated. To do this two additional mass equations for the concentration of a volatile or trace element in the solid and the fluid are solved. The equations we use apply to disequilibrium fractional melting and are based on the equations by Spielgelman (1996). They assume surface equilibrium instead of complete equilibrium between mineral grains and melt, and neglect chemical diffusion within the grain. Furthermore we neglect the effect of freezing on the concentrations in solid and fluid.

The models show that solitary waves are able to transport volatiles while ascending upwards and in the course of this build up small columns with a higher amount of incompatible elements.

Further steps on this study are the implementation of freezing and to investigate the effect of build up and collapse of solitary waves on the redistribution of volatiles and trace elements on a certain area.

[1] McKenzie, D. (1984). The generation and compaction of partially molten rock. Journal of Petrology, 25(3), 713-765.

[2] Spiegelman, M. (1996). Geochemical consequences of melt transport in 2-D: The sensitivity of trace elements to mantle dynamics. Earth and Planetary Science Letters, 139(1-2), 115-132.

Modeling the interaction between mantle exhumation and syn-rift salt tectonics based on the Cretaceous Pyrenean Rifting

- Thibault Duretz
  Univ Rennes, CNRS, Géosciences Rennes UMR 6118, F-35000 Rennes, France
  thibault.duretz@univ-rennes1.fr

- Asti Riccardo
  Univ Rennes, CNRS, Géosciences Rennes UMR 6118, F-35000 Rennes, France

- Lagabrielle Yves
  Univ Rennes, CNRS, Géosciences Rennes UMR 6118, F-35000 Rennes, France

- Brun Jean-Pierre
  Univ Rennes, CNRS, Géosciences Rennes UMR 6118, F-35000 Rennes, France

- Jourdon Anthony
  Univ Rennes, CNRS, Géosciences Rennes UMR 6118, F-35000 Rennes, France

- Clerc Camille
  ISEA, University of New Caledonia, Nouméa, France

- Corre Benjamin
  Univ Rennes, CNRS, Géosciences Rennes UMR 6118, F-35000 Rennes, France

The pre-shortening Cretaceous Pyrenean rift is an outstanding geological laboratory to investigate the effects on lithospheric rifting of a pre-rift salt layer at sedimentary base. The occurrence of a pre-rift km-scale layer of evaporites and shales promoted the activation of syn-rift salt tectonics from the onset of rifting. The pre- and syn-rift sediments are locally affected by high-temperature metamorphism related to mantle ascent up to shallow depths during rifting. The thermo-mechanical interaction between décollement along the pre-existing salt layer and mantle ascent makes the Cretaceous Pyrenean rifting drastically different from the type of rifting that shaped most Atlantic-type passive margins where salt deposition is syn-rift and gravity-driven salt tectonics has been post-rift. To unravel the dynamic evolution of the Cretaceous Pyrenean rift, we carried out a set of numerical models of lithosphere-scale extension, calibrated using the available geological constraints. Models are used to investigate the effects of a km-scale pre-rift salt layer, located at sedimentary cover base, on the dynamics of rifting. Our results highlight the key role of the décollement layer at cover base that can alone explain both salt tectonics deformation style and high temperature metamorphism of the pre-rift and syn-rift sedimentary cover. On the other hand, in absence of décollement, our model predicts symmetric necking of the lithosphere devoid of any structure and related thermal regime geologically relevant to the Pyrenean case.

Modeling lithospheric deformations with frictional plasticity, caveats and perspectives

- Thibault Duretz
  Univ Rennes, CNRS, Géosciences Rennes UMR 6118, F-35000 Rennes, France
  thibault.duretz@univ-rennes1.fr

- René de Borst
  University of Sheffield, Department of Civil and Structural Engineering, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, UK

- Laetitia Le Pourhiet
  Sorbonne Université, CNRS-INSU, Institut des Sciences de la Terre Paris, ISTeP UMR 7193, F-75005 Paris, France

- Alban Souche
  Physics of Geological Processes, The NJORD Center, Geosciences Department, University of Oslo, Norway

Large lithospheric deformations are typically described as either 'brittle' or 'ductile'. Ductile deformations of dry rocks are expected to occur at high temperatures (several hundreds of degrees) and are represented by either pervasive strains or localised shear zones. Brittle deformations are dominant at lower temperatures and can be expressed by the development of faults.

Frictional plasticity is the rheological model which is generally evoked to explain the occurrence of brittle deformations. In this regime, lithospheric strength depends linearly on the pressure (non-lithostatic), which is well documented by both laboratory experiments and borehole data. Thanks to this specificity, shear bands arising from frictional plasticity exhibit specific orientations with regard to principal stress directions. This model is hence successful at explaining the occurrence of steeply dipping normal faults in extension and low angle thrusts faults in compression.

Nevertheless, the inclusion of frictional plasticity in numerical models of lithospheric deformation is problematic.

Typical implementations of frictional plasticity are often fully incompressible, neglect the role of elasticity, use strain softening, involve a Maxwell visco-plastic rheology, and are based on Picard-type solvers. Problems that generally arise are the lack of convergence of the momentum equations and severe mesh dependence of the numerical models.

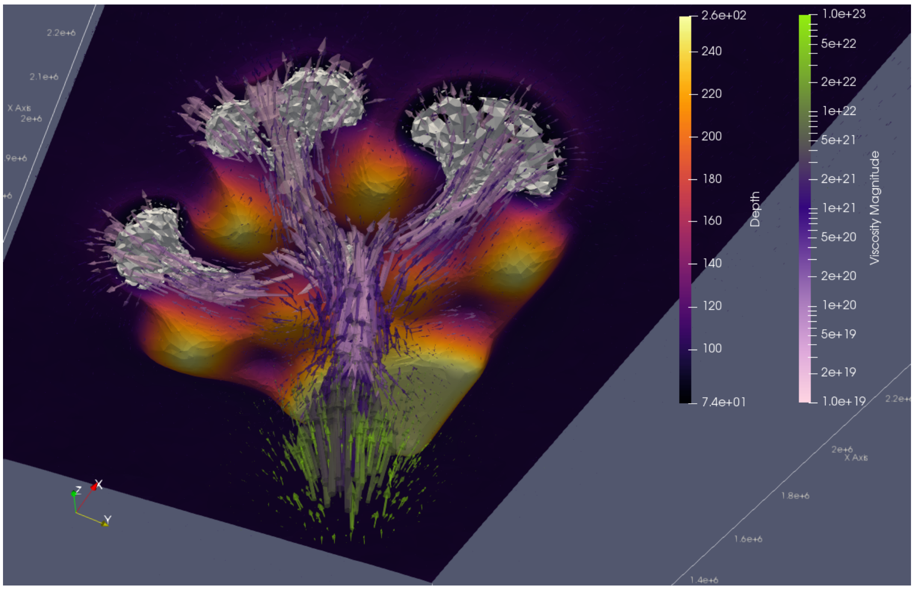
In this contribution, we present numerical implementations of frictional plasticity using the consistent-tangent linearisation (Newton-type solver) with both displacement-based or velocity-pressure compressible formulations. We report quadratic convergence during shear banding. We investigate the role of Kelvin visco-plasticity as way to regularise mesh-sensitive plasticity formulations. Finally, we further extend our models to account for viscous creep (brittle-ductile transition) as well as tensile deformation. We will discuss the ingredients that are necessary to achieve successful numerical simulations (convergent and mesh independent) of lithospheric deformation.

Under what conditions do edge-driven convection and shear-driven upwelling trigger magmatism at lithospheric steps?

- Thomas Duvernay
  Research School of Earth Sciences, The Australian National University
  thomas.duvernay@anu.edu.au

- D. Rhodri Davies
  Research School of Earth Sciences, The Australian National University

Most of Earth's volcanism occurs at tectonic plate boundaries, either where plates move away from one another to create mid-ocean ridges, or where one plate slides beneath another to form a subduction zone. However, an important and widespread class of volcanism occurs within plates, or across plate boundaries. Intra-plate volcanism, as it is referred to, encompasses a large variety of edifices which are usually gathered in small groups. If the classical mantle plume model is able to account for most linear, age-progressive volcanic tracks, it is nevertheless insufficient to capture the entire complexity of intra-plate volcanic provinces, especially on continents. Cenozoic records in both Africa and Australia display weak, episodic activity, which does not distribute spatially nor temporally as would be expected from classical plume-induced magmatism. Additional mechanisms are required to account for these observations. Shallow dynamical processes, such as edge-driven convection (EDC) and shear-driven upwelling (SDU), have been proposed and used to demonstrate that abrupt changes in lithospheric structure can trigger sub-lithospheric instabilities. In particular, step-changes in lithospheric thickness, as often occur at continental margins, are expected to host convecting cells which may induce melting via focused upwellings. Observations, however, demonstrate that continental edges on Earth do not systematically host volcanism, even though they would be argued to enhance the development of EDC and/or SDU. In this respect, one must understand the conditions required for melting to occur. Our study investigates the dynamics of sub-lithospheric mantle around lithospheric steps, in both two- and three-dimensional Cartesian domains. We explore how instabilities are affected by lithospheric heterogeneity, upper-mantle viscosity structure and plate motion. We monitor the occurrence of melting and assess the potential settings and conditions that trigger surface volcanism at lithospheric steps. Additional three-dimensional simulations, which account for the interaction between mantle plumes and these shallow convective regimes, are also discussed, to highlight the potential role of mantle plumes in localizing volcanism.



Sub-lithospheric mantle plume flow when subjected to a heterogeneous distribution of the lithosphere-asthenosphere boundary. Velocity glyphs highlight the paths taken by the buoyant material, while white patches denote potential melting zones.

Numerical and experimental permeability prediction of porous media

- Philipp Eichheimer
  Bayerisches Geoinstitut, University of Bayreuth
  Philipp.Eichheimer@uni-bayreuth.de
- Marcel Thielmann
  Bayerisches Geoinstitut, University of Bayreuth
- Anton Popov
  Institute for Geoscience, Johannes Gutenberg University Mainz
- Gregor J. Golabek
  Bayerisches Geoinstitut, University of Bayreuth
- Wakana Fujita
  Department of Earth Science, Tohoku University
- Maximilian O. Kottwitz
  Institute for Geoscience, Johannes Gutenberg University Mainz
- Boris J.P. Kaus
  Institute for Geoscience, Johannes Gutenberg University Mainz
- Satoshi Okumura
  Department of Earth Science, Tohoku University
- Michihiko Nakamura
  Department of Earth Science, Tohoku University
- Takayuki Nakatani
  Department of Earth Science, Tohoku University

The flow of fluids through porous media such as groundwater flow or magma migration is one of the most important processes in geological sciences. The property controlling the efficiency of the flow is the permeability of the rock, thus an accurate determination and prediction of its value is of crucial importance. For this reason, permeability of rocks has been measured across different scales. As laboratory measurements exhibit a range of limitations, the numerical prediction of permeability at conditions where laboratory experiments struggle has become an important method to complement laboratory approaches. At high resolutions, this prediction becomes computationally very expensive, which makes it crucial to develop methods that maximize accuracy. In this work we introduce the open-source finite difference solver LaMEM that can be used to numerically predict the permeability of porous media under laminar conditions. We employ a stencil rescaling method to increase accuracy due to a better description of the solid-fluid interface, thus reducing the computational cost. To validate the method, we perform a series of tests employing both analytical solutions for simplified geometries as well as results from other numerical approaches for more complicated geometries using Newtonian and non-Newtonian fluids. Additionally we compare our numerical results to laboratory measurements on glass bead samples with porosities ranging from 20% to 2.5%, showing good agreement.

The effects of oblique inherited structures and plate rotations on continent-ocean transform margins

- Georgios-Pavlos Farangitakis
  Department of Earth Sciences, Durham University, Science Site, Durham, DH1 3LE, UK
  georgios-pavlos.farangitakis@durham.ac.uk
- Philip J. Heron
  Department of Earth Sciences, Durham University, Science Site, Durham, DH1 3LE, UK
- Kenneth J.W. McCaffrey
  Department of Earth Sciences, Durham University, Science Site, Durham, DH1 3LE, UK
- Lara M. Kalnins
  School of GeoSciences, University of Edinburgh, The King's Buildings, Edinburgh, EH9 3FE, UK
- Jeroen van Hunen
  Department of Earth Sciences, Durham University, Science Site, Durham, DH1 3LE, UK

In continent-ocean transform margins, oblique structural inheritance and plate motion vector changes have a direct impact on the margin's morphology and duration of transform activity.

Here, we investigate the effects of these two factors using the open source numerical modelling code ASPECT. We model: a) a right-stepping ridge-transform-ridge seed that is rotated from 45° counter-clockwise to 45° clockwise with respect to the extension direction, simulating oblique inheritance and b) a right-stepping ridge-transform-ridge setup extended orthogonally and then rotated by similar angles, simulating a change in relative plate rotation.

Our models infer that high angle oblique compression along the transform fault due to inheritance or change in relative plate motion can increase transform activity duration. Moreover, rotation in this case results in diffuse, long transform zones. The opposite is the case for oblique extension along the transform fault.

These observations are in good accordance with natural examples such as the Ungava Transform Zone, the Gulf of California and the Gulf of Aden, indicating that oblique structural inheritance and changes in relative plate rotation play an important role in the evolution of a continent-ocean transform margin.

The influence of geodynamic processes on the formation of TTG rocks in a plume-lid tectonics setting

- Ria Fischer
  GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
  rfischer@geomar.de

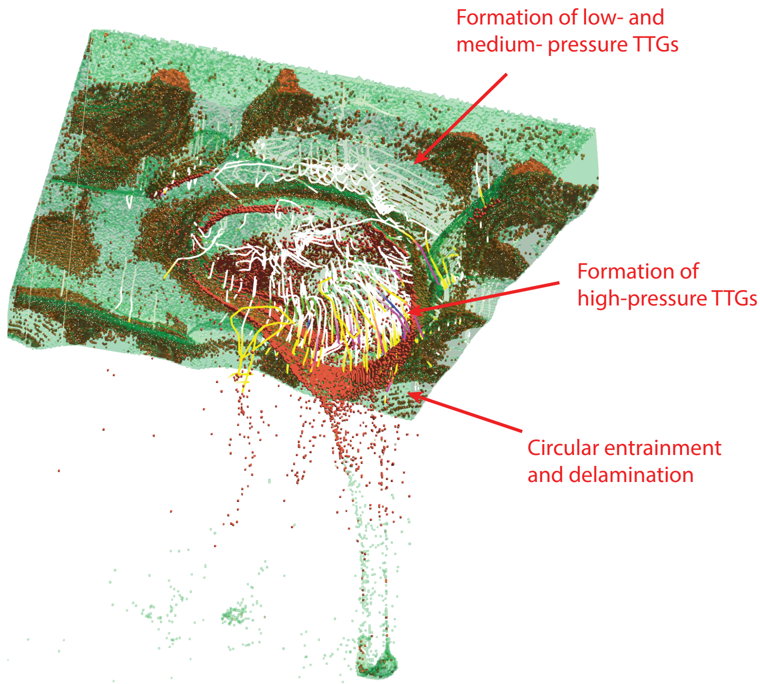
- Taras Gerya
  ETH Swiss Federal Institute of Technology Zurich, Switzerland

- Lars Rüpke
  GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany

The increased upper mantle temperature in the Early Earth precludes the modern plate tectonics regime and stabilizes other types of global tectonics often called plume-lid tectonics (Fischer and Gerya, 2016) or "plutonic squishy lid" tectonics (Rozel et al., 2017).

Plume-lid tectonics is dominated by intrusive mantle-derived magmatism which results in a thickening of the overlaying crust. Melt extraction from hydrated partially molten basaltic crust leads to the production of primordial tonalite–trondhjemite–granodiorite (TTG) continental crust. TTGs make up over half of the Archean crust and can be classified into low-, medium- and high-pressure types (Moyen, 2011). Field studies show that the three different types appear in a ratio of 20%, 60% and 20% (Moyen, 2011).

Further analysis of our 3D petrological-magmatic-thermomechanical numerical modelling experiments reveals two very different modes of TTG formation: (1) Low- and medium-pressure TTG source melt is formed continuously by crustal convection. The ration of low- to medium-pressure TTGs mainly depends on crust thickness. (2) High-pressure TTG source melt is formed during mantle overturn events by delamination or subduction.



Formation of low-, medium- and high-pressure TTG source melt by plume-induced subduction initiation.

The Geodynamic World Builder: a solution for complex initial conditions in numerical modelling

- Menno Fraters
  Earth and Planetary Sciences, UC Davis, Davis, California, USA
  menno.fraters@outlook.com

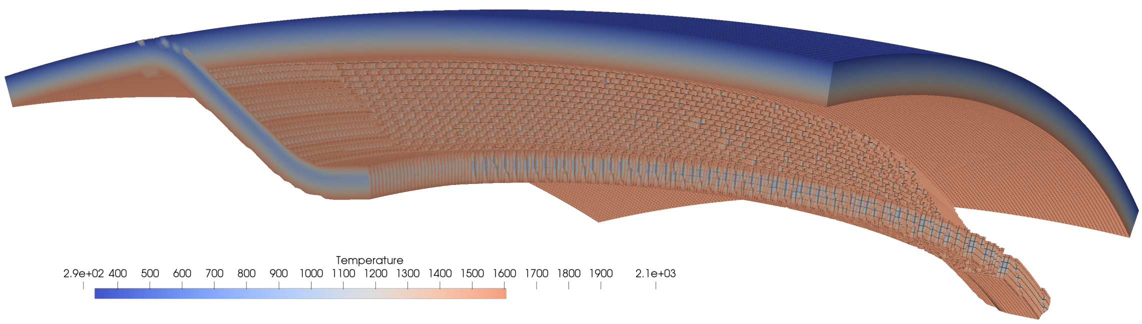
- Cedric Thieulot
  Department of Earth Sciences, Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands

- Arie van den Berg
  Department of Earth Sciences, Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands

- Wim Spakman
  Department of Earth Sciences, Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands
  Centre of Earth Evolution and Dynamics (CEED), University of Oslo, Norway

Creating complex intial conditions of geological settings in 2D, but especially in 3D can be very chalenging. Here we present an open source code library, coined the Geodynamic World Builder (GWB). The GWB is designed to greatly enhance the speed of setting up and modifying such initial conditions by parametrization of the problem. The user defines inputs in a JSON-stype parameter file, which is a structured nested list describing tectonic features, e.g. a continental, an oceanic or a subducting plate. Each of these tectonic features can be assigned a specific temperature model (e.g. linear or a plate model) or a compositional label (e.g. uniform). For each point in the domain, the GWB can return the temperature or composition in that point.

The GWB is written in C++, but can be linked to geodynamic models in almost any programming language through it's C and fortran wrappers. It has already been coupled with the C++ code ASPECT and with the Fortran codes ELEFANT and SEPRAN, and we plan to link it to the Phyton code Underword 2. The GWB can also be used as a stand alone application for visualization purposes. We will show various examples in both 2D and 3D and in cartesian and spherical domains. The GWB has an extensive online User Manual and a well documented API through Doxigen available through http://geodynamicworldbuilder.github.io and can be used with Linux, OSX and Windows operating systems.



An example of a 3d subduction zone in a spherical geometry made with the Geodynamic World Builder.

Strain localization in the lithosphere - A comparison between strain-dependent weakening and grain size sensitive rheologies

- Lukas Fuchs
  Institute for Geosciences, Goethe University Frankfurt, Frankfurt/Main, Germany
  fuchs@geophysik.uni-frankfurt.de

- Thorsten W. Becker
  Institute for Geophysics, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas, USA
  Department of Geological Sciences, Jackson School of Geoscience, The University of Texas at Austin, Austin, Texas, USA

The creation and maintenance of narrow plate boundaries remains one of the major problems in geodynamics. In particular, the cause and consequence of strain localization and weakening within the lithosphere remain debated, even though strain memory and tectonic inheritance, i.e. the ability to preserve and reactivate inherited weak zones over geological time, appear to be critical features of the Wilson cycle. Here, we analyze how a parameterized, apparent-strain dependent weakening (SDW) rheology can describe strain localization and weakening as well as rheological healing in the lithosphere. In nature, frictional-plastic faults and brittle shear zones may be weakened by transient, or static, high fluid pressures, by gouge, or by mineral transformations. Weakening in ductile shear zones below may be governed by a change from dislocation to diffusion creep caused by grain size reduction. In lithospheric models, strain weakening and localization in the shallow parts of the lithosphere has been described by a decrease of the yield strength of the lithosphere with increasing deformation. Strain weakening in viscous shear zones, on the other hand, may be described by a linear dependence of the effective viscosity on the accumulated deformation. We focus on grain-size sensitive rheology to constrain the parameters of SDW and test how suggested microphysical mechanisms can be matched, including but not limited to grain-size evolution. We explore different mechanisms of strain weakening (frictional-plastic (FPSS) and viscous-strain softening (VSS)) and compare them to localization and weakening mechanisms due to different models of grain size evolution for a range of temperatures and a step-like variation of total strain rate with time. FPSS leads to a weakening and strengthening of the effective viscosity of about the same order of magnitude as grain-size sensitive rheology, while the rate depends on the strain-weakening parameter combination. In addition, apparent-strain dependent weakening rheology allows for memory of deformation with time. Once activated and depending on the healing time scales, the memory effect and weakening of the fault zone allows for a more frequent reactivation of the fault at smaller strain rates. These tests can help understand the range of uncertainties in microphysical mechanisms of strain-localization and effects of how they are implemented in geodynamic models.

Eocene subduction west of North America-causes and effects

- Carmen Gaina
  Centre for Earth Evolution and Dynamics, University of Oslo, Norway
  carmen.gaina@geo.uio.no

- Fabio Crameri
  Centre for Earth Evolution and Dynamics, University of Oslo, Norway

- Valentina Magni
  Centre for Earth Evolution and Dynamics, University of Oslo, Norway

- Johannes Jakob
  Centre for Earth Evolution and Dynamics, University of Oslo, Norway

Many of our planet's "crises" were the result of sudden changes in plate tectonic configuration or catastrophic outbursts of volcanism caused by mantle plume impingement at the base of the lithosphere. At the Paleocene–Eocene boundary and in the Early Eocene several mantle plumes, continental collision and mid-ocean ridge subduction triggered a series of changes in seafloor spreading dynamics. Based on a new Paleocene to Miocene global model of oceanic lithosphere age and spreading rates, we revise evidence for changes in seafloor spreading direction in the North Atlantic, Arctic and NE Pacific oceans.

At least two periods of elevated spreading rates, separated by a sharp value decrease, occurred along the entire eastern North American plate boundary from C25 to C18 time (c. 57 to 40 Ma). The collision and incipient subduction of the Early Eocene Siletzia oceanic LIP may have caused the sharp decrease in spreading rate at C23 time in the Labrador Sea and north of Charlie-Gibbs fracture zone. The post C23 rapid Farallon slab-break-off and subsequent upper mantle flow upwelling may have led to further variations in North Atlantic spreading rates at C22-21 time. Eastward Pacific subduction may have resumed at c. 43 Ma as indicated by a steady NE Pacific seafloor-spreading regime, which resumed at or shortly after C21. North American Late Paleocene–Early Eocene kimberlite magma that erupted more than 1000 km from its western plate boundary constitutes additional evidence that tectonic stresses due to changes in the mantle-lithosphere interactions may have affected the entire plate, and therefore also its eastern boundaries.

We run convection models that feature a dynamically self-consistent subduction system and realistic surface topography evolution due to a free surface for testing the hypothesis that subduction regime changes west of North America may have affected the entire plate during the Eocene. Results of 2D numerical modelling suggest that oceanic LIP obduction induces trench advance and upper plate motion changes, which may explain some of our observations.

Evaluating the Accuracy of Hybrid Finite Element/Particle-In-Cell Methods for Modeling Incompressible Stokes Flow

- Rene Gassmoeller
  University of California, Davis
  rene.gassmoeller@mailbox.org

- Harsha Lokavarapu
  University of California, Davis

- Wolfgang Bangerth
  Colorado State University

- Elbridge Gerry Puckett
  University of California, Davis

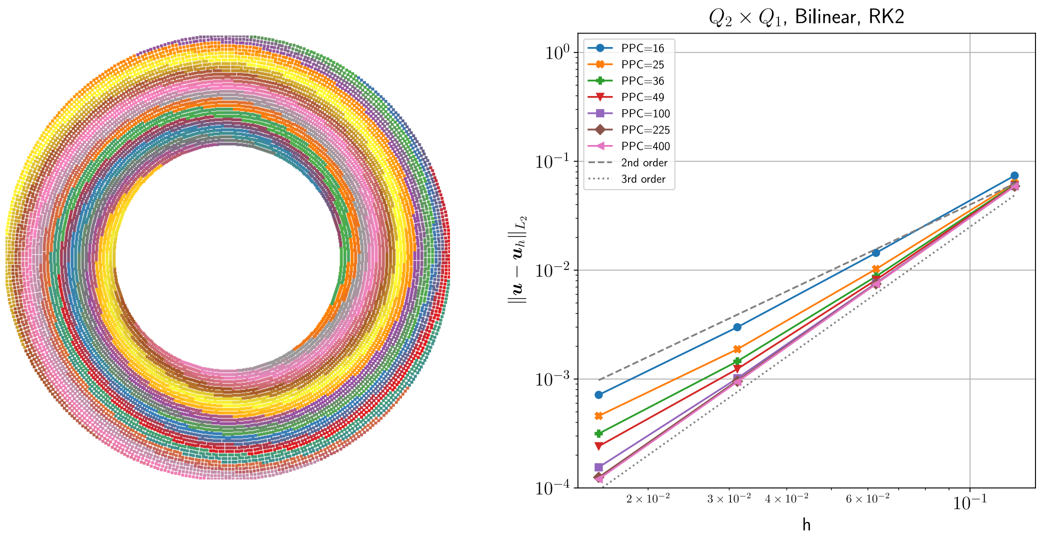
Combining finite element methods for the incompressible Stokes equations with particle-in-cell methods is an important technique in computational geodynamics that has been widely applied in mantle convection, lithosphere dynamics, and crustal-scale modeling. Particles are used to transport along properties of the medium such as the temperature, chemical compositions, or other material properties; the particle methods are therefore used to reduce the advection equation to an ordinary differential equation for each particle, resulting in a problem that is simpler to solve than the original equation for which stabilization techniques are necessary to avoid oscillations.

On the other hand, replacing field-based descriptions by quantities only defined at the locations of particles introduces numerical errors. These errors have previously been investigated, but a complete understanding from both the theoretical and practical sides was so far lacking. In addition, we are not aware of systematic guidance regarding the question of how many particles one needs to choose per mesh cell to achieve a certain accuracy.

In this work we modify two existing instantaneous benchmarks and present a new analytic benchmark for time-dependent incompressible Stokes flow in order to compare the convergence rate and accuracy of various combinations of finite element, particle advection, and particle interpolation methods. Using these benchmarks, we find that in order to retain the optimal accuracy of the finite element formulation, one needs to use a sufficiently accurate particle interpolation algorithm. Additionally, we observe and explain that for our higher-order finite-element methods it is necessary to increase the number of particles per cell as the mesh resolution increases (i.e., as the grid cell size decreases) to avoid a reduction in convergence order.

Our methods and results allow designing new particle-in-cell methods with specific convergence rates, and also provide guidance for the choice of common building blocks and parameters such as the number of particles per cell. In addition, our new time-dependent benchmark provides a simple test that can be used to compare different implementations, algorithms, and for the assessment of new numerical methods for particle interpolation and advection. We provide a reference implementation of this benchmark in ASPECT (the “Advanced Solver for Problems in Earth’s ConvecTion”), an open source code for geodynamic modeling.

[1] Gassmöller, R., Lokavarapu, Bangerth, W. & Puckett, E. G., 2019. Evaluating the Accuracy of Hybrid Finite Element/Particle-In-Cell Methods for Modeling Incompressible Stokes Flow, *Geophysical Journal Internationl*, in review.



Our new benchmarks for time-dependent Stokes flow allow to assess the accuracy of Particle-in-Cell (PIC) methods at any given finite time (left panel). Our theoretical error analysis of PIC methods, and the numerical results of the benchmarks show that the convergence order of PIC methods can depend on the number of particles per cell PPC (right panel). Moreover for some combinations of PIC methods and finite elements, the number of particles per cell needs to be increased with resolution to avoid a degradation of convergence order. Our study provides guidance for when and how to increase the number of particles per cell in such computations.

Net rotation of the lithosphere in mantle convection models with self-consistent plate generation

- Mélanie Gérault
  Massachusetts Institute of Technology, Department of Earth, Atmospheric and Planetary Sciences, Cambridge, MA 02139, USA
  mgerault@mit.edu

- Nicolas Coltice
  Laboratoire de Géologie, Département de Géosciences, Ecole Normale Supérieure, 75005 Paris, France

Lateral variations in the Earth's viscosity structure give rise to a global net rotation between the lithosphere and the mantle. Plate motion reconstructions, mantle flow computations, and inferences from seismic anisotropy all indicate some amount of net rotation using various mantle reference frames. For the present-day, while the direction of rotation is somewhat consistent across studies, recent amplitude predictions range from 0.1 deg/Myr to 0.3 deg/Myr. Further back in time, making up for lost seafloor without constraints on net rotation tends to incorporate artificially high values into plate models. Such uncertainties are a major impediment to a better understanding of fundamental topics that rely on absolute surface kinematic data. Besides, the dynamics that govern the net rotation and its fluctuations in amplitude and direction remain largely unidentified. We address these issues by means of geodynamic modeling. This study provides the first assessment of the net rotation in 3-D spherical mantle convection models with self-consistent plate generation. We run the computations for billions of years of numerical integration. Mantle convection is computed with the finite volume code StagYY using a visco-pseudo-plastic rheology [Tackley, 2008]. We look into how sensitive the net rotation is to heterogeneities in the upper boundary layer, such as the presence of continents of variable thickness. We also explore the links between net rotation and major tectonic events, such as subduction initiation, development and cessation, continental motions, and plate boundary reorganisations. Lastly, we identify governing principles in the models that could guide plate motion reconstructions. In all models, regardless of the yield stress or the presence of continental material, fluctuations in net rotation occur over a few tens of millions of years. The amplitudes vary from nearly zero to over 0.3 deg/Myr, with time averages toward the low end of the present-day estimates. These variations are generally associated with the initiation or cessation of subduction, as well as large-scale reorganisations in the deeper mantle. The results suggest that the net rotation is related to both the tectonic make-up of the surface and the transient response of the mantle. As such, surface observations may not be sufficient to constrain net rotation in the past without acounting for the corresponding mantle flow.

[1] Tackley, P. J. (2008). Modelling compressible mantle convection with large viscosity contrasts in a three-dimensional spherical shell using the yin-yang grid. Physics of the Earth and Planetary Interiors, 171(1-4), 7-18.

Why does Victoria rotate? How preexisting lithospheric heterogeneities control microplate rotation, tectonic regime and the stress field in the East African Rift System

- Anne Glerum
  GFZ German Research Centre for Geosciences, Potsdam, Germany
  ACGlerum@gfz-potsdam.de

- Sascha Brune
  GFZ German Research Centre for Geosciences, Potsdam, Germany
  Institute of Geosciences, University of Potsdam, Potsdam-Golm, Germany

- Manfred Strecker
  Institute of Geosciences, University of Potsdam, Potsdam-Golm, Germany

- D. Sarah Stamps
  Department of Geosciences, Virginia Tech, Blacksburg, United States

The Victoria plate in the East African Rift System (EARS) is one of the largest continental microplates on Earth. The partly overlapping eastern and western EARS branches encompassing Victoria follow the inherited lithospheric weaknesses of the Proterozoic mobile belts. Multiple lines of evidence show that Victoria rotates counter-clockwise with respect to Nubia, in striking contrast to its neighboring plates. However, the cause of this distinctive rotation has remained speculative so far.

Using 3D upper-mantle scale numerical models of extension, we investigate the role of preexisting strength heterogeneities such as mobile belts in the rotation of a continental microplate. We find that the amount of rotation is primarily controlled by the distribution of (i) stronger zones that transmit the drag of the major plates along the edges of the block and (ii) weaker regions that facilitate the rotation. For right-lateral step-overs, this 'edge-driven' mechanism (suggested by Schouten et al. (1993) for oceanic microplates) produces a counterclockwise rotation of the microplate, inducing a clockwise shift of the local extension direction along the overlapping rift branches.

The counterclockwise rotation of Victoria, its rotation pole and its angular velocity are best reproduced in our models if we include preexisting weaknesses that follow the distribution of the mobile belts surrounding the Victoria plate as well as the stronger regions of the Tanzania craton and the Turkana depression. Our models show that under regional, north-to-south decreasing E-W extension this rotation results in local extension directions that strike more WNW-ESE. Together with the oblique orientation of the preexisting weaknesses, this leads to predominantly normal faulting oblique to the regional and local extension direction (Fig. 1). In the most oblique (45°) section of the western branch, the Tanganyika-Rukwa-Malawi segment, this can produce transient strike-slip faulting, although comparison to stress observations suggests a local stress reorientation, possibly due to smaller-scale inherited mechanical anisotropy (e.g. Morley 2010).

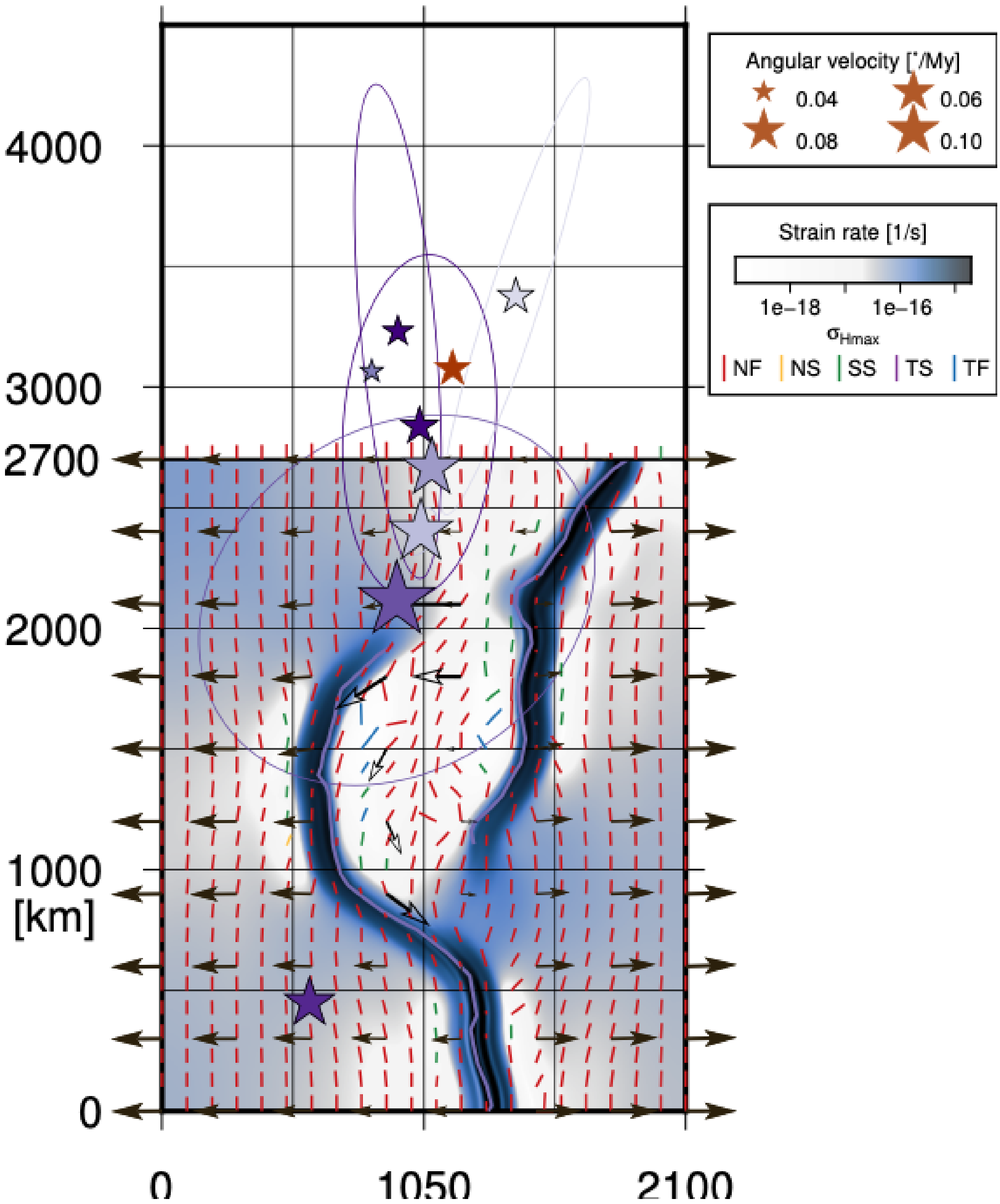
[1] Fernandes, R. M. S., Miranda, J. M., Delvaux, D., Stamps, D. S. and Saria, E. (2013), Re-evaluation of the kinematics of Victoria Block using continuous GNSS data. Geophysical Journal International 193, 1-10.

[2] Kreemer, C., Blewitt, G. and Klein, E. C. (2014), A geodetic plate motion and Global Strain Rate Model. Geochemistry, Geophysics, Geosystems, 15, 3849–3889.

[3] Saria, E., Calais, E., Stamps, D. S., Delvaux, D. and Hartnady, C. J. H. (2014), Present-day kinematics of the East African Rift. Journal of Geophysical Research: Solid Earth, 119, 3584-3600.

[4] Schouten, H., Klitgord, K. D. and Gallo, D. G. (1993), Edge-driven microplate kinematics. Journal of Geophysical Research 98, B4, 6689–6701.

[5] Morley, C. K. (2010), Stress re-orientation along zones of weak fabrics in rifts: An explanation for pure extension in 'oblique' rift segments? Earth and Planetary Science Letters 297, 3–4, 667–673.



Top view of model predictions after 10 My of model time with continuous far-field east-west extension of 5 mm/yr. Blue colors represent the strain rate at a depth of 3 km. Bars indicate the direction of maximum horizontal compressive stress and are colored according to tectonic regime (i.e. NF – normal faulting; NS – oblique normal faulting; SS – strike-slip faulting; TS – oblique thrust faulting; and TF – thrust faulting). Within the rift branches, only normal faulting occurs after 10 My, at an angle to both the extension direction and the mobile belt trend. The velocity field at 3 km depth is represented by black arrows, of which the open head arrows are 4 times exaggerated to better show the microplate rotation in the overall east-west extending system. Purple lines indicate the axes of the initial mobile belts. Purple stars pinpoint the rotation poles of Victoria with respect to Nubia as derived from geodetic and fault-slip data (Fernandes et al. 2013; Saria et al. 2014; Kreemer et al. 2014 and references therein). The brown star is the rotation pole of the model shown; it falls within the uncertainty of the most recent observed pole.

3D numerical models of thermal convection inside Triton's icy shell

- Gregor J. Golabek
  Bayerisches Geoinstitut, University of Bayreuth, Bayreuth, Germany
  gregor.golabek@uni-bayreuth.de

- Alain M. Plattner
  University of Alabama, Tuscaloosa, AL, USA

- Francis Nimmo
  UC Santa Cruz, Santa Cruz, CA, USA

- Taras V. Gerya
  ETH Zürich, Zürich, Switzerland

- Paul M. Schenk
  Lunar and Planetary Institute, Houston, TX, USA

Heating due to obliquity tides may drive the present-day geological activity on Neptune's major moon Triton [1]. One of the various surface types discovered during the Voyager 2 flyby in 1989 is the so-called cantaloupe terrain [2] that is comprised of non-circular dimples with a mean wavelength of 47 km [3]. A compositionally-driven overturn has been proposed [3] to explain the formation of the cantaloupe terrain; however the very young age of Triton's surface [4] makes this explanation unlikely since such an overturn happens only once.

Here we test whether thermal convection inside Triton's ice shell is able to reproduce the basic surface features of the cantaloupe terrain. For this purpose we employ the state-of-the-art finite-difference marker-in-cell code I3ELVIS [5] to model visco-plastic convection in 3D cartesian geometry using the sticky air method [6,7] to simulate a free surface. The initial model setup is based on the results of 1D thermal models of Triton's evolution until present-day [1]. We test both the influence of plastic yield stress and Rayleigh number on the model outcome. Using the autocovariance method we compare the outcome of numerical simulations to the observed topography of the cantaloupe terrain.

Our preliminary results indicate that for plastic yield stresses ranging from 0.05 – 0.5 MPa the surface remains deformable, while large-scale overturn events (cf. [8]) are absent. On the other hand ice viscosities $< 10^{16}$ Pa s are necessary to produce surface deformation on length scales comparable to those of the cantaloupe terrain.

[1] Nimmo & Spencer, Icarus 246, 2-10 (2015).
[2] Smith et al., Science 246, 1422-1449 (1989).
[3] Schenk & Jackson, Geology 21, 299-302 (1993).
[4] Schenk & Zahnle, Icarus 192, 135-149 (2007).
[5] Gerya & Yuen, Phys. Earth Planet. Int. 163, 83-105 (2007).
[6] Schmeling et al., Phys. Earth Planet. Int. 171, 198-223 (2008).
[7] Crameri et al., Geophys. J. Int. 189, 38-54 (2012).
[8] O'Neill & Nimmo, Nat. Geosci. 3, 88-91 (2010).

The rheological control on primordial heterogeneity preservation in Earth's lower mantle

- Anna J.P. Gülcher
  Geophysical Fluid Dynamics group, Institute of Geophysics, ETH Zürich, Switzerland
  anna.guelcher@erdw.ethz.ch

- Maxim D. Ballmer
  Geophysical Fluid Dynamics group, Institute of Geophysics, ETH Zürich, Switzerland
  UCL Earth Sciences, London, UK

- Paul J. Tackley
  Geophysical Fluid Dynamics group, Institute of Geophysics, ETH Zürich, Switzerland

The composition and structure of the mantle are shaped by the evolution of the Earth's interior, but also control its dynamics through time. Cosmochemical and geochemical constraints suggest that the mantle hosts an ancient primordial reservoir that may be enriched in SiO_2 with respect to the upper mantle. Hypotheses of primordial-material preservation in a convecting mantle involve delayed mixing of intrinsically dense and/or strong heterogeneity. A promising regime of mantle convection has been presented by Ballmer et al. (2017) which involves the persistence of intrinsically viscous primordial domains (enriched in the strong mineral bridgmanite) in the mid-mantle for longer than the age of the Earth, with whole-mantle circulation being accommodated around them. This regime has been successfully produced in 2D spherical annulus convection models using composite-dependent rheology (Gebhardt et al., in prep), but the effects of rheological and tectonics parameters upon primordial heterogeneity preservation in the models remain unknown. Indeed, material properties that govern the rheology of the lower mantle are ill-constrained.

In this study, we use state of the art 2D numerical models with a spherical annulus geometry to provide a more rigorous assessment on the convective regime put forward by Ballmer et al. (2017). In particular, we explore the effects of rheological parameters on the style of mantle convection and primordial heterogeneity preservation in the models. These parameters include the temperature/pressure dependency of viscosity and the plate yielding strength. Preliminary results show that the temperature-dependency of viscosity greatly affects the dynamic style of mantle convection and compositional heterogeneity. In particular, the presence of strong slabs and weak plumes enhances primordial material fragmentation and the preservation of slab graveyards in the lower mantle. This gives rise to a complex compositional heterogeneity pattern consisting of both primordial and subducted slab material within the lower mantle. The plate yielding strength governs the abundancy of subducting slabs in the numerical models. Our results shed light on the control of rheological parameters on mantle dynamics and mixing in numerical convection models, and are useful for addressing the long-standing debate of the feasibility of primordial heterogeneity in the Earth's mantle.

[3] Ballmer, M.D., Houser, C., Hernlund, J.W., Wentzcovitch, R.M. and Hirose, K. (2017). Persistence of strong silica-enriched domains in the Earth's lower mantle, supplementary material. Nature Geoscience, 10(3), 236-240.

[2] Gebhardt, D., Gülcher, A. J. P., Ballmer, M.D. and Tackley, P.J., (In preperation). Variable dynamic styles of primordial heterogeneity preservation in Earth's lower mantle.

Strain-dependent weakening in Earth's lower mantle and its control on convection dynamics

- Anna J.P. Gülcher
  Geophysical Fluid Dynamics group, Institute of Geophysics, ETH Zürich, Switzerland
  anna.guelcher@erdw.ethz.ch

- Gregor J. Golabek
  Bavarian Geo Institute, University of Bayreuth, Germany

- Maxim D. Ballmer Geophysical Fluid Dynamics group, Institute of Geophysics, ETH Zürich, Switzerland
  UCL Earth Sciences, London, UK

- Paul J. Tackley
  Geophysical Fluid Dynamics group, Institute of Geophysics, ETH Zürich, Switzerland

The lower mantle is the largest geochemical reservoir in the Earth's interior, and it controls the style of mantle convection and, through it, the evolution of our planet. The nature of mantle dynamics – such as whether convection involves the entire lower mantle or not – remains controversial. The main constituents of lower-mantle rocks are bridgmanite (Br) and smaller amounts of ferropericlase (Fp). Bridgmanite is substantially stronger than ferropericlase [Yamazaki and Karato, 2001], and recent studies have revealed that the ferropericlase accommodates most strain when the multiphase material is deforming [Girard et al., 2016]. It is suggested that for large strain deformation, the lower mantle material rheologically weakens due to the interconnection of the weaker ferropericlase [Yamazaki and Karato, 2001; Girard et al., 2016]. This indicates that shear localization may exist in the lower mantle, potentially causing the formation of compositionally distinct domains, possibly primordial in composition [Ballmer et al., 2017]. Therefore, the rheological nature of bridgmanite-ferropericlase aggregates (see Figure) may be crucial for the dynamics of mantle convection.

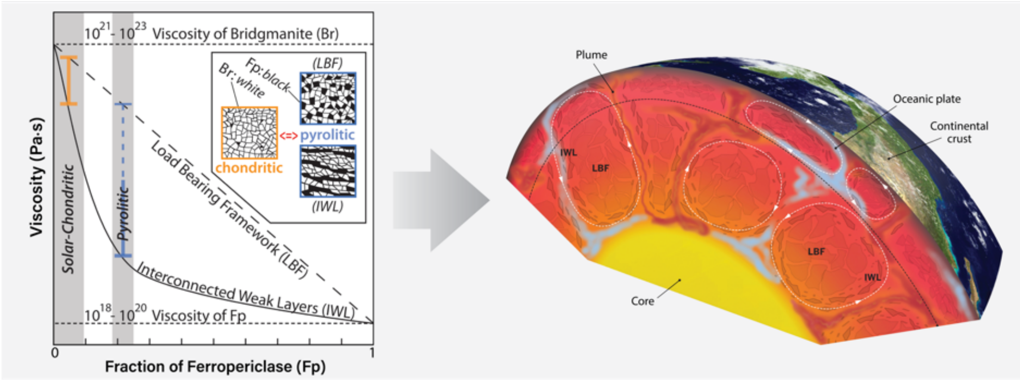
To better understand the feedback between the viscosity structure obtained by deforming Br-Fp aggregates and the dynamics of mantle convection, we present 2D numerical models of thermomechanical convection in a spherical annulus geometry that includes a new implementation of tracking the strain ellipse at each tracer through time. We apply a simplified strain weakening model that allows lower mantle materials to rheologically weaken once a certain strain threshold has been reached, and test the first-order effect of strain weakening on convection dynamics in the lower mantle. Preliminary results indicate that strain localizes along both up- and downwellings in the lower mantle and that rheological weakening has a stabilizing effect on these conduits. Our results form an first step towards future investigations on the effects of the rheological behaviour of varying Br-Fp mixtures on mantle dynamics. This is essential for addressing the feasibility of isolated domains – and long-lived geochemical reservoirs - in Earth's lower mantle.

[1] Ballmer, M.D., Houser, C., Hernlund, J.W., Wentzcovitch, R.M. and Hirose, K. (2017). Persistence of strong silica-enriched domains in the Earth's lower mantle, supplementary material. Nature Geoscience, 10(3), 236-240.

[2] Chen, J. (2016). Lower-mantle materials under pressure. Science, 351(6269), 122-123.

[3] Girard, J., Amulele, G., Farla, R., Mohiuddin, A. and Karato, S.I. (2016). Shear deformation of bridgmanite and magnesiowüstite aggregates at lower mantle conditions. Science, 351(6269), 144-147.

[4] Yamazaki, D., & Karato, S. I. (2001). Some mineral physics constraints on the rheology and geothermal structure of Earth's lower mantle. American Mineralogist, 86(4), 385–391.



Left: bulk viscosity of Br-Fp mixtures as a function of Fp fraction (from Ballmer et al., 2017). The rheology of lower-mantle materials is bracketed by the "load-bearing framework" (LBF) model and the non-linear "inter-connected weak layers" (IWL) model. Right: suggested mantle convection dynamics in which shear localization induces IWL along slabs or plumes and mixing is less efficient for the LBF part of the lower mantle (modified from Chen, 2016)

Comparison of StagYY and ASPECT 2D mantle convection codes in achieving plate-like mantle convection

- Erin Heilman
  Jackson School of Geosciences, University of Texas at Austin
  erin.heilman@utexas.edu

- Thorsten W. Becker
  Jackson School of Geosciences, University of Texas at Austin

Plate tectonics like mantle convection depends on the Rayleigh number, rock rheology including plastic yield stress, and heating mode. Previous models show Earth like plate dynamics, but the mechanisms behind yielding and the relationship between rock mechanics and models remain debated (e.g. Bercovici, 2003; Tackley, 2000, Korenaga, 2017). Here we experiment with these parameters and the formulation of compressibility and temperature dependent viscosity using two mantle convection codes, a version of StagYY (Tackley, 2008) and the latest version of ASPECT (Heister et al., 2017). StagYY uses a multi-grid solver and finite-volume schemes for solving the conservation equations, while ASPECT utilizes finite elements and has adaptive mesh refining capabilities (Heister et al, 2017; Tackley, 2008). We seek to understand any differences in the results which might depend on the numerical approach and the transitions between mantle convection styles, and explore the convective and rheological parameters for both compressible and incompressible fluid formulations for 2D cylindrical models. Results are analyzed in terms of computational efficiency and accuracy, as well as the parameter space under which plate-like convection arises.

[1] Bercovici, D., 2003. The generation of plate tectonics from mantle convection. Earth and Planetary Science Letters, 205(3-4), pp.107-121.

[2] Heister, T., Dannberg, J., Gassmöller, R. and Bangerth, W., 2017. High accuracy mantle convection simulation through modern numerical methods–II: realistic models and problems. Geophysical Journal

[3] Korenaga, J., 2017. Pitfalls in modeling mantle convection with internal heat production. Journal of Geophysical Research: Solid Earth, 122(5), pp.4064-4085.

[4] Tackley, P.J., 2000. Self-consistent generation of tectonic plates in time-dependent, three-dimensional mantle convection simulations. Geochemistry, Geophysics, Geosystems, 1(8).

[5] Tackley, P.J., 2008. Modelling compressible mantle convection with large viscosity contrasts in a three-dimensional spherical shell using the yin-yang grid. Physics of the Earth and Planetary Interiors, 171(1-4), pp.7-18.

LLSVPs of primordial origin: Implications for the evolution of plate tectonics

- Philipp Hellenkamp
  Institute for Geophysics, University of Münster, Germany
  p_hell02@uni-muenster.de

- Claudia Stein
  Institute for Geophysics, University of Münster, Germany

- Ulrich Hansen
  Institute for Geophysics, University of Münster, Germany

Early periods of Earth's history are of great interest for the evolution of plate tectonics. For instance, neither the formation of lithospheric plates nor the nature of Archean plate tectonics is well known. As a remnant of the magma ocean period, a compositionally dense layer at the core-mantle boundary is assumed to interact with the convective flow of the Earth's mantle forming todays LLSVPs. Since plate motions are strongly coupled to the convection of mantle material, stabilizing effects of compositionally dense material have a profound impact on mantle convection and plate tectonics and will be of major importance for its evolution.

To investigate the influence of a dense basal layer, we use a numerical approach employing thermo-chemical mantle convection models with self-consistent plate generation. Considering different possible scenarios of the post magma ocean period we analyze the influence of different parameters, i.e. the density contrast between the dense basal material and the ambient mantle and the volume of the enriched layer.

Generally we observe that a stagnant lid forms which is initially mobilized episodically before turning to a permanently mobile surface. However, the temporal evolution of the episodic stage is considerably altered due to the presence of dense basal material. The time when an episode occurs, is determined by the mechanism which induces this mobilization. The mechanism itself is controlled by the density and volume of the enriched layer. Therefore, we distinguish between four different initiation mechanisms, which occur for different configurations of the density and volume of enriched material.

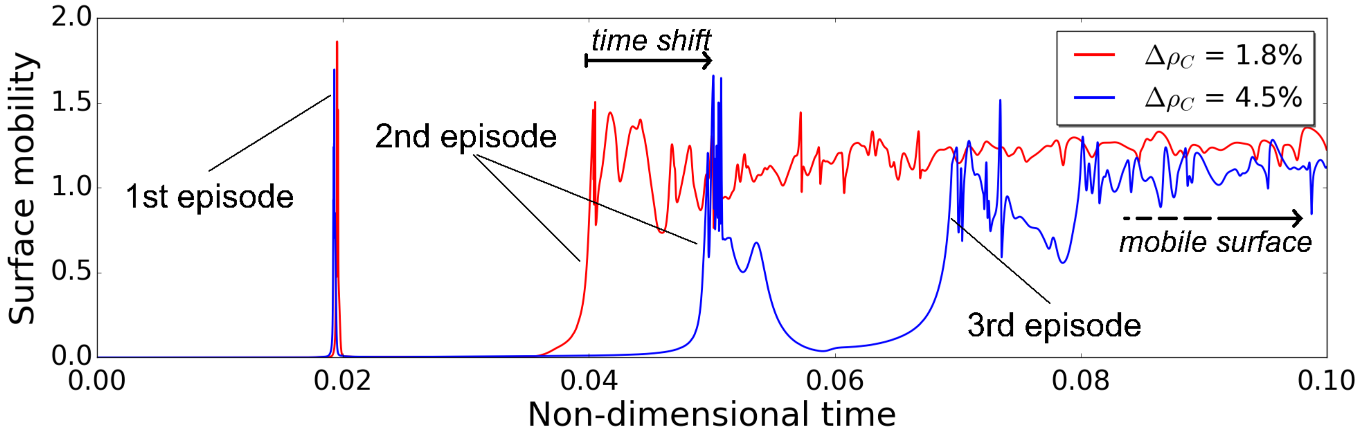


Figure 1: Characteristic temporal evolution of the surface mobility for a system which contains an enriched basal layer. Here shown exemplary for a layer volume of 5% with a density excess of 1.8% (red line) and 4.5% (blue line). The example demonstrates the altered number and the delay of mobilization episodes which both occur as the LLSVP density is varied.

Latent Variable Approach to Analysis of Seismic Tomography

- John Hernlund
  Earth-Life Science Institute (ELSI), Tokyo Institute of Technology
  hernlund@gmail.com
- Christine Houser
  Earth-Life Science Institute (ELSI), Tokyo Institute of Technology
- Vedran Lekic
  Department of Geology, University of Maryland

We have developed an entirely new method for analyzing lack of correlation between S and P wave velocity variations in the Earth's mantle, akin to "latent variable" methods used in other fields. We wish to know the extent to which temperature T variations alone can explain both S and P wave velocity variations in the Earth's lower mantle, or whether some other variable X (say) is required. Here, X could represent a composition variation, a phase variation, change in the pairing of electron spin-states, or variations in any material property that influences seismic velocity differently than temperature alone. The usual approach is to identify a candidate for X from the outset, apply estimates of the conversion factors between X (as well as T) and seismic velocities, and attempt to map and measure the size of of variations in X directly. In our new approach, instead of assuming any *a priori* knowledge regarding the nature of X, we seek to maintain complete ignorance about what X might be or how it may influence seismic velocities. The goal is to map out the entire parameter space of possibilities for any kind of X, and then to decide *a posteriori* whether any of the patterns (and relations to T) that emerge from the parameter space search may correspond to particular kinds of physical and/or chemical properties.

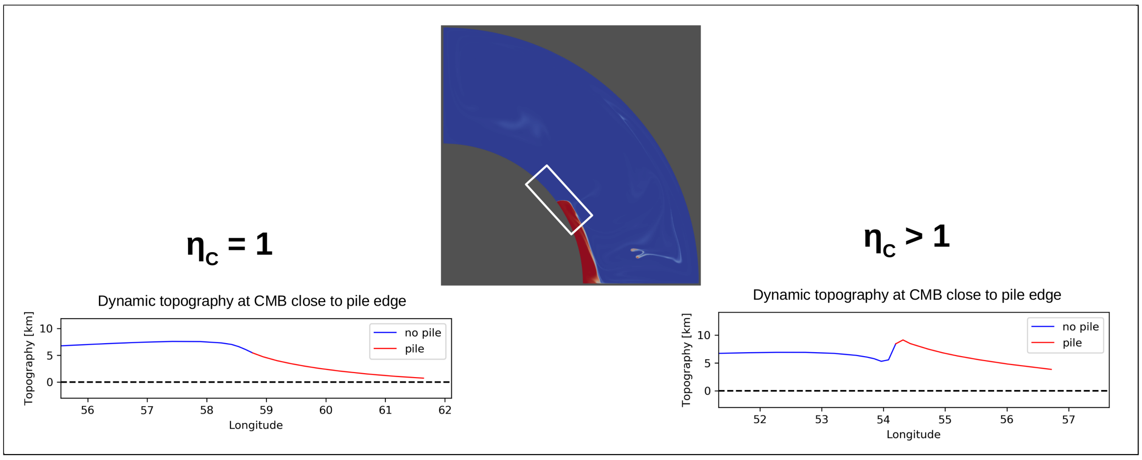
Linearly inverting 2 velocities for 2 variables requires at least 4 coefficients, giving rise to 4 apparent degrees of freedom (conversion factors for S and P velocities for each of T and X). This is a problem because we do not initially assume anything about X, which means that we will need to search a 4-parameter space in order to see what kind of patterns might arise. However, a parameter space with 4-degrees of freedom is practically difficult to address, even though it is the simplest situation one could envision for the latent variable problem. And while we might be able to constrain T-dependent coefficients based on mineral physics data, there remains a significant range of uncertainty in temperature mapping that also needs to be addressed.

Our preliminary results reveal a range of solutions for X at different depth ranges in the mantle. In the mid-lower mantle there are many possible solutions for X, some of which form coherent structures. In the lowermost ≈800 km of the mantle, the non-proportional variation between S and P velocity variations associated with the large low shear velocity provinces (LLSVP, where S decreases faster than P) dominates in slow regions, while a signal consistent with post-perovskite (S faster than P) can be separated in the bottom ≈300 km of the mantle.

Core-mantle boundary topography and its relation to lowermost mantle viscosity structure

- Björn H. Heyn
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway
  b.h.heyn@geo.uio.no
- Clinton P. Conrad
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway
- Reidar G. Trønnes
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway
  Natural History Museum, University of Oslo, Norway

In order for the large low shear velocity provinces (LLSVPs) in the lowermost mantle to be chemically distinct from the rest of the convecting mantle, their properties such as density and viscosity must differ significantly from the ambient mantle. Previous studies have shown the importance of increased density to stabilize such large-scale thermochemical piles at the base of the mantle. More recently, it has been shown that an increase of intrinsic pile viscosity by about one order of magnitude will reduce long-term entrainment of the piles significantly, thus extending the lifetime of primordial LLSVP structures. The combination of excess density and increased viscosity can be explained, for example, by enrichment in iron-rich bridgmanite during the magma ocean stage of planetary evolution. Since these pile structures take active part in mantle convection by influencing its large-scale flow pattern, e.g. by affecting the source locations of plumes, we expect to see the influence of the LLSVPs on the core-mantle boundary (CMB) topography. Based on numerical models in a 2-D annular geometry, we calculate the dynamic topography for various pile densities and viscosities with special focus on the interface between piles and plumes. While the long-wavelength component of topography beneath the pile is mostly affected by the pile density, we identify a prominent short-wavelength pattern at the edge of the pile that allows us to discriminate piles with an intrinsic viscosity increase from those without. Moreover, this specific pattern of topography exhibits a characteristic time-evolution in connection with the cycle of plumes rising from the edges of the LLSVPs. Detection of this topography fluctuation, if seismologically possible, would allow us to predict locations from which a plume will rise in the near future, even though the plume head has not started to detach itself from the lower thermal boundary layer. The amplitude of the fluctuations may provide a constraint on the magnitude of the viscosity contrast between the thermochemical piles and lower mantle material that surrounds it.

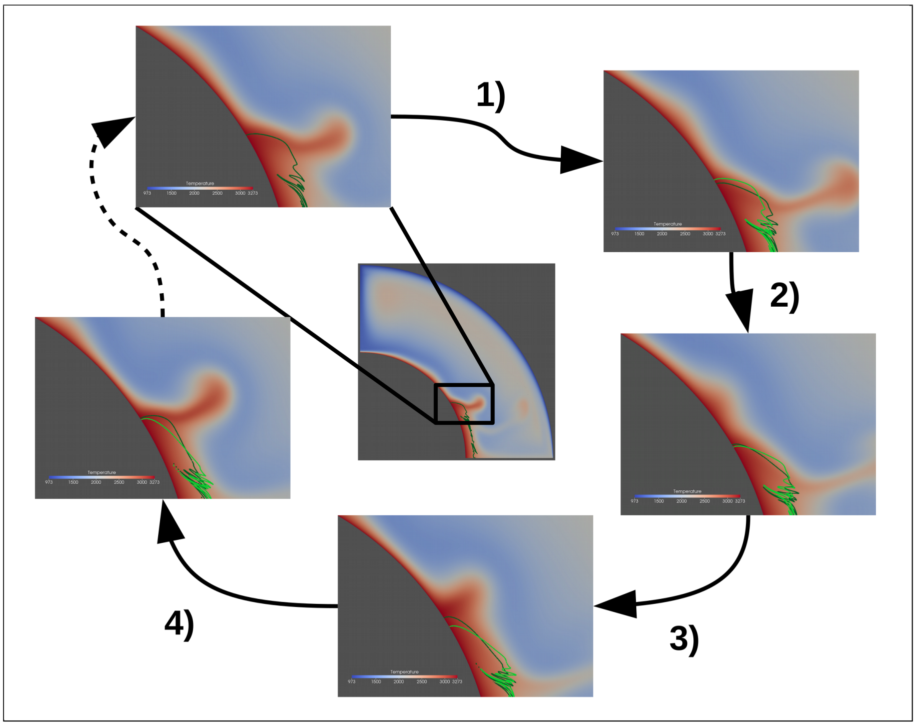


A compositional viscosity contrast η_C between pile (red) and ambient mantle (blue) can be identified by a small topographic depression (lower right) which is absent if the pile does not have a higher intrinsic viscosity (lower left).

Periodic plume generation at the edges of thermochemical piles

- Björn H. Heyn
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway
  b.h.heyn@geo.uio.no
- Clinton P. Conrad
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway
- Reidar G. Trønnes
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway
  Natural History Museum, University of Oslo, Norway

Deep-rooted mantle plumes are thought to be originating from the margins of the Large Low Shear Velocity Provinces (LLSVPs) visible in seismic tomography. Lateral mantle flow is forced upwards as these edges, but it is not well understood under which circumstances this results in a plume. In this study, we show that plumes interacting with the margin of a dense thermochemical pile temporarily increases its local thickness, until material at the pile top cools down and the pile start to collapse back towards the core-mantle boundary (CMB) under the influence of gravity. This causes the dense material to spread along the CMB against the dominant flow direction towards the pile, which causes a local thickening of the lower thermal boundary layer and the beginning of a new plume. The resulting plume cycle is reflected in the lateral motion of the local pile margin and its thickness up to a few degree into the pile, while the general thickness of the pile is not affected. The frequency of plume generation is mainly controlled by the rate at which slab material is transported to the CMB, thus the subduction velocity and the sinking rate of slabs in the lower mantle, which is depending on slab viscosity and the temperature-dependence of viscosity.



The plume cycle: a rising plume increases local pile thickness (1) until the pile top cools down and the plume cannot support the pile any longer (2). The pile then collapses under influence of gravity (3) and spreads along the CMB, thereby triggering a new plume (4). Dark green lines indicate the current pile shape, light green makes the shape of the previous snapshot; the background shows the temperature field.

Numerical insights into craton formation and stabilisation

- Charitra Jain
  Department of Earth Sciences, Durham University, Durham, United Kingdom
  charitra.jain@durham.ac.uk

- Antoine B. Rozel
  Institute of Geophysics, Department of Earth Sciences, ETH Zurich, Zurich, Switzerland

- Emily J. Chin
  Scripps Institution of Oceanography, UC San Diego, La Jolla, United States

- Jeroen van Hunen
  Department of Earth Sciences, Durham University, Durham, United Kingdom

Geophysical, geochemical, and geological investigations have attributed the stable behaviour of Earth's continents to the presence of strong and viscous cratons underlying the continental crust. The cratons are underlain by thick and cold mantle keels, which are composed of melt-depleted and low density peridotite residues [1]. Progressive melt extraction increases the magnesium number Mg# in the residual peridotite, thereby making the roots of cratons chemically buoyant [2, 3] and counteracting their negative thermal buoyancy. Recent global models have shown the self-consistent production of Archean continental crust by two-step mantle differentiation [4]. These models exhibit intense recycling of crust with delamination and eclogitic dripping in the first 500 million years and this behaviour is similar to the "plutonic-squishy lid" that has been suggested for the early Earth. However, no stable continents form and no major regime transition from "vertical tectonics" towards "horizontal tectonics" is observed. This points to the missing ingredient of cratonic lithosphere in these models, which could act as a stable basement for the crustal material to accumulate on and may help initiate plate tectonics. Based on the bulk FeO and MgO content of the residual peridotites, it has been proposed that cratonic mantle formed by hot shallow melting with mantle potential temperature, which was higher by 200-300 °C than present-day [5]. We aim to introduce Fe-Mg partitioning between mantle peridotite and melt to track the Mg# variation through melting, and parametrise craton formation using the corresponding P-T formation conditions.

[1] Boyd, F. R. High-and low-temperature garnet peridotite xenoliths and their possible relation to the lithosphere-asthenosphere boundary beneath Africa. In Nixon, P. H. (ed.) *Mantle Xenolith*, 403–412 (John Wiley & Sons Ltd., 1987)

[2] Jordan, T. H. Mineralogies, densities and seismic velocities of garnet lherzolites and their geophysical implications. In *The Mantle Sample: Inclusion in Kimberlites and Other Volcanics*, 1–14 (American Geophysical Union, Washington, D. C., 1979)

[3] Schutt, D. L. & Lesher, C. E. Effects of melt depletion on the density and seismic velocity of garnet and spinel lherzolite. *Journal of Geophysical Research* **111** (2006)

[4] Jain, C., Rozel, A. B., Tackley, P. J., Sanan, P. & Gerya, T. V. Growing primordial continental crust self-consistently in global mantle convection models. *Gondwana Research* **73**, 96–122 (2019

[5] Lee, C.-T. A. & Chin, E. J. Calculating melting temperatures and pressures of peridotite protoliths: Implications for the origin of cratonic mantle. *Earth and Planetary Science Letters* **403**, 273–286 (2014)

Growing primordial continental crust self-consistently in global mantle convection models

- Charitra Jain
  Department of Earth Sciences, Durham University, Durham, United Kingdom
  Institute of Geophysics, Department of Earth Sciences, ETH Zurich, Zurich, Switzerland
  charitra.jain@durham.ac.uk

- Antoine B. Rozel
  Institute of Geophysics, Department of Earth Sciences, ETH Zurich, Zurich, Switzerland

- Paul J. Tackley
  Institute of Geophysics, Department of Earth Sciences, ETH Zurich, Zurich, Switzerland

- Patrick Sanan
  Institute of Geophysics, Department of Earth Sciences, ETH Zurich, Zurich, Switzerland

- Taras V. Gerya
  Institute of Geophysics, Department of Earth Sciences, ETH Zurich, Zurich, Switzerland

The majority of continental crust formed during the hotter Archean was composed of Tonalite-Trondhjemite-Granodiorite (TTG) rocks. In contrast to the present-day loci of crust formation around subduction zones and intra-plate tectonic settings, TTGs are formed when hydrated basalt melts at garnet-amphibolite, granulite or eclogite facies conditions. Generating continental crust requires a two step differentiation process. Basaltic magma is extracted from the pyrolytic mantle, is hydrated, and then partially melts to form continental crust. Here, we parameterise the melt production and melt extraction processes and show self-consistent generation of primordial continental crust using evolutionary thermochemical mantle convection models. To study the growth of TTG and the geodynamic regime of early Earth, we systematically vary the ratio of intrusive (plutonic) and eruptive (volcanic) magmatism, initial core temperature, and internal friction coefficient. As the amount of TTG that can be extracted from the basalt (or basalt-to-TTG production efficiency) is not known, we also test two different values in our simulations, thereby limiting TTG mass to 10% or 50% of basalt mass. For simulations with lower basalt-to-TTG production efficiency, the volume of TTG crust produced is in agreement with net crustal growth models but overall crustal (basaltic and TTG) composition stays more mafic than expected from geochemical data. With higher production efficiency, abundant TTG crust is produced, with a production rate far exceeding typical net crustal growth models but the felsic to mafic crustal ratio follows the expected trend. These modelling results indicate that (i) early Earth exhibited a "plutonic squishy lid" or vertical-tectonics geodynamic regime, (ii) present-day slab-driven subduction was not necessary for the production of early continental crust, and (iii) the Archean Earth was dominated by intrusive magmatism as opposed to "heat-pipe" eruptive magmatism.

Multivariate statistics of mantle convection models generating plate-like tectonics

- Alexandre Janin
  Laboratoire de Géologie, Ecole Normale Supérieure, Paris (France)
  alexandre.janin@ens.fr

- Marie Bocher
  E.T.H. Zurich

- Nicolas Coltice
  Laboratoire de Géologie, Ecole Normale Supérieure, Paris, France

Making the connection between observations connected to mantle flow (heat flow, kinematics, stresses, uplift and subsidence rates, gravity, topography) requires having a good understanding of the statistics of both physical models and measurements. The goal of this poster is to focus on the statistics of 3D spherical mantle convection models of mantle convection that generate plate-like tectonics. We first compute long time series of convective flows for several models changing the rheological parameters and the heating modes. To obtain a relevant statistics, we run them for more and 100 billion years each.

From these datasets, we compute one-point statistics, extracting the probability distribution functions and correlation times. As observed by Yanagisawa and Hamamo (1999), the skewness depends on the heating mode: internal heat generates homogeneous hot volumes with cold small areas corresponding to subducting slabs.

We then compute two-point spatial correlations to estimate how the heat flow information at the surface and the velocity correlate with the temperature field inside the system. We extract radial and lateral correlation functions showing that the viscosity jump at 660 km reduces the correlation between the surface and the deep mantle. We also show that the radial correlation of the temperature field is substantial within 1000 km in the interior of the flow, and reaches 2000 km in thermal boundary layers. The maximum sensitivity of the velocity is smaller than the heat flow, but exceeds the depth of the boundary layer.

From this preliminary study, we show that the correlation between the surface and the interior are promising to perform inversion of the mantle temperature field from geophysical observations.

On the accuracy of gravity fields and their derivatives obtained with Newton integrals on a hollow sphere tessellated with hexahedra

- Ludovic Jeanniot
  Utrecht University, Netherlands
  l.jeanniot@uu.nl

- Cedric Thieulot
  Utrecht University, Netherlands

- Bart Root
  TU Delft, Netherlands

- Wim Spakman
  Utrecht University, Netherlands

In order to compute synthetic Earth gravity data one must define a spherical geometry which is filled with a density model from the crust to deep mantle. We use the direct integration method to compute globally gravity acceleration, gravity anomalies, potential and gradients.

We have written a gravity post-processor plugin for this task in the state of the art ASPECT finite element code [Heister et al, GJI 2017].

We first present the results of a benchmark for the gravity post-processor plugin using a hollow sphere filled with a constant density of 3300 kg/m^3:

- Gravity fields and their derivatives are then calculated at 10 locations above the hollow sphere surface, and compared to their analytical solution.

- We perform a series of numerical experiments to test the sensitivity of gravity computation on the numerical discretisation of the hollow sphere, the quadrature order and the altitude at which gravity is calculated.

We find that the hollow sphere must have a high resolution - at least near surface - to obtain an error in gravity anomalies of an order lesser than the milligal. We therefore use the mesh refinement capabilities of ASPECT to increase resolution towards the model surface.

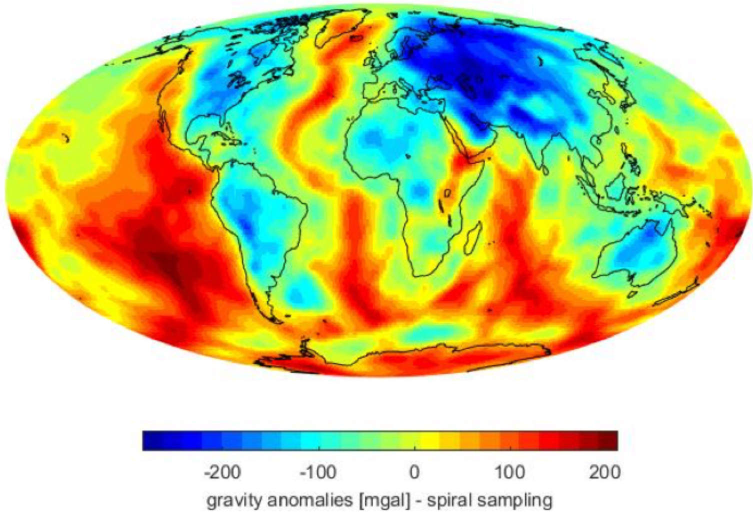
We then present the results of a second benchmark where gravity is calculated to only the MOHO:

- A density of 0 is set for the continental and oceanic crust, above a mantle of density 450 kg/m^3.

- We compare gravity prediction from the direct integration method in ASPECT with a spherical harmonic code.

Both codes give similar results but discrepancies of gravity anomalies exist at the ocean-continent transition.

Finally, three density models are tested separately: a density fields obtained from SL2013 and S40RTS tomographic models for the deep mantle, and the density model CRUST1.0 for the thin upper lithosphere layer. We combine these 3 datasets into one to create a composite model which is compared to the global seismic model LLNL-G3D-JPS of Simmons et al. (2015). We test the sensitivity of gravity prediction on the use of various conversion scaling factors of shear wave velocity to density. We find that the scaling factor profile also has a major impact on gravity prediction.



Gravity anomalies for CRUST1.0. The density of the mantle beneath CRUST1.0 is set at 3300 $kg.m^{-3}$.

Testing the small timestep approach

- Tim Jones
  Carnegie Institution for Science
  tjones@carnegiescience.edu

- Nate Sime
  Carnegie Institution for Science

- Cian Wilson
  Carnegie Institution for Science

- Peter van Keken
  Carnegie Institution for Science

The finite element (FE) method is used simulate a range of geodynamic phenomena, including subduction zones, plume dynamics, fluid migration and whole mantle thermochemical convection. Such geodynamic problems often have strongly nonlinear solutions, making the computation particularly challenging. A common approach is to compute a linearized solution by assuming that a small enough timestep will effectively reduce the impact of nonlinearity on the solution – the small timestep approximation. It is worthwhile examining how such an approximation fairs under commonly formulated constitutive relations used in geodynamic models. Here we present simplified model problems using isoviscous to highly nonlinear viscoplastic rheologies. We test, for each case, how a small timestep strategy performs against a full nonlinear solve using Newton's method.

Using geodynamic models to test plate tectonics scenarios for Alpine mountain building

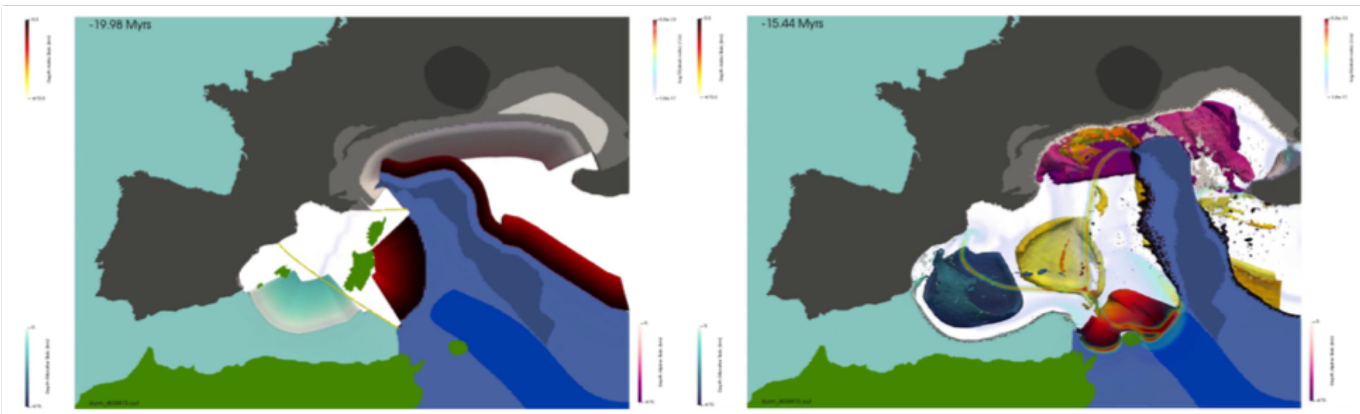
- Boris J.P. Kaus
  Johannes-Gutenberg-University Mainz

- Eline Le Breton
  Free University, Berlin

Using geological and geophysical data, it is possible to reconstruct the past motion of the plates involve in the Alpine orogeny and propose possible scenarios for their geological evolution. Those scenarios have not yet been tested for geodynamic consistency.

Here, we show results of 3D thermomechanical geodynamic simulations of the Alps starting with plate tectonic reconstructions at 20 Ma based on the work of Le Breton et al. (2017). The models include viscoelastoplastic rheologies and a free surface, and thus simulate the spontaneous occurrence of shear zones. Whereas the models are started with plate tectonic reconstructions, many details of these models, such as subduction angle, length of the subducted plates, their thermal structure as well as their rheology, are unknown. The models are run forward in time to see to which extend they are consistent with kinematic reconstructions. Perhaps unsurprisingly, our initial modelling attempts show a wide variety of behavior, including many slab break off events and slab rollbacks in various directions. Yet, in all cases tested so far, the model evolution does not follow what has been inferred for the Alps, with Adria frequently moving towards the east rather than to the west, no Alpine chain forming and in some cases new subduction zones developing within the Mediterranean that swallow Sardinia and Corsica. This thus reiterates the difficulty of reproducing geological scenarios with dynamically consistent models and shows that more work is required to come up with consistent plate tectonic and geodynamic scenarios, with a multi-disciplinary collaboration.

[1] Le Breton E, Handy MR, Molli G, Ustaszewski K (2017) Post-20 Ma Motion of the Adriatic Plate: New Constraints From Surrounding Orogens and Implications for Crust-Mantle Decoupling. Tectonics 36:3135–3154. doi: 10.1002/2016TC004443



Results of 3D geodynamic simulations, based on plate-tectonic reconstructions, showing a map view, with the 3D geometry of slabs, colored by their respective depth.

Tidal dissipation in Io's and Europa's silicate mantle: Influence of a partially molten layer

- Mathilde Kervazo
  Laboratoire de Planétologie et de Géodynamique, Université de Nantes, UMR-CNRS 6112
  mathilde.kervazo@univ-nantes.fr

- Gabriel Tobie
  Laboratoire de Planétologie et de Géodynamique, Université de Nantes, UMR-CNRS

- Gaël Choblet
  Laboratoire de Planétologie et de Géodynamique, Université de Nantes, UMR-CNRS

- Caroline Dumoulin
  Laboratoire de Planétologie et de Géodynamique, Université de Nantes, UMR-CNRS

- Marie Běhounková
  Charles University, Prague, Czech Republic

Io, the inner most of Jupiter's Galilean satellites, is the most volcanically active, and probably one of the most remarkable body in the outer Solar System [1]. The presence of a subsurface ocean on the second Galilean moon Europa [2], along with the spectacular volcanic activity exhibit by its neighboring satellite Io, raise the possibility of seafloor volcanoes [3], which has major implications for Europa's ocean habitability.

Combined radiogenic heating and tidal heating could sustain partial melting in Europa's mantle during billions of years [4], especially during periods of enhanced eccentricity which may lead to melt accumulation in the asthenosphere [5]. Evaluating the coupling between melt generation and heat production is essential to assess the possibility of sea floor volcanism on Europa and to understand the mechanism at the origin of the tidally-induced volcanism on Io.

In the present study, we model the viscoelastic deformation of Io's and Europa's mantle using an Andrade rheology. We test the influence of a molten layer, assuming different rheological laws for the influence of partial melt on anelastic properties of rocks. A simplified parameterization for melt production and extraction will be used to determine for each tested astenosphere configuration whether an equilibrium between heat generation and extraction can be reached or not. For Io, we determine the rheological structure of the silicate mantle (lithosphere/molten astenosphere) required to explain the present-day heat budget and the heat flux pattern. For Europa, we estimate the maximal heat production that could be generated by considering different molten layer configuration and different eccentricity values.

[1] Lopes, R. M., and Williams, D. A., Io after Galileo. Reports on Progress in Physics, 68(2), 303 (2005).
[2] Khurana, KK., et al., Nature, Vol. 395, pp. 777 (1998).
[3] Thomsom, R. and Delaney, J., JGR: Planets, Vol. 106, pp. 12355-12365 (2001).
[5] Běhounková, M. et al., Sustainability of the melting in the silicate mantle of Europa, EPSC (2019).
[5] Moore, W. et al., Thermal evolution of Europa's silicate mantle, Europa (2009).

The Asthenosphere and Mantle Dynamics

- Scott D. King
  Department of Geosciences, Virginia Tech, Blacksburg, VA, USA
  sdk@vt.edu

As unlikely as it may seem, it is the properties of the asthenosphere that control the structure and evolution of the mantle. The two large low shear velocity provinces (LLSVPs) in the lower mantle represent the two primary regions of upwelling lower mantle and neither LLSVP is directly associated with a plate boundary. While it is commonly asserted that the pattern of plate motions reflects the pattern of mantle convection, this lower mantle pattern regulates the transportation of primitive material from the deep mantle to the surface. The viscosity of the asthenosphere has a profound effect on the pattern of deep mantle thermal anomalies. If the asthenosphere is weaker than the upper mantle by more than an order of magnitude, then one or two large plumes dominate the lower mantle structure, consistent with the structure we observe today. If, on the other hand, the asthenosphere is less than an order of magnitude weaker than the upper mantle, then narrow cylindrical upwellings and cold down going sheets dominate the entire mantle flow pattern and this flow reflects the near surface flow pattern. I present 3D spherical convection calculations that span the age of the Earth with decreasing concentrations of heat producing elements, a cooling core boundary condition, and a mobile lid. Whether the lid is mobile or stagnant has the most significant effect on the mantle thermal evolution; however the choice of mobile versus stagnant lid has little effect on the distribution of hot and cold anomalies within the mantle.

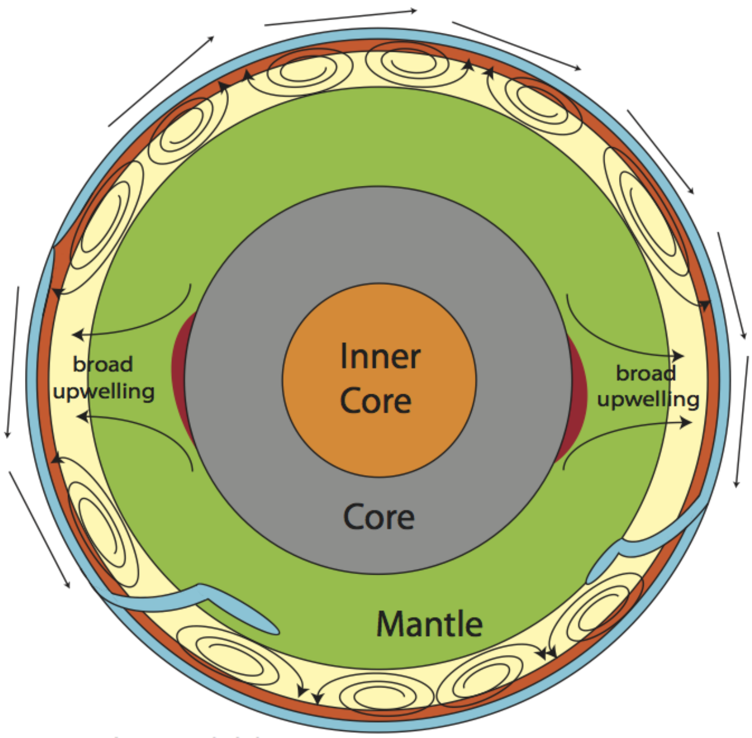


Plate velocities, subducted slabs, and LLSVPs show that plate motions and lower mantle flow are decoupled, consistent with the presence of a weak asthenosphere.

Anisotropic viscosity of olivine: the relationship between texture parameters and rheological behavior

- Ágnes Király
  Centre for Earth Evolution and Dynamics, University of Oslo
  agnes.kiraly@geo.uio.no

- Clinton P. Conrad
  Centre for Earth Evolution and Dynamics, University of Oslo

- Lars N. Hansen
  Dept. of Earth and Environmental Sciences, University of Minnesota

Olivine, the primary mineral in the upper mantle, is anisotropic in its mechanical properties. As a result, significant shearing of the upper mantle causes olivine crystals to form a preferred orientation, which we can observe, for example, using seismic wave propagation. The crystallographic alignment of olivine grains also results in anisotropic viscous behavior that may result in significant changes in effective viscosity as the direction of flow changes. Recent laboratory measurements have provided crucial constraints on viscosity during complicated deformation paths, but are only able to test a limited number of paths, making direct application to mantle deformation difficult. Thus, in our previous work, we used the existing experiments to define and calibrate a mechanical model of slip system activity and texture development within olivine aggregates that can predict the viscous response for arbitrary deformation paths.

The textural evolution (developing LPO) and mechanical behavior of olivine aggregates are highly coupled. When the olivine crystals start to align with the shear direction, the anisotropic viscosity decreases resulting higher strain rates. The higher strain rates result in a increasingly rapid development of the shear-parallel LPO. On the other hand, if the shear direction is perpendicular to the LPO the viscosity increases, resulting lower strain rates and slower changes in the LPO direction.

Here we use the previously calibrated micro-mechanical and texture development models to explore the mechanical response of an olivine aggregate for a wide range of deformation paths that are relevant to shearing the upper mantle. We analyze a large set of models to better understand the relationship between parameters describing the rheology of the aggregate (e.g. the anisotropic fluidity tensor) and parameters that describe the texture, such as the M- or J-index or the different distribution parameters (Point, Girdle and Random) of each main axis.

Our results show that the rheology of the aggregate mainly depends on the distribution and the mean orientation of the olivine a-axis, while the distribution of the b-axis and the c-axis is less relevant on the mechanical behavior.

Anisotropic viscosity can have large effects on plate motions, the initiation and the dynamics of subduction zones, and in general, on any geodynamic processes where the lithosphere interacts with the (anisotropic) asthenosphere. The results from this study can help to find a link between olivine texture and rheology, which can be used to better infer to the mantle rheology from seismic anisotropy studies.

Double subduction: Insights from 2D thermo-mechanical models and application to the Alps

- Jan Philipp Kruse
  Goethe University, Frankfurt am Main, Germany
  kruse@geophysik.uni-frankfurt.de

- Nikolaus Froitzheim
  IMG, University Bonn, Bonn, Germany

- Harro Schmeling
  Goethe University, Frankfurt am Main, Germany

The geodynamic evolution of the Alps as well as of the whole mediterranean region is strongly discussed since many years. A very important archive for the understanding of the evolution of moutain belts like the Alps are exhumed high- and ultrahigh-pressure metamorphic rocks. During subduction rocks can be brought to depth of more than 100 km and are maybe exhumed afterwards by different processes. One specific example is the exhumation of high- and ultrahigh-pressure rocks over- and underlain by low-pressure rocks. This process is not well understood until now.

Froitzheim et al. (2003) suggested for the Adula nappe in the Central Alps, which is such high- and ultrahigh-pressure unit described above, an exhumation concept that is related to double subduction. The aim of our study is to test their hypothesis with 2D thermo-mechanical models.

We use the 2D finite-difference code FDCON (Schott & Schmeling, 1998) with a geometrical setup according to the geological reconstrution of Froitzheim et al. (2003). FDCON includes the marker-in-cell method, a free surface approximation (Crameri et al., 2012) and an erosion/sedimantation equation (Yang et al., 2018).

The first goal is to explore the conditions under which a second subduction zone is activated by varying the convergence velocity as well as the viscosity of a weak zone at which the second subduction is believed to initiate. Afterwards we compare our synthetic pressure and temperature conditions (and their gradients) of specific lithological units with that given by Froitzheim et al. (2003).

First results show that different modes of double subduction (from distinct to rather distinct) occur and that models with convergence velocities applicable to the mediterranean region indicate exhumation of the important units. Surprisingly also the layering of the exhumed units is in good agreement with that given by Froitzheim et al. (2003).

[1] Froitzheim, N., Pleuger, J., Roller, S., 2003. Exhumation of high- and ultrahigh-pressure metamorphic rocks by slab extraction

[2] Crameri, F., Schmeling, H., Golabek, G. J., Duretz, T., Orendt, R., Buiter, S. J. H., May, D. A., Kaus, B. J. P., Gerya, T. V., Tackley, P. J., 2012. A comparison of numerical surface topography calculations in geodynamic modelling: An evaluation of the "sticky air" method

[3] Yang, H., Chemia, Z., Artemieva, I. M., Thybo, H., 2018. Control on off-rift magmatism: A case study of the Baikal Rift Zone

[4] Schott, B., Schmeling, H., 1998. Delamination and detachment of a lithospheric root

Variability of subducting slab morphologies in the mantle transition zone: Integrated petrological and thermo-mechanical modeling

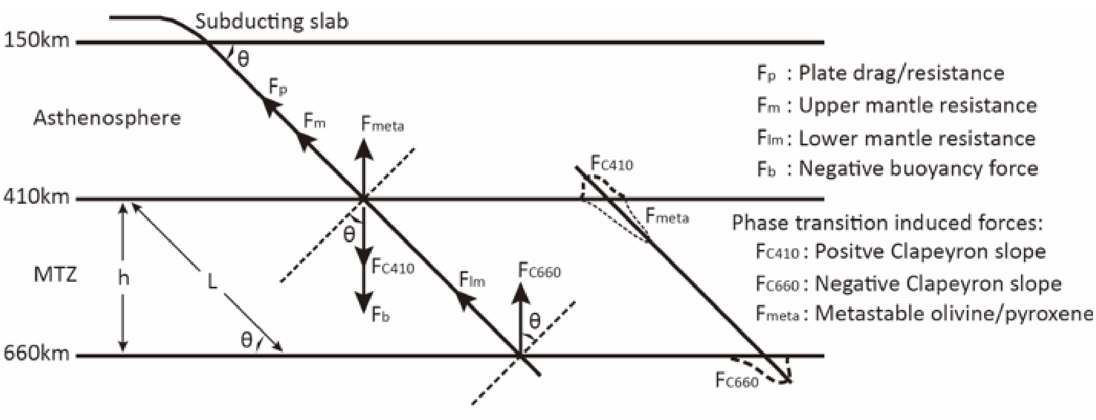
- Zhong-Hai Li
  University of Chinese Academy of Sciences, China
  li.zhonghai@ucas.ac.cn

- Taras Gerya
  ETH-Zurich, Switzerland

- James Connolly
  ETH-Zurich, Switzerland

Variable morphologies of subducting slabs are observed in tomographic images of the mantle transition zone (MTZ), where slabs appear to stagnate in the MTZ or enter the lower mantle. These contrasting morphologies of subducting slabs are dependent on the joint effects of various dynamic, kinematic and geometric factors. Force balance analysis indicates that the favorable conditions of slab stagnation in the MTZ include old/cold slab subducting into the mantle with large Clapeyron slopes at 410 km and 660 km discontinuities, as well as the significant trench retreat and shallow dip angle. However, these conditions are often not achieved together for specific subduction zones on the Earth, which thus require systematic studies to distinguish their relative effects. Here, we analyze the slab mode selection in the MTZ based on coupled petrological-thermomechanical numerical model. The model results indicate that (1) water activity and partial melting weaken the subduction channel and form a hot and weak mantle wedge beneath the island arc that affects slab dynamics. (2) The Clapeyron slope of phase transition at 660 km can significantly contribute to the slab stagnation in the MTZ, whereas the Clapeyron slope at 410 km does not change the general mode selection, but does affect the trench motion and further the length of flattened slab. (3) A sharp viscosity jump between the lower and upper mantles can promote slab stagnation in the MTZ, which has a similar effect with a strong viscosity-depth gradient. (4) Fast trench retreat is the most critical factor controlling slab stagnation, especially the long slab flattening in the MTZ. (5) The age/thickness of converging plates can also influence the slab/MTZ interaction by modifying the slab dip angle and trench motion. (6) A thin, weak layer at the bottom of MTZ does not play significant roles in the slab mode selection. The combined force balance analysis and numerical studies are compared with the comprehensive observations of natural subduction zones, which improve understanding of the dynamics of slab/MTZ interaction and the resulting variability of subducting slab morphologies.

[1] Li et al. (2019), Variability of subducting slab morphologies in the mantle transition zone: Insight from petrological-thermomechanical modeling, Earth-Sci. Rev., https://doi.org/10.1016/j.earscirev.2019.05.018.



Slab parallel force balance: $F_{//} = (F_b + F_{C410} - F_{meta})\cdot\sin(\theta) - F_{C660}\cdot\sin(\theta) - F_p - F_m - F_{lm}$

Slab perpendicular force at 410km: $F_{\perp 410} = (F_b + F_{C410} - F_{meta})\cdot\cos(\theta)$

Slab perpendicular force at 660km: $F_{\perp 660} = (F_{C660})\cdot\cos(\theta)$

→ Slab anticlockwise rotation in the MTZ

Slab rotation torque: $M \sim F_{\perp 410}\cdot\frac{L}{2} + F_{\perp 660}\cdot\frac{L}{2} = (F_b + F_{C410} + F_{C660} - F_{meta})\cdot\cos(\theta)\cdot\frac{h}{2\sin(\theta)}$

Force balance analysis of subducting slab in the upper mantle.

How long can subducting slab survive in the mantle transition zone?

- Mingqi Liu
  Department of Earth Sciences, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich
  mingqi.liu@erdw.ethz.ch

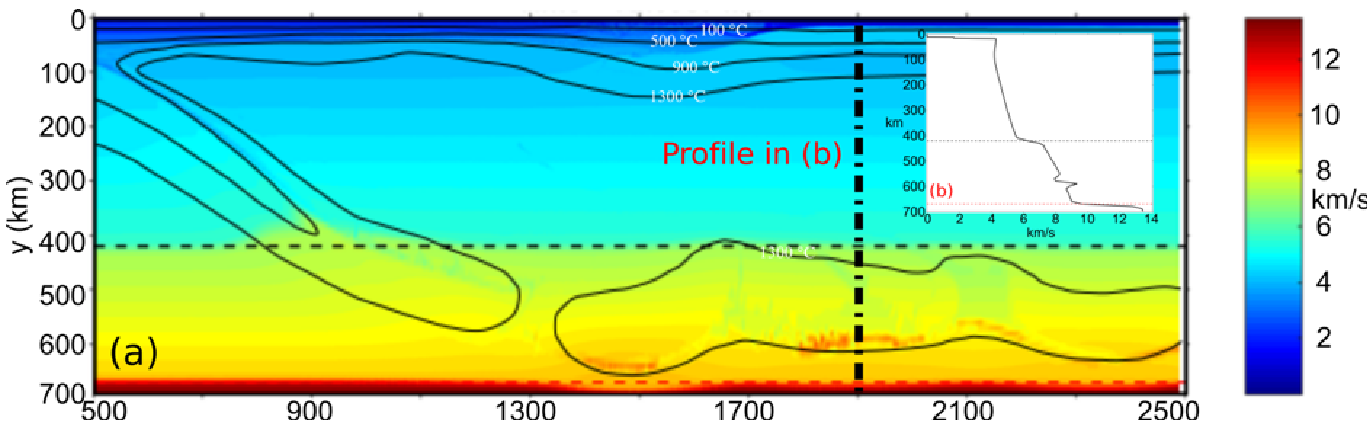
- Zhonghai Li
  College of Earth and Planetary Sciences, University of Chinese Academy of Sciences Beijing, China

- Taras Gerya
  Department of Earth Sciences, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich

Seismic tomographic image provides a modern-day snapshot of a time-dependent process and shows that most subducting slabs lie down in the mantle transition zone beneath the circum-Pacific area [Goes et al., 2017]. A number of mechanisms have been proposed to explain stagnating slabs including: phase transition in cold slabs; trench migration; weakening of the slab due to recrystallization; spatial and temporal variations in slab strength; viscosity increase with depth; and metastable transformation of olivine [King et al., 2015]. However, it is unclear whether the diversity of subducted slab geometries is a manifestation of the same process captured at different times in the lifetime of the subducting system. Also, there is little study on the stagnation time of subducting slabs in the mantle transition, which is extremely important for the geodynamic processes. In order to study the stagnation time and the controlling factors, petrological-thermo-mechanical numerical models are constructed with variables ages of the oceanic plate with(out) hydration. The model results suggest that with the stagnation time of subducting slab in the mantle transition zone, the P-wave velocity anomaly of subducting slab gradually decrease when compared with the ambient mantle. For the same stagnation time in the mantle transition zone, old subducting oceanic slab has a bigger P-wave velocity anomaly than the young slab and the subducting slab without hydration can produce a bigger P-wave velocity anomaly than with hydration. Through systematic numerical models and compared with the seismic tomographic results, we will fit formula between the seismic velocity perturbation and stagnation time in a first approximation and investigate the influence of subducting slabs on subducting system, in particular to understand the geodynamic processes.

[1] Goes S, Agrusta R, Van Hunen J, et al. (2017), Subduction-transition zone interaction: A review. Geosphere, 13(3): 644-664.

[2] King S D, Frost D J, Rubie D C. (2015), Why cold slabs stagnate in the transition zone. Geology, 43(3): 231-234.



Numerical modelling results. (a) The seismic wave velocity structure at the evolution time of 72 Ma and black lines are isotherms in °; (b) The profile of seismic wave velocity is indicated on the black dashed line in the figure (a).

Global Mantle Flow Modeling Revisited: Plateness Investigation and Large-scale Driving Mechanism for Continental Plate Motions

- Shangxin Liu
  Virginia Tech
  sxliu@vt.edu

- Scott D. King
  Virginia Tech

Plate motions and geoid (or gravitational potential) are two important constraints on mantle flow. Only a small number of previous studies (e.g., Ricard & Bai, 1991; Forte et al., 2010; and Ghosh et al., 2013) tried to fit both two surface observables in one fully dynamically-consistent global mantle flow model. While these previous studies achieve generally good fits in global geoid and plate motions, the plateness of the individual plates have not been systematically investigated yet. We construct a series of instantaneous Stokes flow models driven by the buoyancy structures from seismic tomography, well-resolved upper mantle slabs, and lithospheric thermal age to fit both the plate motions and geoid using the code ASPECT, which has been well-benchmarked in 3-D spherical shell geometry (Liu & King, 2019). We investigate the effects of the rheology and buoyancy structures on the plateness of the individual plates. There is a trade-off between the plateness and geoid fits in terms of the strength of the lithosphere. A more plate-like surface velocity requires stronger lithosphere than the one required to maintain a good geoid fit. This indicates that to fully reconcile a plate-like surface motion and geoid in one global circulation model, a horizontally-strong and vertically-weak anisotropic lithosphere may need to be considered. Well-resolved upper mantle slabs significantly improve the global plateness and the predicted continental plate motions, including the ones with only a little near-field subduction zones, such as North America. However, whether the North American plate is driven by the near-field slabs of Aleutian, central American, and Caribbean subduction zones along the margins, or by the large-scale suction induced by far-field subducting slabs remains unclear. Based on our global mantle flow models constrained by both plate motions and geoid, we further investigate the driving mechanism for the North American plate by the comparison between the models with only near-field slabs and the ones with all the global slabs. Our tests show that in addition to the marginal subduction zones, large-scale suction by the far-field slabs is an important driving force for North American plate. Continental plates are more easily coupled to this large-scale suction through their underlying strong cratonic roots. This new finding on the large-scale driving effect from the far-field slabs on the plate motions is also physically consistent with the classical theory of the surface response functions from the deep mantle buoyancy structures (e.g., Hager & O'Connell 1981).

[1] Ricard, Y., & Bai, W. (1991). Inferring the viscosity and the 3-D density structure of the mantle from geoid, topography and plate velocities. Geophysical Journal International, 105(3), 561-571.

[2] Forte, A. M., Moucha, R., Simmons, N. A., Grand, S. P., & Mitrovica, J. X. (2010). Deep-mantle contributions to the surface dynamics of the North American continent. Tectonophysics, 481(1-4), 3-15.

[3] Ghosh, A., Becker, T. W., & Humphreys, E. D. (2013). Dynamics of the North American continent. Geophysical Journal International, 194(2), 651-669.

[4] Liu, S., & King, S. D. (2019). A benchmark study of incompressible Stokes flow in a 3-D spherical shell using ASPECT. Geophysical Journal International, 217(1), 650-667.

[5] Hager, B. H., & O'Connell, R. J. (1981). A simple global model of plate dynamics and mantle convection. Journal of Geophysical Research: Solid Earth, 86(B6), 4843-4867.

A geodynamic reconstruction of the Mediterranean Subduction Zone

- Rosalia Lo Bue
  Università di Padova
  rosalia.lobue@phd.unipd.it

- Manuele Faccenda
  Università di Padova

Most of our knowledge about the subduction process comes from present-day geophysical data, such as seismic tomography, and geological data. The evolution of a subduction process is very uncertain, nevertheless it could provide important elucidations and help us understand the interaction between tectonic activity and mantle convection. The Central-Western Mediterranean region was involved in a complex subduction process, which was characterized by the rapid retreat of the Ionian slab, the opening of back-arc extensional basins, lateral tearing which split adjacent segments of the subducting lithosphere, and consequent progressive narrowing of the slab. Currently, as shown by seismic tomographies, an active subduction residue is located under the Calabro-Peloritan Arc. The present-day tectonic structure derives from the evolution of this process. Therefore, the Mediterranean offers an excellent opportunity to study the evolution of a subduction environment involving slab roll-back and tearing. Here we want to reconstruct Mediterranean basin dynamic evolution through 3D thermo-mechanical numerical modelling. We present a geodynamic reconstruction of the Mediterranean subduction zone during the last 30 Myr, performing 3D numerical experiments using the code I3MG (Gerya T.,2010). This code solves the conservation equations of mass, momentum and heat, and it is based on a finite differences method combined with a marker-in-cell technique. For this work, we started from an initial setup for the Western Mediterranean area corresponding to the hypothetical situation of 30 My ago according to paleogeography derived from other authors (Hinsbergen, D. J., et al,2014). The model consists of three main continental plates (Africa, Adria and Europe) and a subducting oceanic plate (Ionian Ocean). A wide slab is located from Gibraltar to Corsica and its initial depth is 200km. The lithosphere temperature distribution has been determined according to the half-space cooling equation (Turcotte and Schubert, 2014), while the underlying asthenosphere is characterized by a constant adiabatic temperature gradient. The models are run from this initial configuration to a final model configuration resembling the present-day surface and deeper structure.

[1] Gerya, T. (2010). Introduction to Numerical Geodynamic Modelling. Cambridge University Press.

[2] Turcotte, D., & Schubert, G. (2014). Geodynamics. Cambridge university press.

[3] Hinsbergen, D. J., Vissers, R. L., & Spakman, W. (2014). Origin and consequences of western Mediterranean subduction, rollback, and slab segmentation. Tectonics, 33(4), 393-419.

Shallow lower mantle viscosity modulates the pattern of mantle structure

- Diogo L. Lourenço
  Department of Earth and Planetary Sciences, University of California, Davis, 95616, USA
  dlourenco@ucdavis.edu

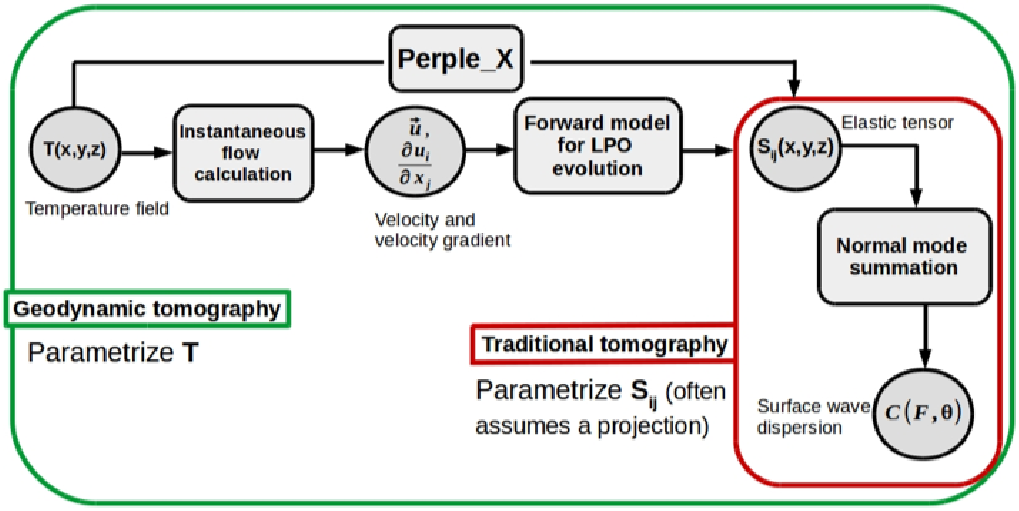
- Maxwell L. Rudolph
  Department of Earth and Planetary Sciences, University of California, Davis, 95616, USA

Tomographic images of Earth's lowermost mantle reveal a dominantly spherical harmonic degree-2 pattern with two large, low-shear velocity provinces (LLSVPs) beneath Africa and the Pacific Ocean. The dominantly degree-2 pattern of seismic shear velocity (V_s) heterogeneity in the lower mantle is strongly correlated with the pattern of convergence and divergence at the surface, with the LLSVPs underlying regions of long-wavelength surface divergence and located away from regions of ongoing and recent subduction. Given this relationship between large-scale structure in the lower mantle and the pattern of plate motions at the surface, it is surprising that mantle structure, even at the largest scales, does not remain correlated at all depths. All mantle tomography models demonstrate a reduced correlation between the structure at transition zone depths and the patterns of heterogeneity within both the lower mantle and the lithosphere. A loss of correlation between structure at different depths requires that seismically fast and slow anomalies are not vertically continuous across the mantle transition zone, which could be the result of slab stagnation or the lateral deflection of large-scale upwelling structures. Here we show that (1) the loss of correlation across the transition zone is primarily the consequence of seismically fast material in the transition zone beneath the Philippine Sea Plate and that similar changes in the correlation of structure in global models of mantle circulation require a relatively large increase in viscosity between the upper mantle and lower mantle and a reduced convective vigor, and (2) models that include a dynamically significant phase transition at 660 km depth predict structures that are not in good agreement with seismic tomography.

A Bayesian Approach to Geodynamic Tomography

- John Keith Magali
  Universite Lyon 1
  john-keith.magali@etu.univ-lyon1.fr
- Thomas Bodin
  Universite Lyon 1
- Navid Hedjazian
  Universite Lyon 1
- Henri Samuel
  Institut de Physique du Globe de Paris
- Suzanne Atkins
  Universite Lyon 1

Constraining present-day mantle flow can be done through analysis of different sets of indirect observations. In the upper mantle, seismic anisotropy originates from the alignment of olivine crystals (lattice prefered orientation LPO) due to mantle deformation. In line with this, we study how long period seismic waves could be used to constrain the patterns of mantle deformation. A recurring issue is that observations of seismic anisotropy depend on the 21 parameters of the elastic tensor, which cannot be resolved independently at every location. This large number of parameters is usually reduced by arbitrarily imposing spatial smoothness and symmetry constraints to the elastic tensor. In this work, we propose to use geodynamic constraints to reduce the number of model parameters. Instead of inverting for anisotropy, we parametrize our inverse problem directly in terms of physical quantities governing the flow in the mantle: a scalar temperature field, and a single activation energy describing a thermally-dependent viscosity. The forward problem consists of three steps: (1) calculation of mantle flow induced by temperature anomalies, (2) modeling of the strain-induced development of LPO assuming pure olivine, and (3) computation of azimuthally-varying surface wave dispersion curves. We show how a fully nonlinear Bayesian inversion of surface wave dispersion curves can retrieve the temperature and viscosity field, without having to explicitly parameterize the elastic tensor. We test the power of this approach by considering a spherical anomaly whose temperature and rheology is different from the surrounding viscous fluid. The solution is an ensemble of models (i.e. thermal structures) representing a posterior probability, thus providing uncertainties for each model parameter.



Geodynamic tomography (green) in comparison with traditional tomographic techniques (red). In geodynamic tomography, the unknown model to be inverted for only consists of a single scalar temperature field denoted by T , whereas in traditional tomography, the model is a fourth-order elastic tensor S ij with 21 independent coefficients. Oftentimes, tomographers assume a hexagonally symmetric medium onto S ij to reduce model complexity. The complete forward problem (in green) is casted in a Bayesian McMC framework. One of the advantages of geodynamic tomography is the reduction of model parameters due to constraints from geodynamics.

New Parameterization of Peridotite Melting and the Geochemistry of Magmas for Geodynamic Models

- Antonio Manjón-Cabeza Córdoba
  Institute of Geophysics, ETH Zürich, Switzerland
  antonio.manjon@erdw.ethz.ch

- Maxim D. Ballmer
  Department of Earth Sciences, University College London, UK
  Institute of Geophysics, ETH Zürich, Switzerland

- Esteban Gazel
  Department of Earth and Atmospheric Sciences, Cornell University, USA.

Rigorous testing of numerical model predictions requires quantitative comparison to real data. However, significant challenges remain in terms of comparing predicted compositions of mantle melts and geochemical data. For example, coupling thermodynamic models of mantle melting (e.g. pMELTS) with large 3D simulation is computationally expensive and/or unstable. On the other hand, simplified parameterizations of mantle peridotite melting only predict the solidus and degrees of melting, and so far are unable to constrain the major-element geochemistry of primary magmas. Here, we present a new melting parameterization of the mantle based on fitting of peridotite melting experiments and of selected thermodynamic model results (pMELTS) to fill gaps in the experimental database. The fitting parameters are pressure, temperature, critical porosity, water content and the initial pressure of melting. Based on these, the parameterization returns the amount of melt produced, the total degree of melting, plus major element compositions in the form of wt% of oxides: SiO_2, TiO_2, Al_2O_3, FeO, MgO, CaO, Na_2O, K_2O (in addition to H_2O). Future extensions of our parameterization will consider CO_2 as well as variable starting bulk-rock compositions (various peridotites and pyroxenites). While our parameterization lacks the intrinsic self-consistency of thermodynamic models, it is highly applicable for large geodynamic problems: since it is based on simple polynomic functions, it has a high degree of stability, low computational costs and is straight-forward to implement. Finally, we show the first application of our parameterization to geodynamic toy-models of flow and melting such as for a Mid-Ocean Ridge or Edge-Driven Convection (EDC). Our final goal is to use this parameterization to compare numerical-model predictions of plume-EDC interaction with fluid inclusions of actual primary melts from the Canaries.

The Origin of Volcanic Archipelagos by Interaction of Edge-Driven Convection and Mantle Plumes

- Antonio Manjón-Cabeza Córdoba
  Institute of Geophysics, ETH Zürich, Switzerland
  antonio.manjon@erdw.ethz.ch

- Maxim D. Ballmer
  Department of Earth Sciences, University College London, UK
  Institute of Geophysics, ETH Zürich, Switzerland

Intraplate volcanism is a widespread phenomenon which remains poorly understood. In particular, Atlantic intra-oceanic volcanism near the African continental margin displays several characteristics that do not fully conform with the predictions of plume theory. It has been suggested that Edge-Driven Convection (EDC) plays a major role in the generation of magmas beneath archipelagos like the Canaries, Cape Verde or the Cameroon Volcanic Line. To explore the role of EDC vs. plume in the generation of Atlantic volcano chains, we have conducted a series of 2D and 3D numerical models using CITCOM. 2D models focus on EDC alone, and we explore model parameters involving rheology (Rayleigh number, activation energy, etc.) and geometry of the transition between oceanic and continental lithosphere (width, height, etc.). On the other hand, 3D models focus on the interaction between mantle plumes and EDC, and we explore the influence of the characteristics of the plume (excess temperature, buoyancy flux, etc.) and the relation with the edge (distance from the edge, height, etc.). Our results suggest EDC can distort plume ascent and imprint characteristic properties on the related volcanism, resulting in irregular age progressions and elongated melting zones. In addition, our models predict that the chemical characteristics of primary magmas depend on the mantle upwelling geometry, for example: the greater the buoyancy flux or the excess temperature, the smaller the influence of EDC , and the less enriched the resulting magmas will be. We conclude that, although EDC alone is not a suitable mechanism for extensive intraplate magmatism, it can have important effects on plume ascent, reconciling some poorly understood characteristics of eastern Atlantic volcano chains. Finally, explaining some characteristics of these archipelagos by transient phenomena cannot be ruled out. Plume arrival and growth, and changes in buoyancy flux may be significant, since the time-spans required for steady-state modeling are similar or larger than the age of the Atlantic ocean.

Dynamics of catastrophic plate boundary formation in the western Pacific

- Ben Maunder
  Imperial College London, South Kensington, London, UK
  b.maunder@imperial.ac.uk

- Julie Prytulak
  Durham University, Durham, UK

- Saskia Goes
  Imperial College London, South Kensington, London, UK

- Mark Reagan
  University of Iowa, Iowa City, USA

The initiation of subduction is a crucial part of the Wilson cycle, yet to this day remains poorly understood. Here we present the first numerical model to match the constraints provided by the recent results of IODP drilling Expedition 352 in the Izu-Bonin-Mariana fore-arc region, during which the first continuous and in-situ record of subduction initiation was recovered. By carefully considering the balance of internal and external forcing on the system, and by calculating the timing and extent of different types of magmatism, we are able to reproduce the observed magmatic progression: from fore-arc basalts (which have no subduction imprint) to boninites (which are an early subduction product), before the system evolves into fully down-dip subduction. We are able to perfectly match the rapid timescale of this progression, as well as the spatial distribution of the different rock types relative to the trench: a strong indication that this 'spontaneous' model of subduction initiation does indeed apply to the western Pacific.

A requirement of successful models is that they are dominated by internal forces, starting from an initially force-balanced setting. By increasing the relative magnitude of external push, we observe that subduction initiation transitions into an 'induced' mode, during which no fore-arc basalts are generated. As such, such a 'spontaneous' initiation event is necessarily large scale and fore-arc basalts can be considered a smoking gun for this type of event. Indeed, rocks, chemically similar to the Exp. 352 fore-arc basalts are also found in the belt of fragments of the previous Tethys Ocean that stretches from the Alps to the Himalayas indicating that Tethyan subduction systems may have initiated in similar, large scale, catastrophic events.

Interior dynamics of a super-Earth constrained by general circulation models

- Tobias Meier
  Center for Space and Habitability, University of Bern, Bern, Switzerland
  tobias.meier@csh.unibe.ch
- Dan J. Bower
  Center for Space and Habitability, University of Bern, Bern, Switzerland
- Tim Lichtenberg
  Department of Physics, University of Oxford, Oxford, United Kingdom
- Mark Hammond
  Department of Physics, University of Oxford, Oxford, United Kingdom
- Paul J. Tackley
  Institute of Geophysics, ETH Zurich, Zurich, Switzerland

Close-in Super-Earths experience efficient heating by stellar irradiation and tidal heating that may drive long-lived, partially molten interiors with a tectonic regime largely unknown from the Solar System planets. Here, we use constraints from general circulation models (GCMs)[2] fitted to transit phase curves [1] in order to infer the potential interior dynamics of super-Earth 55 Cancri e using a numerical geodynamic model of mantle flow (StagYY, [3]).

In particular, we investigate differences in heat transport and convective style between the day- and night-sides. Using solid-state convection models we find that plumes emerging from the thermal boundary layer at the core-mantle boundary tend to migrate towards the day side. The surface temperature on both the day and night side of the planet is sufficiently hot to mitigate the formation of an upper thermal boundary layer such that downwellings are not observed. In this regard, the dynamics of close-in super-Earths are markedly different from Earth which has a dominant mode of convection driven by the upper thermal boundary layer (i.e., subduction).

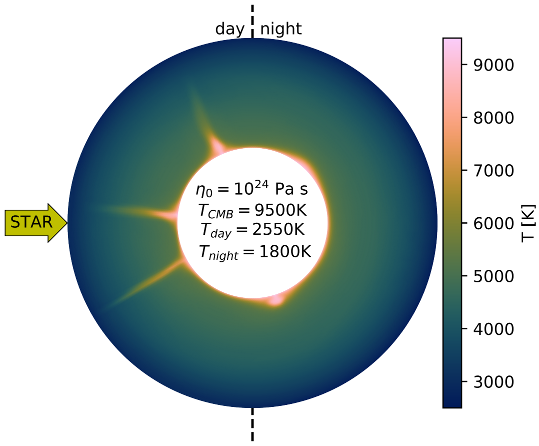
The high mantle temperature, driven by intense insolation at the surface, also means that there might be regions in the mantle that are molten. We therefore investigate the distribution of regions with high melt production and the formation of a surface magma ocean using solid-state convection models that additionally facilitate melting processes. These regions are important in terms of outgassing and therefore may constrain the exchange of volatiles between the mantle and the atmosphere. We thus compare the style of convection for models with and without melt.

With the ever-growing number of close-in super-Earths detected by current and near-future space missions, such as TESS, CHEOPS, PLATO and ARIEL, inferences on the interplay between interior and atmospheric dynamics will enable a deeper understanding of the nature of rocky exoplanets.

[1] Demory, B. O., et al.: A map of the large day–night temperature gradient of a super-Earth exoplanet. Nature 532, 207, 2016.

[2] Hammond, M. and Pierrehumbert, R.: Linking the Climate and Thermal Phase Curve of 55 Cancri e, The Astrophysical Journal, Vol. 849, pp. 152–165, 2017.

[3] Tackley, Paul J.: Modelling compressible mantle convection with large viscosity contrasts in a three-dimensional spherical shell using the Yin-Yang grid, Physics of the Earth and Planetary Interiors, Vol. 171, pp. 7–18, 2008.



Temperature field for 55 Cnc e using a reference viscosity $\eta_0 = 10^{24}$ Pa s ($\eta_0 = \eta(T = 1200\,\mathrm{K}, P = 0)$), CMB temperature $T_{\mathrm{CMB}} = 9500$ K, dayside temperature $T_{\mathrm{day}} = 2550$ K and nightside temperature $T_{\mathrm{night}} = 1800$ K.

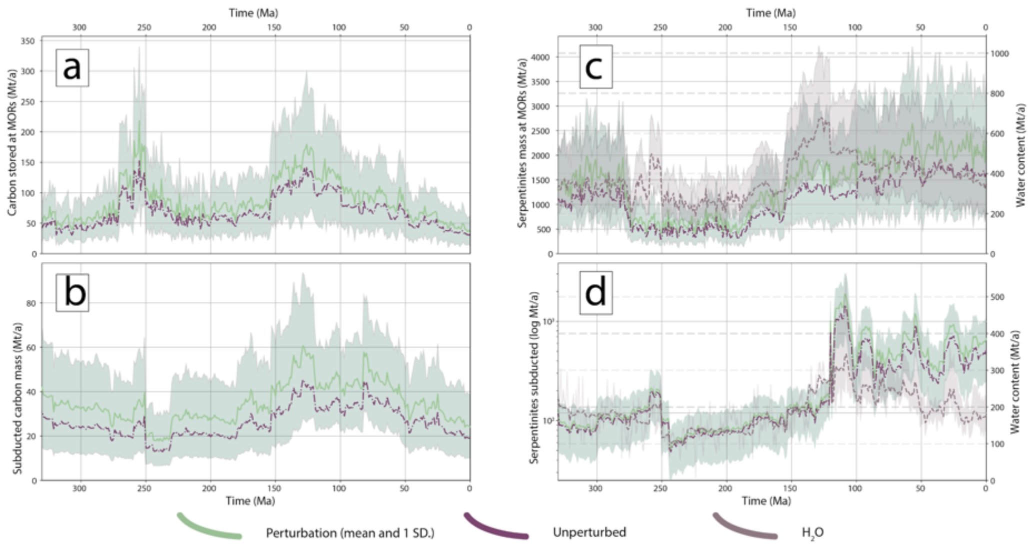
Carbonate, serpentinite and water storage and supply in subducted upper oceanic lithosphere for the past 330 Ma

- Andrew S. Merdith
  Laboratoire de Géologie de Lyon, Université Claude Bernard Lyon 1, Lyon, France
  andrew.merdith@univ-lyon1.fr

- Suzanne E. Atkins
  Laboratoire de Géologie de Lyon, Université Claude Bernard Lyon 1, Lyon, France

- Michael G. Tetley
  Département de Géosciences, École Normale Supérieure, Paris, France

The subduction of upper oceanic lithosphere acts as a primary driver of the Earth's deep carbon and water cycles, providing a key transportation mechanism between surface systems and the deeper Earth. Here we present mass estimates amount of carbonate, serpentinite and water stored in upper oceanic lithosphere from 330 Ma to present day. Flux estimates are calculated using a full plate tectonic reconstruction coupled to a tectonic-petrological model for estimating the proportion of peridotite exhumed—and the resulting degree of serpentinisation—at points along spreading segments of mid-ocean ridges to build a descriptive model of upper oceanic lithosphere. We then track the continuous, kinematic evolution of these points until they intersect with a subduction zone. To address the uncertainties of modelled spreading rates in synthetic ocean basins, we consider the recent preserved spreading history of the Pacific Ocean to be representative of the earlier Panthalassa Ocean. Present-day subducting upper oceanic lithosphere contains 400–600 Mt/a of serpentinites (equating to ∼150–250 Mt/a of water, including water stored in basalts) and 10–30 Mt/a of carbon as carbonate. The highest rates of serpentinite subduction occur in the last 100 Ma, comparably, carbon subduction (20–80 Mt/a) peaks during the Early Cretaceous, as upper oceanic lithosphere subducted during this period formed in times of warm bottom water. We suggest that variation in subduction regimes act as the principal control in the subduction of carbon stored in upper oceanic lithosphere, as for the past 330 Ma the volume of carbon stored across all ocean basins varies by less than an order of magnitude. Inversely, the serpentinite (and associated water) flux at subduction zones appears to be primarily controlled by spreading regimes at mid-ocean ridges, as slow spreading ridges typically occur during times of supercontinent breakup. This is observed in the Atlantic, Arctic and parts of the Indian ocean, where upper oceanic lithosphere is ∼100 times more enriched in serpentinite than the Panthalassa and Pacific oceans.



(a) Mass of carbon sequestration at mid-ocean ridges; (b) mass of carbon entering a subduction zone; (c) mass of serpentinites and water storage at mid-ocean ridges; and (d) mass of serpentinites and water entering a subduction zone. Water content is assumed to be 13 wt% of serpentinite mass and 6.5 wt% of the upper volcanic layer (i.e. basalts). The purple line is our raw, unperturbed result, the green line and shaded area are the perturbation mean and standard deviation. The grey line and shaded area are H_2O mean and standard deviation (calculated from basalts and serpentinites).

Numerical Investigation of a Novel Rheology-linked Origin for Seismic Tremor and Low-Frequency Earthquakes

- Jason Morgan
  Royal Holloway University of London, United Kingdom
  jason.morgan@rhul.ac.uk
- Albert de Montserrat
  Università degli Studi di Padova, Italy
- Alex Clarke
  Royal Holloway University of London, United Kingdom
- Paola Vannucchi
  Royal Holloway University of London, United Kingdom

Subduction-linked seismic tremor has fascinated seismologists since its recognition near the turn of the century. Typical scenarios for its occurrence have focused on the role of fluid-changes in modulating failure within a near-critically-stressed rock. An apparently significant problem for this mechanism is that it can naturally explain neither the near-constant size-threshold for tremor events in a given locale nor the spatial clustering typical of these events. Previously, researchers have mainly focused on the typical matrix+block structure of the subduction melange complex that fills the region/channel between subducting and overriding plates to highlight that that stronger blocks could form asperities along the plate 'interface'. Here we use numerical elasto-visco-plastic model experiments to explore a different hypothesis for the origin of tremor, one in which tremor can spontaneously initiate within a heterogeneous matrix+block 'melange' assemblage that fills a subduction channel once the formerly weaker matrix has been strengthened by well-known diagenetic processes to become stronger than its embedded formerly-stronger blocks. The 2-D numerical models that we explore here include elastic, Mohr-Coulomb-plastic, and viscous effects. Varying volume fractions ($\sim$10-40%) and characteristic aspect ratios (3-10) of blocks were assessed, including a few experiments with a heterogeneous distribution of initial block sizes. We document several characteristic deformation regimes that can occur within a heterogeneous melange which fills the interfacial subduction channel, only one of which can lead to tremor-like behaviour coupled with the generation of conditions that could also trigger the low-frequency earthquakes also known to occur in subduction-linked tremor systems. The first regime occurs when the matrix viscosity is low enough ($< 10^{17}$-10^{18} Pa·s for a 100m-thick subduction channel) so that stresses are too low to initiate block or matrix failure. In this case the plate interface creeps aseismically. If the matrix viscosity exceeds this channel-width-dependent threshold, and the blocks have a higher yield stress than the matrix, then broadly-distributed brittle failure will occur within the matrix without a characteristic fault size typical to seismic tremor. In contrast, when the blocks have a lower yield stress than the matrix, then blocks will repeatedly fail in brittle tremor-like events with a characteristic magnitude that depends on the product of typical block size and yield stress. Due to repeated block failure events and associated deformation of the weaker blocks, the region of the matrix near block tips will become stressed enough for it too to yield in localized higher-stress-release events that we suggest as a possible origin for the low-frequency earthquakes often associated with regions of subduction tremor. Note that as this deformation proceeds the tremors and low-frequency earthquakes do not relieve the stress within the subduction channel, so that this region can still release stress during a megathrust event. We will also discuss algorithmic issues related to convergence of the compressible elasto-viscoplastic rheologies that we consider here, and the effects on numerical convergence of potential healing and strain-softening effects.

Grain Expectations: Microphysics of Plate Boundaries from Geological to Human Timescales

- Elvira Mulyukova
  Yale University, Department of Geology and Geophysics
  elvira.mulyukova@yale.edu

- David Bercovici
  Yale University, Department of Geology and Geophysics

Localized lithospheric deformation associated with plate tectonics requires a mechanism for weakening across the entire width of the lithosphere. We explore the microphysics of weakening of lithospheric materials, and in particular the coupled evolution of mineral grain size and intragranular defects and their control on lithospheric strength. We propose a model for the interaction between grain-boundaries and dislocation density to reduce the net free energy of grains during dynamic recrystallization (DRX). The driving forces for DRX arise from heterogeneity in dislocation density and grain boundary curvature. Our model shows that grain growth driven by variation in grain boundary curvature can be impeded by variation in dislocation density; this occurs because the dislocation accumulation in the smaller grains is suppressed due to the large stress that is needed to bend and elongate a short dislocation (as dictated by the small grain size), while the larger grains can have long dislocations and reach a steady state dislocation density dictated by the applied stress. As the grains grow, to minimize their surface energy, the increase in dislocation density and associated internal energy offsets the driving forces for grain growth. In a lithospheric setting, slower grain growth means that it would require less mechanical work to establish weak localized shear zones through grain damage, and retard the healing of previously damaged zones. Furthermore, the competition of two different time-scales – that of grain growth and the dislocation kinetics – can lead to oscillating behavior over 1 to 10 years as the grain size and dislocation density advance towards their steady states. These oscillations affect the rheology of lithospheric rocks, e.g. their strengthening and weakening through time, and have a potential application to geological processes such as postseismic creep in ductile shear zones. Ongoing developments of this model incorporate the discontinuous processes of subgrain formation, which allows for additional means of grain-size reduction by DRX, and hence more significant localization in the lithosphere.

Retreating subduction zones migration paths dependence on the Earth layers rheology

- Jessica Munch
  ETH Zürich
  Jessica.munch@erdw.ethz.ch

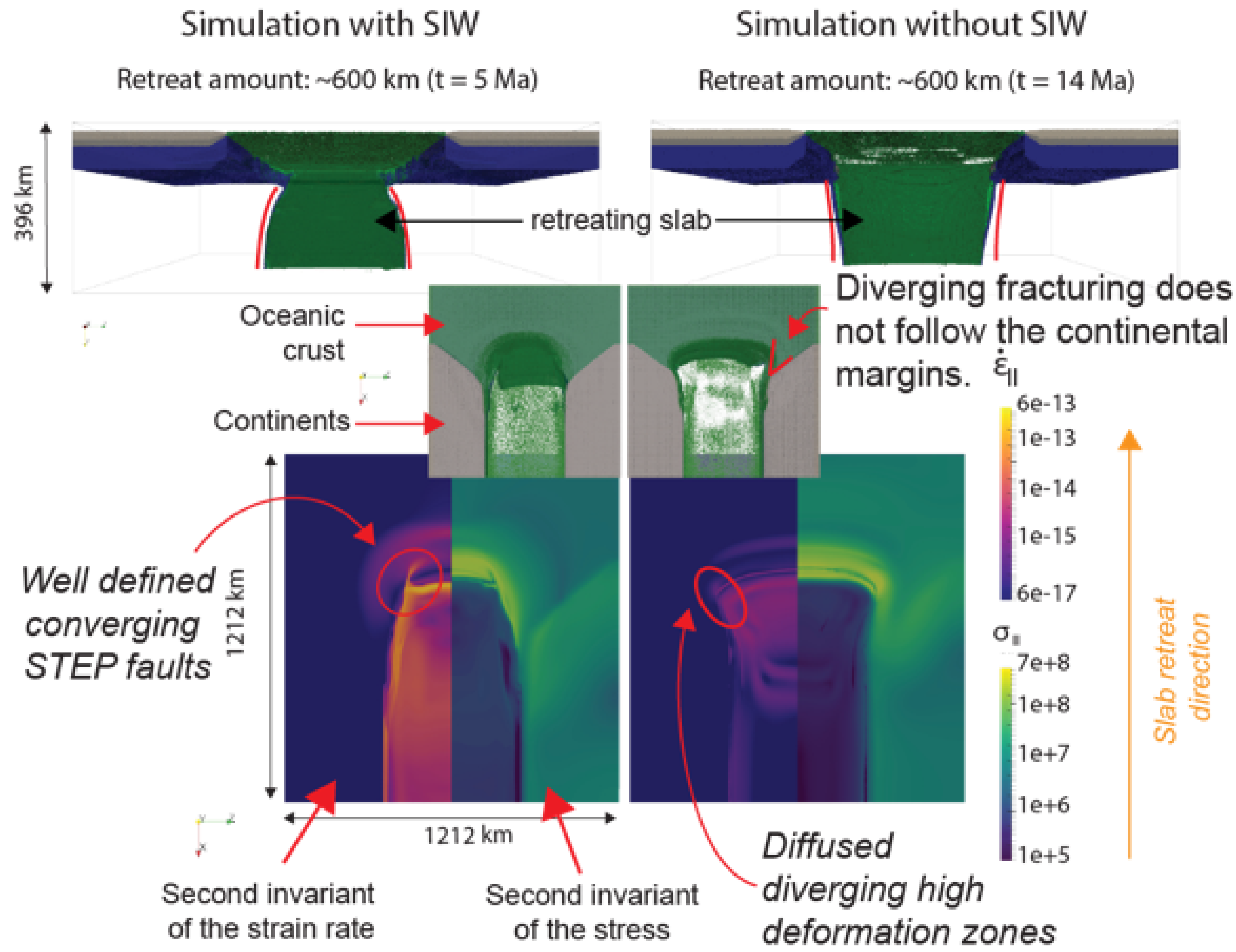
- Taras Gerya
  ETH Zürich

- Kosuke Ueda
  ETH Zürich

Retreating subduction zones (e.g. Caribbean, Scotia or Gibraltar) are observable all over the world in settings ranging from full oceanic domains to oceanic domains surrounded by continents. They are migrating via fracturing at STEP faults, which are located at the edges of the slab. The resulting fracture trajectories appear to be highly dependent on the material's rheology and on its response to stresses.

3D simulations of retreating slabs show that when we vary the weakening mechanism from a more ductile to a more brittle deformation (by (de)activating strain induced weakening - SIW - in our models), we notice very different migration outcomes depending on the nature of the fracture mechanism. Activated SIW favours very localised STEP faults spontaneous formation and allow for slab retreat via converging fracturing paths (Figure). In contrast, in case of deactivated SIW, stresses localise much less on the plate, leading to divergent fracture propagation (Figure). When we vary the mantle resistance to slab penetration, slab retreat velocity varies but the fundamental convergence or divergence behaviour of the fracturing paths with respect to SIW is still observed (although we notice some differences in the fracture trajectories). We also notice that the trench shape depends on the retreat rate. Fast retreating slab form an arched shape trench whereas slow retreating slab tend to be associated to a more linear to "S" shaped trenches. Fracture paths converge at a slower rate when the slab retreat slows down. This observation highlights the importance of the partitioning between viscous and brittle/plastic deformation both for the dynamics of slab retreat and for subduction zone migration trajectories. The influence of sediments, by surficial material loading and unloading, and possibly beyond, by deep fluid transport and weakening, in the evolution of the retreating slab has a similar first-order impact (Sobolev and Brown 2019). This potential is further assessed using coupled thermomechanical and surface processes codes that adds dynamic erosion and sediments into the system.

[1] Sobolev, S. V. and M. Brown (2019). "Surface erosion events controlled the evolution of plate tectonics on Earth." Nature 570(7759): 52.



Evolution of retreating subduction zones between two diverging continental margins. Left pannel shows simulations where SIW is activated right pannel shows simulations where SIW is deactivated. When SIW is activated, we observe converging fracturing paths leading to the narrowing of the slab. When SIW is deactivated, we notice diverging fracturing paths leading to a widening of the slab.

On the deep mantle water cycle caused by the onset timing of plate motions driven by the mantle convection

- Takashi Nakagawa
  Department of Earth Sciences, The University of Hong Kong
  ntakashi@hku.hk

Here I provide a few possible evolution scenarios on the surface seawater associated with the deep mantle water cycle in plate motions driven by the mantle convection. The primary motivation of this investigation is that the onset timing of surface plate motions may have an uncertainty, which ranges from 1 to 4 billion years ago suggested from the geologic records (Hopkins et al., 2008; Korenaga, 2013). However, in the recent investigation on the evolution of surface seawater in plate motions driven by mantle convection, it seems to be difficult to explain the evolution hypothesis of surface seawater. This hypothesis is known as the continental freeboard hypothesis (e.g. Erikson, 1999). Based on this hypothesis, the amount of surface seawater may not be changed over 2.5 billon years at least. With numerical mantle convection simulations incorporating the deep mantle water cycle, the total amount of water would be required to find ten times as much as the ocean mass the present-day Earth so that the system can reach the consistent amount of surface seawater at present (Nakagawa et al., 2018). This accomplishment is not still well-understood for the evolution of the surface seawater based on the freeboard hypothesis. One potential issue on Nakagawa et al. (2018) is that the onset timing of surface plate motion might be much earlier than the expected from the geologic records, which may initiate before the timing of the current constraints. For further understanding of the evolution of surface seawater over the geologic time-scale, I investigate the model sensitivity of total water in the planetary system and the initiation timing of surface plate motions. On the initiation timing of surface plate motion, I control the onset timing of the occurrence of surface plate motion driven by mantle convection with the friction coefficient of the oceanic lithosphere. This modeling approach may constrain the onset timing of surface plate motion so that it could be consistent with the geologic records on the evolution of surface seawater.

[1]Erikson, P. G. (1999) Precambrian Research, 97, 143-154.

[2] Hopkins, M., T. M. Harrison, and C. E. Manning (2008) Nature, 456, 493-496.

[3] Korenaga, J. (2013) Annual Review of Earth and Planetary Sciences, 41, 117-151.

[4] Nakagawa, T., H. Iwamori, R Yanagi, and A. Nakao (2018) Progress in Earth and Planetary Sciences, 5, 51, doi: 10.1186/s40645-018-0209-2.

Time dependent 3-D numerical modeling of the cratonic evolution

- Jyotirmoy Paul
  Centre for Earth Sciences, Indian Institute of Science, Bangalore 560012
  jyotirmoyp@iisc.ac.in

- Attreyee Ghosh
  Centre for Earth Sciences, Indian Institute of Science, Bangalore 560012

The interior of cratons is devoid of any significant seismo-tectonic activities for several hundreds of million years in spite of the fact that many of them are located adjacent to plate boundaries. Such long-term tectonic inertness in a tectonically active planet like the Earth was initially thought to be a result of cratons' intrinsic chemical buoyancy. However, later it has been shown that only buoyancy cannot protect the cratons from destructive forces of the mantle. Indeed, they need to be strong enough to remain tectonically stable above a convecting mantle. Using a scaling approach, Paul et al. (2019) have given a probable estimate of minimum viscosity of cratonic roots and their surrounding asthenosphere for cratons to survive for billions of years, provided mantle shearing is the only destructive force. This estimate was based on 3-D full spherical instantaneous mantle convection models using density anomalies derived from seismic tomography. In our present study, we construct 3-D full spherical time-dependent models and investigate the evolution of cratons since the last 410 Myrs. At first, the present-day locations of cratons are reconstructed back to 409 Ma assuming them as rigid blocks. This reconstruction is performed using GPlates 2.0 (Gurnis et al., 2012) following the plate reconstruction model of Matthews et al. (2016). Surface velocities for the last 410 Myrs are obtained from the finite rotation of Euler poles using GPlates. We use the surface velocities as boundary condition to drive flow in our convection models and update them at 1 Myr intervals from 409 Ma till the present day. Cratons are allowed to evolve according to the mantle flow guided by the plate motions. It is observed that cratons with 10 times viscosity contrast surrounded by asthenosphere of less than 10^{19} Pa-s viscosity, which is the weakest model in our study, get destroyed completely within 410 Myrs. We have increased the craton and asthenosphere viscosity step by step and have generated 9 different models where craton viscosity ranges from 10 -1000 times the ambient layer viscosity and the asthenosphere viscosity varies from 10^{19} to 10^{21} Pa-s. We find, if a craton has to survive for more than 410 Myrs, it has to be at least 100 times more viscous than the ambient layer and the asthenosphere viscosity should be no less than 1020 Pa-s, provided convective shearing is the only destructive agent acting underneath the cratons.

[1] Gurnis, M., Turner, M., Zahirovic, S., DiCaprio, L., Spasojevic, S., Müller, R. D., Boyden, J., Seton, M., Manea, V. C., and Bower, D. J., 2012. Plate tectonic reconstructions with continuously closing plates, Computers and Geosciences, 38(1), 35–42.

[2] Paul, J., Ghosh, A., and Conrad, C., 2019. Traction and strain rate at the base of the lithosphere: An insight into cratonic stability, Geophysical Journal International, 217(2), 1024–1033.

[3] Matthews, K. J., Maloney, K. T., Zahirovic, S., Williams, S. E., Seton, M., and Mueller, R. D., 2016. Global plate boundary evolution and kinematics since the late Paleozoic, Global and Planetary Change, 146, 226–250.

The effect of mantle plumes on the generation and evolution of the Archean terranes

- Andrea Piccolo
  Institute of Geosciences, JGU, Mainz,Germany
  piccolo@uni-mainz.de
- Boris J.P. Kaus
  Institute of Geosciences, JGU, Mainz, Germany
- Richard W. White
  School of Earth and Environmental Sciences, University of St Andrews, St Andrews, United Kingdom
- Richard M. Palin
  Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO, USA

It is usually assumed that the Archean upper mantle was hotter than the modern-day mantle (Δ T$_P$ $\sim$ 200 °C). Estimate span from 1400-1600 °C and featured a high variability within the same age. These discrepancies have significant implications on the dynamics of the system and on continental crust forming processes, the bulk of which was produced during Archean. The earliest continental crust is mainly formed by Tonalite- Trondhjemite-Granodiorite suites (TTGs), which is widely accepted to be the product of hydrous meta-basalt partial melting. However, there is still no consensus on the geodynamic processes that created continental crust. TTGs melts required to be generated at high pressures. These conditions could be reached in an arc-related geodynamic setting or at the bottom of an evolving oceanic plateau. It is not clear if oceanic arcs were widespread during the Archean, while there is strong evidence that oceanic plateaus were more widespread than nowadays. However, the effects of different T$_P$ on the dynamics of plume-lid interactions and on continental crust production are not explored. Since the upper mantle T$_P$ estimations vary, we here explore the effect of different uppermantle thermal states on plume-lid dynamics. We combine state-of-the-art thermodynamic models, with the 3D numerical code LaMEM. We performed systematic 2D and 3D simulations, assuming an initial small and short- lived mantle plume (T$_P$=1600°C , r=150-200 km) and explore the effect of T$_P$, initial lithospheric thickness and melt extraction parameters. Our results suggest that at higher T$_P$($\geq$1450) even a short-lived mantle plume can potentially trigger a large-scale delamination of the whole lithosphere, inducing an enhanced production of continental crust. Meanwhile at lower T$_P$, the stability of the lithosphere is a function of its initial thickness, the amount of radiogenic heating and the convective Rayleigh number of the upper mantle. In the latter scenario, the amount of continental crust produced is limited, and is mainly concentrated around the rims of the plume. In most experiments, the oceanic plateau gravitationally collapses, while the old oceanic crust is over-thrusted at its rim. There are differences between 2D and 3D experiments, particularly with respect to the pressure at which melting occurs that produces continental crust. 3D experiments feature a consistent lower pressure, while in 2D models the conditions are more variable and shifted towards higher pressures. Both 2D and 3D experiments show a decrease of T$_P$ as a result of dripping, which affects the final thickness of newly generated crust. Our results show that T$_P$ exerts a strong control on the dynamics of the system and on TTGs formation.

India-Eurasia convergence history revisited

- Adina E. Pusok
  Scripps Institution of Oceanography, UCSD, La Jolla, CA, United States
  Department of Earth Sciences, University of Oxford, Oxford, United Kingdom
  adina.pusok@earth.ox.ac.uk

- Dave R. Stegman
  Scripps Institution of Oceanography, UCSD, La Jolla, CA, United States

The fast convergence between India and Eurasia in the Cretaceous remains one of the major tectonic puzzles. Present-day plates move at rates less than 100 mm/yr, but for a period of 20 Myr in the Cretaceous, the Indian plate moved at rates higher than 180 mm/yr. Two main theories have been brought forward in the last decades: plume push (i.e., Cande and Stegman, 2011) and double subduction (i.e., Jagoutz et al. 2015). The plume-push hypothesis is based on the concurrence of the maximum activity of the Reunion plume and the superfast motion of India between 70-65 Ma. On the other hand, the double subduction hypothesis is based on the fact that the Southern Eurasian margin is riddled with fragmented oceanic remains, indicating that multiple subduction systems operated within the Neo-Tethys since 130 Ma, when the Indian plate separated from Gondwana. Aitchison et al. (2004) suggested that the high Indian plate motion resulted from the combined slab pull of two northward dipping subduction zones, and later numerical models confirmed that rates of convergence across coupled double subduction systems can be significantly faster than across single subduction systems because of slab pull by two slabs (Jagoutz et al., 2015, Pusok and Stegman, 2019).

Here, we show that previously ignored features in the convergence rate data represent signals of subduction processes. We compile convergence data from more than 30 studies and then use numerical models of single and double subduction to propose a new sequence of events to explain the India-Eurasia convergence for the last 80 Ma. In this study, we run 2-D numerical models to investigate the convergence signal of various processes: plume push and double subduction. We start from a single subduction setup, where subduction is already initiated and we stress the system by controlling the convergence rate of the Indian plate, in order to mimic the effect of a plume-push (i.e. imposing influx/outflux boundary conditions). Under certain conditions, a second subduction may develop and transform into a stable double subduction system. We then run simulations with various plume forcings and mantle viscosity structures, and show that despite uncertainties in estimating subduction or mantle parameters, the India-Eurasia convergence magnitudes and shape can be reconstructed in a logical sequence of subduction events.

The effect of sediment fluxes on the dynamics and style of convergent margins

- Adina E. Pusok
  Scripps Institution of Oceanography, UCSD, La Jolla, CA, United States
  Department of Earth Sciences, University of Oxford, Oxford, United Kingdom
  adina.pusok@earth.ox.ac.uk

- Dave R. Stegman
  Scripps Institution of Oceanography, UCSD, La Jolla, CA, United States

- Madeleine Kerr
  Harvey Mudd College, Claremont, CA, United States

Subduction zones represent the only major pathway by which continental material can be returned to the Earth's mantle. Quantifying the sediments mass flux through subduction zones is not only important to the general problem of petrogenesis of continental crust, but also to the understanding whether large volumes of existing continental crust are ever recycled back into the mantle over long periods of geologic time. When sediments are considered, convergent margins appear to fall into one of two classes: accretionary and erosive. Accretionary margins are dominated by accretion of thick piles of sediments (¿1km) from the subducting plate, while tectonic erosion is favored in regions where the sedimentary cover is ¡1 km. However, as data help define geometry of the global subduction system, the consequences of the two styles of margins on subduction dynamics remain poorly resolved.

In this study, we run systematic 2-D numerical simulations of ocean-continent subduction to investigate how sediment fluxes influence subduction dynamics and the plate coupling. We vary: i) the thickness and viscosity of the sediment layer, ii) the viscosity and buoyancy of the upper plate, iii) the driving velocity of the subducting plate (i.e. kinematic boundary conditions), and iv) the presence of highly viscous "strong blocks" in the upper plate to represent cratonic blocks. Our results show 3 modes of subduction interface: a) Tectonic erosion margin (high viscosity sediment layer), b) Low angle accretionary wedge margin (low viscosity, thin sediment layer), and c) High angle accretionary wedge margin (low viscosity, thick sediment layer). We find that the properties of the sediment layer modulate the extent of viscous coupling at the interface between the subducting and overriding plates. When the viscous coupling is increased, an erosive style margin will be favored over an accretionary style. On the other hand, when the viscous coupling is reduced, sediments are scrapped-off the subducting slab to form an accretionary wedge. We investigate the behavior of these modes with changing boundary conditions (i.e. free subduction vs kinematic boundary conditions) and variable sediment fluxes to the subduction trench.

Micro and macro-scale geodynamic modelling of convergent margins

- Francesco Rappisi
  Università degli Studi di Padova
  Francesco.rappisi@phd.unipd.it

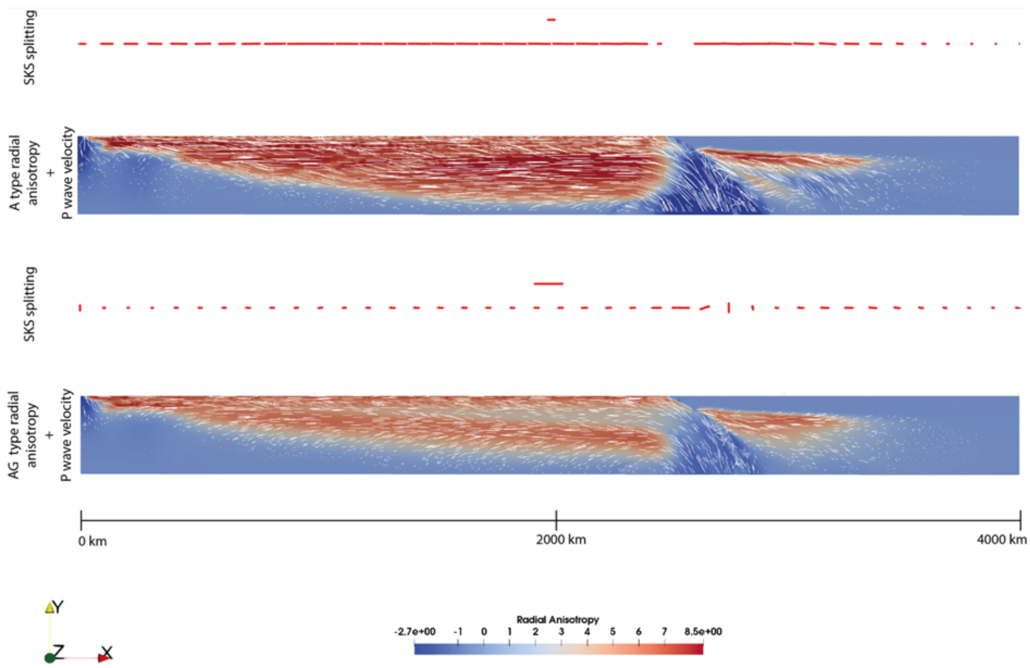
- Manuele Faccenda
  Università degli Studi di Padova

Seismic anisotropy (the dependence of seismic wave velocity on propagation and/or polarization directions) is widely observed throughout the crust and the upper mantle, and for this reason it is of fundamental importance to know its distribution when we want to use seismology as a tool for investigating the interior of the Earth. Mantle seismic anisotropy mainly arises from the strain-induced preferential alignment of intrinsically anisotropic crystals (CPO) such as olivine and pyroxene which is directly related to mantle flow patterns. Thus, studying seismic anisotropy provides important information about the geodynamic processes that affect the upper mantle.

Our work aimed at the calibration of the parameters of the D-Rex software used for the strain-induced fabric estimation of olivine and orthopyroxen aggregates, starting from the comparison between the results of our numerical tests and laboratory experiments performed by other authors. This comparison was carried out from a qualitative point of view through the use of the pole-figures, and quantitative by comparing the M-index (index of the strength of the fabric) of the various aggregates with increasing strain.

In a second phase, passing from micro-scale experiments on single aggregates to macro-scale on 2D models of convergent margins, we procedeed by comparing the SKS waves splitting results performed on our anisotropic models whose elastic tensor was generated with a new set of D-Rex parameters, and the ones obtained using the elastic tensors proposed by other authors or calculated with the D-Rex parameters used so far in this field of study. We recall that the SKS waves splitting studies return two important information that are the fastest polarization direction and the delay between the fast and slow wave components that correspond respectively to the average preferential direction of the olivine fast axis and to an estimation of the layer thickness of the anisotropic body.

In conclusion of our preliminary studies, we therefore propose a new set of parameters for the calculation of the strain-induced fabrics calibrated on the basis of the comparisons just described and so considered more realistic and hence closer to geological scenarios observed in nature.



From the top to the bottom: the 2D model of radial anisotropy and P-waves velocity obtained using the A-type slip system and the D-Rex parameters according to Kaminski, Ribe and Browaeys 2004, and the SKS splitting from top view (XZ plane); the 2D model of radial anisotropy and P-waves velocity obtained using an AG-type slip system and a new set of D-Rex parameters, and the SKS splitting from top view (XZ plane).

Subduction of Non-Newtonian Plates: Thin-Sheet Dynamics of Slab Necking and Breakoff

- Neil M. Ribe
  Lab FAST, CNRS and Université Paris-Sud, Orsay, France
  ribe@fast.u-psud.fr

- Bingrui Xu
  Dept. of Aeronautics and Astronautics, Fudan University, Shanghai, China

Several lines of geophysical evidence suggest that the lower portion of a subducting slab can under some conditions detach from the upper portion via a necking instability. To shed light on this process, we present a semi-analytical model for the negative buoyancy-driven subduction of a dense sheet of viscous fluid having a composite Newtonian/non-Newtonian rheology. The viscosity of the sheet is $\eta = (1/\eta_1 + 1/\eta_2)^{-1}$, where η_1 is a constant Newtonian viscosity and η_2 is a nonlinear strain rate-dependent (shear-thinning) viscosity with a power-law exponent $n > 1$. The starting point for the model is the hybrid boundary-integral/thin-sheet (BITS) formulation of Xu & Ribe (*Geophys. J. Int.* **206** 1552-1562, 2016), which describes the coupled dynamics of the subducting sheet and the ambient mantle by a single integral equation for the velocity on the sheet's midsurface. The equation is solved numerically using an algorithm based on discrete differential geometry.

The principal dimensionless parameters controlling the behavior are n; the Newtonian viscosity ratio $\gamma = \eta_1/\eta_0$, where η_0 is the viscosity of the ambient mantle; and the "nonlinear weakening factor" $\lambda = (\eta_1/C)(h_0 g\delta\rho/\eta_0)^{1-1/n}$, where C is the shear-thinning viscosity prefactor, h_0 is the initial thickness of the sheet, and $g\delta\rho$ is the sheet's (negative) buoyancy. To begin, we consider the instantaneous sinking speed V of the slab as a function of its geometry and the parameters γ and λ. We derive a general scaling law for V that is valid for any value of n, and show that the numerical solutions for V (suitably nondimensionalized) collapse onto the same universal curve for $n = 1$ and 3. Turning to time-dependent flows, we consider two cases: "free" necking, where the subducting slab pulls the attached negatively buoyant surface portion of the sheet; and "constrained" necking, where the attached plate contains a positively buoyant section that slows or stops subduction when it reaches the trench. Free necking for $n \geq 3$ can occur, but it requires low values of $\gamma \approx 100$ and unrealistically high values of $\lambda > 100$. By contrast, constrained necking is an efficient process that can occur for $n = 3$ and reasonable values of $\lambda \approx$ 10-20 inferred from laboratory experiments on olivine.

Dynamics of Arc-Continent collision: implications for basin formation in the overriding plate

- Andres Felipe Rodriguez Corcho
  The University of Melbourne, Parkville, Victoria, Australia
  rodrigueza2@student.unimelb.edu.au
- Sara Moron Polanco
  The University of Melbourne, Parkville, Victoria, Australia
  The University of Sydney, NSW Australia
- Romain Beucher
  The University of Melbourne, Parkville, Victoria, Australia
- Camilo Montes Rodriguez
  Universidad del Norte, Barranquilla, Colombia
- Rebecca Farrington
  The University of Melbourne, Parkville, Victoria, Australia
- Louis Moresi
  The University of Melbourne, Parkville, Victoria, Australia
  Australian National University, Australian Capital Territory, Australia

Arc-continent collision is the process where an intra-oceanic arc collides with a continental margin. Most research concerning extension and basin formation in an arc-continent collision setting have been focused in the trench-arc complex (subduction zone + arc) with little attention to the processes taking place in the overriding plate. Back-arc and fore-arc extension models are routinely invoked as the mechanism responsible for opening of accommodation space, often unencumbered by supporting geologic data. Most examples of arc-continent collision define a four stages evolution model: 1) Intra-oceanic magmatism and arc formation; 2) Initial accretion followed by subduction congestion and slab-break off; 3) Advanced accretion/orogeny; and 4) Subduction polarity reversal followed by orogenic collapse, renewed magmatism, and shortening. In contrast, geological evidence in the Northwestern South America margin (NWSAm) suggest that subduction polarity reversal was followed by short-lived arc magmatism (15 Ma), non-magmatic flat subduction, and basin formation in the overriding plate. The formation of basins in the NWSAm cannot be easily explained by back-arc or fore-arc extension models because at the time of major basin opening/filling there was not an active magmatic arc nearby. We use 2D mechanical numerical modelling to investigate the conditions that lead to lithospheric extension in the overriding plate in an arc-continent collision setting. We focus in two main geodynamic mechanisms: 1) Subduction transference; and 2) Subduction polarity reversal.

Linking upper- and lowermost heterogeneity of the Earth's mantle: mantle convection with thermochemically heterogeneous top and bottom boundary layers

- Tobias Rolf
  Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway
  tobias.rolf@geo.uio.no

The Earth's mantle is full of thermal and chemical heterogeneity. At shallow depth, this is most evident in the presence of oceanic and continental plates. In the lowermost mantle, seismic tomography has revealed the presence of large (chemically anomalous) provinces with low shear-wave velocity. These large-scale heterogeneities have both been investigated previously and both affect the dynamics of the mantle (e.g. strength and positioning of plumes, convection pattern, long-wavelength geoid, location of subduction zones, seafloor age distribution). But if/how bottom and top heterogeneity interact in the self-organized Earth's mantle is poorly known and hardly investigated. This is however relevant to understand the driving behind Earth's plate-mantle system and questions like how a rather stable (in time) pattern of dense provinces in the deep mantle can co-exist with an ever-reorganizing layout of tectonic plates and continental configuration at the surface (i.e. the supercontinent cycle).

I will present 2D and 3D mantle convection simulations to investigate this issue. I computed a set of 3D spherical cases featuring plate-like behavior and the drift of continents (resembling their present-day shape on Earth) as well as an initial layer of primordial material atop the core-mantle boundary (CMB); the density of this layer is varied. Consistent with previous results, the density contrast determines the longevity of primordial material in the lowermost mantle. A degree-2 structure can evolve and persist for up to 500 Myr (possibly longer). A systematic correlation between surface continents and deep primordial provinces has not been detected. The presence of dense primordial provinces suppresses surface plate and continental drift velocities somewhat. The effect is larger with larger density contrast of the primordial material and thus the fractional area of the CMB covered by it. However, the effect on plate velocity is smaller (10-15%) compared to whether continents are present or not (30-40%).

Other than that, no systematic influence of the deep dense provinces on classical plate motion diagnostics has been detected. This implies that the heterogeneity in the surface boundary layer exerts is dominant for the system dynamics compared to the bottom boundary layer. This is favored by the intrinsic weakness of primordial material in the model. I thus support the initial set of calculations with additional 2D models in which the influence of the bottom boundary layer and its heterogeneity is boosted by higher intrinsic viscosity of primordial material and stronger basal heating relative to internal heating.

Nnumerical simulations of mantle convection with grain size evolution

- Antoine Rozel
  ETH Zürich
  antoine.rozel@erdw.ethz.ch

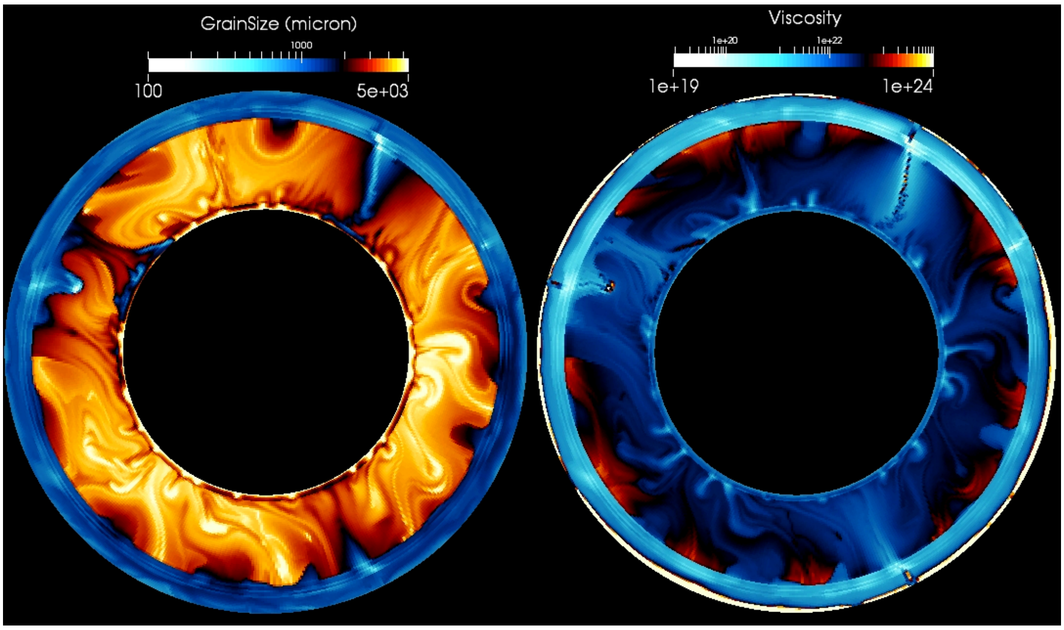
- Gregor Golabek
  BGI Bayreuth

- Jana Schierjott
  ETH Zürich

- Marcel Thielmann
  BGI Bayreuth

- Paul Tackley
  ETH Zürich

We present a set of numerical simulations of long term mantle convection using a composite rheology (diffusion and dislocation creep) and a non-equilibrium grain size. In order to obtain a realistic viscosity profile, a new analytical approach is used to guess the rheological parameters of diffusion and dislocation creep before running the simulations. The results show that the partitioning diffusion-dislocation creep can be anticipated despite the complexity of the grain size evolution equation. Additionally, it appears the viscosity profile is overall time-independent, despite cooling, due to the grain size. In our approach, the phase transitions play an important role as grain sizes are reset while crossing them.



Grain size (left, in micron) and viscosity (right, in Pa·s) in our models. Note the importance of the phase transitions on the grain size field. The viscosity self-consistently obtained is comparable to what is inferred from post-glacial rebound studies.

Anomalous bathymetry at ridge-transform-intersections explained by oblique mantle dynamics

- Lars Rüpke
  GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
  lruepke@geomar.de

- Ingo Grevemeyer
  GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany

- Karthik Iyer
  GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany

- Jason P. Morgan
  Royal Holloway, University of London, United Kingdom

- Colin Devey
  GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany

Oceanic Fracture Zones are prominent long linear bathymetric scars that often cut across entire ocean basins. Plate tectonics provided a simple framework for their creation, that they are linked to the scar created by a stepwise transform fault offset along a mid-ocean spreading center. However, the origin of transform fault and fracture zone relief has remained a persistent enigma.

Here we analyze high-resolution multibeam bathymetric maps of multiple oceanic transform fault systems at a wide spectrum of spreading rates. These observations are combined with 3D geodynamic simulations using ASPECT. We show that the observed bathymetric features can be explained by oblique mantle dynamics that emerge in visco-plastic simulations driven by a surface strike-slip boundary condition. The imposed strike-slip motion transforms into an oblique and extensional shear zone at depth, which results in plate thinning in the inside corner region. Key to this a mechanical instability that arises in response to the older and stronger plates inducing deformation in and entrainment of the younger plate. The importance of this mechanism scales with age-offset yet is evident at all slip rates thereby explaining a first order bathymetric feature found at ridge-transform intersections of ultraslow to fast spreading ridges.

A novel method of simulating multiphase hydrothermal flow in the system H_2O-NaCl

- Falko Vehling
  GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
  lruepke@geomar.de
- Lars Rüpke
  GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
- Jörg Hasenclever
  Hamburg University, Germany

Hydrothermal venting at the ocean floor is a key mechanism of biogeochemical exchange between the solid earth and the global ocean. Fluids expelled around these vents sustain unique ecosystems (Boetius, 2005), mobilize metals from the crust to the ocean floor to form massive sulfide ore deposits, and transport trace elements and isotopes that are now thought to play an important role in global-scale biogeochemical ocean cycles (German et al., 2016). Much has been learned about these systems and their role in the Earth System from direct seafloor observations, ocean drilling, and geophysical imaging. Yet, the inner workings of submarine hydrothermal system remain inaccessible to direct observations. Instead, the hydro-geochemical regime within the crust needs to be inferred from indirect observations like vent fluid chemistry. Vent fluid salinity values often deviate from the seawater value pointing to phase separation and segregation phenomena at depth. Simply put, when seawater is heated to the point where it intersects the two-phase boundary, it splits into a low-salinity vapor and a higher-salinity brine phase. Segregation of these phases can result in the venting of fluids that have a higher or lower salinity than seawater.

Establishing a quantitative relationship between the observed variations in vent fluid salinity and hydrothermal processes at depth requires multiphase hydrothermal flow models that can resolve the circulation of seawater over a sufficiently wide PTX range. Implementing such multi-phase behavior in numerical models remains challenging mainly due to the high non-linearity of the underlying equation-of-state and the large density contrast between the vapor and the brine phase. We have recently presented a new methodology for simulating multi-phase behavior in hydrothermal systems (Vehling et al., 2018). It is based on a finite-volume method, uses pressure and enthalpy as primary variables, and solves the underlying conservation equations for mass and energy implicitly with a Newton-Raphson scheme on unstructured meshes. This methodology, by being implicit and able to handle unstructured meshes, allows for large computational time steps and for resolving complex structures. We have now extended this methodology to the system H_2O-NaCl. This code is based on the same methodology used by Vehling et al. (2018) but has been augmented with a salt conservation equation. In addition, we have implemented a pressure-enthalpy-salt version of the pressure-temperature-salt-based equation-of-state by (Driesner and Heinrich, 2007). We here present results of multi-phase simulations for brine formation and mobilization in hydrothermal systems and analyze the accuracy and efficiency of the method.

[1] Boetius, A., 2005, Lost city life: Science, v. 307, no. 5714, p. 1420-1422.

[2] Driesner, T., and Heinrich, C. A., 2007, The system H2O-NaCl. Part I: Correlation formulae for phase relations in temperature-pressure-composition space from 0 to 1000 degrees C, 0 to 5000 bar, and 0 to 1 X-NaCl: Geochimica Et Cosmochimica Acta, v. 71, no. 20, p. 4880-4901.

[3] German, C. R., Casciotti, K. A., Dutay, J. C., Heimburger, L. E., Jenkins, W. J., Measures, C. I., Mills, R. A., Obata, H., Schlitzer, R., Tagliabue, A., Turner, D. R., and Whitby, H., 2016, Hydrothermal impacts on trace element and isotope ocean biogeochemistry: Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences, v. 374, no. 2081.

[4] Boetius, A., 2005, Lost city life: Science, v. 307, no. 5714, p. 1420-1422.

[5] Driesner, T., and Heinrich, C. A., 2007, The system H2O-NaCl. Part I: Correlation formulae for phase relations in temperature-pressure-composition space from 0 to 1000 degrees C, 0 to 5000 bar, and 0 to 1 X-NaCl: Geochimica Et Cosmochimica Acta, v. 71, no. 20, p. 4880-4901.

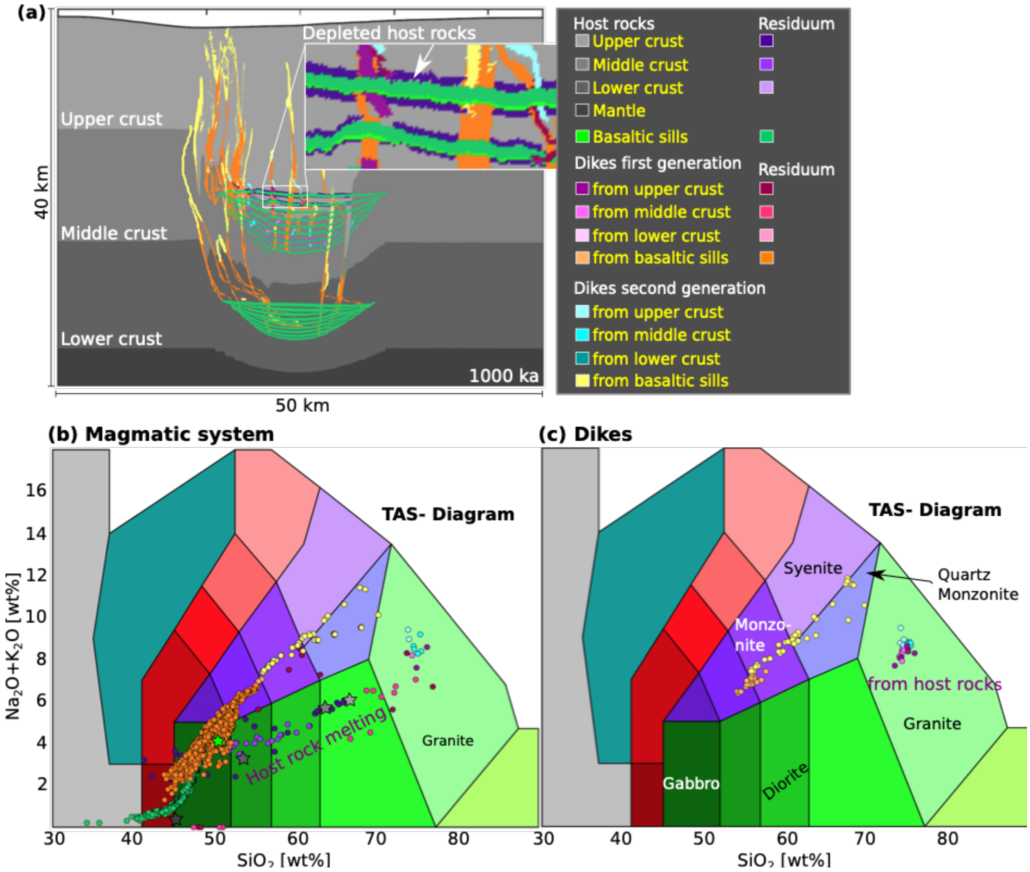
[6] German, C. R., Casciotti, K. A., Dutay, J. C., Heimburger, L. E., Jenkins, W. J., Measures, C. I., Mills, R. A., Obata, H., Schlitzer, R., Tagliabue, A., Turner, D. R., and Whitby, H., 2016, Hydrothermal impacts on trace element and isotope ocean biogeochemistry: Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences, v. 374, no. 2081.

[7] Vehling, F., Hasenclever, J., and Rupke, L., 2018, Implementation Strategies for Accurate and Efficient Control Volume-Based Two-Phase Hydrothermal Flow Solutions: Transport in Porous Media, v. 121, no. 2, p. 233-261.

Establishment of a phase diagram database and its application to crustal magmatic systems

- Lisa Rummel
  Institute of Geosciences, Johannes Gutenberg University of Mainz, 55128 Mainz, Germany
  lirummel@uni-mainz.de
- Tobias S. Baumann
  Institute of Geosciences, Johannes Gutenberg University of Mainz, 55128 Mainz, Germany
- Boris J.P. Kaus
  Institute of Geosciences, Johannes Gutenberg University of Mainz, 55128 Mainz, Germany
- Richard W. White
  School of Earth & Environmental Sciences, University of St Andrews, KY16 9AL, Scotland, UK

Self-consistent geodynamic models of magmatic systems are a challenge as rocks continuously change their chemical compositions, which may affect the mechanical behavior of the system. Melt extraction events create new rocks by injecting magma into fractures while depleting the source region. As the chemistry of these source rocks changes locally depending on the conditions of melt extraction, new phase diagrams are required to track the future rock evolution for each chemical state. This will change density, melt fraction as well as the mineralogical and chemical compositions, which has a direct feedback on the mechanical processes. As a consequence, a sufficiently large number of phase diagrams is required to study the evolution of magmatic systems in detail (>58,000 phase diagrams were computed). As each of the melting diagrams may depend on 10 oxides as well as pressure and temperature, this is a 12-dimensional computational problem. Since computing a single phase diagram for a fixed chemical composition (as a function of pressure and temperature) may take several hours, computing new phase diagrams during an ongoing numerical simulation is computationally unfeasible. One strategy to avoid such a problem is to precompute diagrams and create a phase diagram database using Perple_X, which contains all bulk rock compositions (BRCs) that could emerge during petro-thermo-mechanical simulations. To avoid the time-consuming repetition of geodynamic simulations to collect required BRCs, we apply a forecast method that uses the entries of the existing database to predict possible requests of chemical composition. Sampling is executed within boundaries that are defined manually or through principal component analysis (PCA) in a parameter space consisting of clustered database entries. To study the longevity and chemical evolution of crustal plutonic systems, the phase diagram database is coupled with a thermomechanical code (MVEP2). Basaltic sills are periodically injected into the crust to model heat influx from the mantle. Accumulated sills turn into long-lived mush chambers by using a lower rock cohesion or due to high intrusion depths. The resulting melts can be highly evolved and are extracted to form dikes in the overlying crust. Associated partial melting of crustal host rocks is promoted by the water amount, and occurs around dense distributed dikes and sills.



Snapshot of the magmatic system (after 1000 ka). Melts from the host rocks are extracted mostly from areas around the heat providing sills (a). Compositions of the system (b) and of the generated dikes (c) are shown on a TAS diagram for plutonic rocks. The colors of the circles represent the respective rock phases (a).

StagBL: A Modern Solver and Discretrization Library for Geodynamics - Advances and Benchmarks

- Patrick Sanan
  ETH Zurich
  patrick.sanan@erdw.ethz.ch

StagBL is an open-source parallel solver and discretization library for geodynamic simulation, encapsulating and optimizing operations essential to staggered-grid finite volume Stokes flow solvers. These form the basis for highly-efficient application codes for long-term mantle convection and lithospheric dynamics. extscStagBL prevents common bottlenecks to improving scalability, swapping solvers, adapting to new architectures, and optimizing performance. The extscStagBL project addresses these issues by providing a streamlined library to provide a path to performance from toy codes to quality, scalable implementations. It provides a parallel staggered-grid abstraction in C and Fortran, and an interface (`DMStag`) for PETSc. Planned features allow applications to define boundary conditions, interact with particle systems, and efficiently solve Stokes systems in small (direct solver), medium (simple preconditioners), and large (block factorization and multigrid) model regimes. By implementing common kernels beneath a uniform abstraction layer, StagBL enables optimization for modern hardware, thus reducing community barriers to large-scale parallel simulation on modern architectures, and a platform to develop innovative new tools. By working directly with leading application codes and providing an API and examples for others, StagBL aims to become a community tool supplying scalable, portable, reproducible performance to novel science in regional- and planet-scale geodynamics. We present the latest publicly-available version of StagBL, along with small application codes demonstrating its usage and performing scaling benchmarks.

Stress concentration from the upper mantle heterogeneity in the Central and Eastern United States

- Arushi Saxena
  Center for Earthquake Research and Information, University of Memphis
  asaxena@memphis.edu
- Eunseo Choi
  Center for Earthquake Research and Information, University of Memphis
- Christine Powell
  Center for Earthquake Research and Information, University of Memphis

The central and eastern US (CEUS) hosts a number of intraplate seismic zones including the New Madrid Seismic Zone (NMSZ) and the East Tennessee Seismic Zone (ETSZ), which generate thousands of small-magnitude earthquakes (Mw ¡ 5) annually. Most of these earthquakes lie on the preexisting weak structures created during two rifting episodes in Cambrian and Triassic time periods. These structures are favorably oriented for reactivation in the tectonic stress field. However, local stress fields from the upper mantle and crustal heterogeneities can also be a significant source of the region's deviatoric stresses. Here, we investigate the effects of upper mantle structures (deeper than 100 km) on the stress field in the CEUS using numerical modeling. We focus on two pronounced upper mantle features found in recent tomography studies of the CEUS. One is the anomalously low magnitude and similar spatial distribution of P and S wave anomalies in the depth range 100 to 250 km beneath the NMSZ (Nyamwandha et al., 2016). We attribute the low-velocity anomalies to elevated temperature, water content or orthopyroxene (Opx) content). The velocity anomalies are converted to temperature and viscosity variations under various combinations of these factors assuming Maxwell viscoelastic rheology in our time dependent numerical models. All the models consistently show stress concentration in the upper crust (¡ 20 km) from the weaker upper mantle. Opx content and high temperatures are favored because they can simultaneously satisfy Vp and Vs anomalies of a similar magnitude. The other upper mantle feature we considered is a large positive P wave anomaly west of the ETSZ at depth range 200 km to 600 km, that was interpreted as lithospheric foundering (Biryol et al., 2016). We setup instantaneous mantle flow models based on the temperatures converted from their tomography results, assuming diffusion and dislocation creep. We calculate differential stress and coulomb stress at optimal fault orientations of the seismic zones in the CEUS. Theoretically, we isolate the upper mantle effects by subtracting the results of the models having homogeneous upper mantle with the model based on all the heterogeneity calculated from the tomography. Our analysis implies that the upper mantle structures below the CEUS has notable contribution in increasing the stress state of the seismic zones. Moreover, these heterogeneities increase the Coulomb stress at preexisting fault orientations in the seismic zones, bringing them closer to failure.

[1] Nyamwandha, Cecilia A., Christine A. Powell, and Charles A. Langston. "A joint local and teleseismic tomography study of the Mississippi Embayment and New Madrid seismic zone." Journal of Geophysical Research: Solid Earth 121.5 (2016): 3570-3585.

[2] Biryol, C. Berk, et al. "Relationship between observed upper mantle structures and recent tectonic activity across the southeastern United States." Journal of Geophysical Research: Solid Earth 121.5 (2016): 3393-3414.

Back-arc ridge jumps in narrow slabs

- Nicholas Schliffke
  Department of Earth Sciences, Durham University, DH1 3LE, Durham, United Kingdom
  Nicholas.j.schliffke@durham.ac.uk

- Jeroen van Hunen
  Department of Earth Sciences, Durham University, DH1 3LE, Durham, United Kingdom

- Frédéric Gueydan
  Géosciences Montpellier, Université Montpellier 2, place E. Bataillon 34095 Montpellier cedex 5, France

- Valentina Magni
  The Centre for Earth Evolution and Dynamics (CEED), University of Oslo, SemSaelandsvei 24, PO Box 1048, Blindern, NO-0316 Oslo, Norway.

- Mark B. Allen
  Department of Earth Sciences, Durham University, DH1 3LE, Durham, United Kingdom

Back-arc rifting is observed in extensional subduction settings, where extensional stresses have caused rupture of the overriding lithosphere. In several narrow subduction zones with a long subduction history, such as the Scotia arc, central Mediterranean or Marianas, several ridges have been active in the course of history. Nearly instantaneously, the ridges have been jumping closer to the trench in a regular pattern. The dynamics behind this process remain unknown.

To understand this process we run 3D-models to simulate a long narrow slab subducting between two continental plates which retreats and creates necessary STEP-faults self-consistently. After the creation of a back-arc basin, transform faults between trench and back-arc basin form. Our results suggest that ridge jumps are a consequence of the fact that these transform faults, which link the ridge with the trench (and decoupling the overriding plate from neighboring plates), fail to remain active once the trench is too distant from the ridge. Without active transform faults, the overriding plate is coupled strongly to neighboring plates, the link between ridge and trench disappears, and a new ridge opens due to stress localization closer to the trench. In a parameter study, we show that the timing between ridge jumps are reduced for narrow slabs, and subduction fails completely for slabs narrower than 400km, where the energy to create STEP-faults is insufficient. Finally, the new ridge tends to form closer to the trench for narrower slabs, consistent with the location of maximum strain induced by the toroidal flow around the slab.

Two-phase flow modelling of partially molten continental crust: Evolution of magma bodies and mush zones for time-dependent heating modes

- Harro Schmeling
  Institute of Geosciences, Goethe University Frankfurt, Germany
  schmeling@geophysik.uni-frankfurt.de
- Pirunthavan Kumaravel
  Institute of Geosciences, Goethe University Frankfurt, Germany
- Herbert Wallner
  Institute of Geosciences, Goethe University Frankfurt, Germany

The physics of formation and evolution of magma bodies, and particularly of mush zones and eruptible melt caps within the continental crust is not well understood. We approach this problem by a thermo-mechanical-compositional two-phase flow formulation based on the conservation equations of mass, momentum, composition and energy for melt and solid. The approach includes compaction of the solid matrix and melting, melt segregation, melt ascent and freezing. We assumed meta-greywacke as the initial rock type and use a simplified melting law of a binary solid solution system to track chemical composition, i.e. the enrichment or depletion in SiO2 of the advected silicic melt and solid. The rheology is based on dislocation creep of quartzite or granite, and includes plasticity and the effect of melt porosity. As initial condition, one model series assumes supersolidus temperatures within the lower part of the crust. In this case melt separates from the solid matrix and accumulates in high melt porosity magma bodies within 10's ka. During and after this separation phase magma ascends by the newly discovered CATMA mechanism, which stands for ***C**ompaction/decompaction **A**ssisted **T**wo-phase flow **M**elt **A**scent* (Schmeling et al., 2019). Other melt ascent mechanisms observed in the models include diapirism and the spontaneous formation and rise of porous solitary waves. Melt - solid separation together with chemical separation result in a dual melt porosity distribution with melt rich magma bodies ($>60\%$ melt) collected in a cap on top of low melt fraction mushes ($<20\%$). The melt volume ratio of mush to cap is less or of the order of one, i.e. significantly less than estimates from natural examples such as the Altiplano-Puna magma body. Alternative models with time-distributed heat input mimicking episodic basaltic underplating events are shown in which the mush/cap melt volume ratio rises to values significantly larger than 1 (i.e. smaller cap volumes). The amount of heat input and episodicity is systematically varied, as well as the retention number controlling the melt mobility with respect to the matrix. The effect of these variations on the size and wavelength of the rising magma bodies as well as their emplacement depth is studied.

[1] Schmeling, H., G. Marquart, R. Weinberg, H. Wallner, 2019: Modelling melting and melt segregation by two-phase flow: new insights into the dynamics of magmatic systems in the continental crust. Geophys. J. Int., 217, 422 - 450

Scale-dependent rheology: insights from laboratory experiments

- Nicolò Rubens Sgreva
  Laboratoire FAST, CNRS/Univ. Paris-Sud/Univ. Paris-Saclay, Orsay, France
  nicolo.sgreva@u-psud.fr

- Ichiro Kumagai
  School of Science and Engineering, Meisei University, Hino, Tokyo 191-8506, Japan

- Anne Davaille
  Laboratoire FAST, CNRS/Univ. Paris-Sud/Univ. Paris-Saclay, Orsay, France

- Kei Kurita
  Earthquake Research Institute, University of Tokyo, Tokyo, Japan

Many geological processes, from the settling of crystals and nodules in a magma chamber to the upwelling of magma bodies in lithosphere, take place in systems that are heterogeneous in composition, density and mechanical properties. However, description and prediction of material flows in these systems requires the definition of an “effective rheology”. An important issue then is the scale on which this rheology will remain valid.

We therefore present here an experimental study using aqueous dispersions of superabsorbent polymers. In water, these polymer powder grains swell up to 200 times and form elastic gel grains whose size can be controlled by controlling the size of the initial powder. The rheology of the water-grains dispersions therefore combines viscous, elastic and plastic aspects. It can be investigated using the free-fall of spheres of different diameters (between 3 and 30 mm-diameter) and densities. As the typical size of the gel grains was varied between 1 and 6 mm, there is a range where it becomes comparable to the size of the falling spheres. We therefore systematically studied the influence of the grain size on the effective rheology of the aqueous dispersions.

We observe four different regimes for the fall of the spheres. (1) A steady-state motion where the sphere reaches a constant terminal velocity. It happens only for high density contrast between sphere and fluid and for spheres that are large enough compared with gel grain sizes. (2) An irregular regime where spheres have irregular vertical motion and horizontal oscillations. (3) A stop&go regime in which periods of no-motion, where the sphere’s vertical velocity goes to zero, and periods of irregular falls (linear or logarithmic) are followed one another. (4) A no-motion regime appears when spheres are not buoyant enough to overcome the yield stress of the fluid.

The first and the last regime are typical of a visco-elasto-plastic fluid, with a yield stress that depends on the size of the gel, but also on the size of the intruder. The other two regimes directly come from the interaction between the sphere and the gel scales, showing how the effective rheology is scale-dependent.

Slab dragging

- Wim Spakman
  Faculty of Geosciences, Utrecht Univ., the Netherlands
- Douwe J.J. van Hinsbergen
  Faculty of Geosciences, Utrecht Univ., the Netherlands
- Menno Fraters
  Faculty of Geosciences, Utrecht Univ., the Netherlands
  UC Davis, USA
- Cedric Thieulot
  Faculty of Geosciences, Utrecht Univ., the Netherlands

In the current subduction paradigm of plate tectonics, the *surface motion* of the subducting plate contributes to the sinking slab by plate motion perpendicular to the subduction trench. We recently discovered a new, potentially globally governing, role of subducting plate motion as driver of lateral transport of entire subduction systems. This occurs in the direction of the local 'absolute' motion of the subducting plate, i.e. plate motion in the mantle frame of reference. We call this process 'slab dragging', which represents the impact of the *globally* forced subducting-plate motion on *regional* subduction evolution.

In this presentation we present the concept of slab dragging, the few propositions since the early 80-ties, and some of the current evidence for slab dragging of the Gibraltar slab and the Tonga-Kermadec slab. The east-dipping Gibraltar slab is being transported to the NNE by the African plate at a rate of 6-7 mm/yr during the past ∼8 Myr (Spakman et al. 2018). The west-dipping Tonga-Kermadec slab has been transported northward by trench-parallel absolute Pacific plate motion by more than 1000 km in the past 30 Myr, i.e., at a rate of ∼30 mm/yr (van de Lagemaat et al. 2018). Such lateral transport of slab is locally resisted by the viscous mantle which in effect may impact on the tectonic evolution overhead as well as on slab morphology and subduction zone evolution. Lateral transport of slab has been largely overlooked since the advent of plate tectonics. We propose that slab dragging is a globally occurring process with potentially large impact on subduction evolution.

Towards 3D geodynamic modelling of the Altiplano-Puna magma system

- Arne Spang
  Johannes Gutenberg-University, Mainz, Germany
  arspang@uni-mainz.de

- Tobias S. Baumann
  Johannes Gutenberg-University, Mainz, Germany

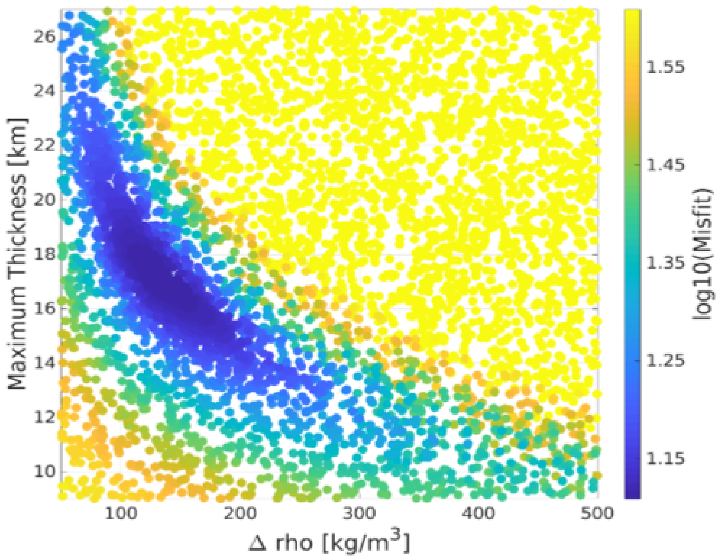
- Boris J. P. Kaus
  Johannes Gutenberg-University, Mainz, Germany

The Altiplano-Puna Magma Body (APMB) in the central Andes is considered to be the largest active melt zone in the Earth's crust today. For the past decades, multiple research projects have looked at the uplift rates above the APMB and successfully reproduced the observations with 2D or 3D numerical models, using simplified (elastic) rheologies and/or source geometries.

Yet, rocks are not just elastic but have a temperature-dependent viscoelastic rheology. Here, we therefore develop 3D models of the system using such more realistic rheologies, while also taking observed gravity anomalies into account. By forward modelling the gravitational effect of the APMB and the thickened Andean crust, we try to unite geometries inferred from S-wave tomography with crustal density models and bouguer data.

The resulting 3D setup and the 3D thermo-mechanical finite difference code LaMEM is then used to make predictions about surface deformation which can be compared to observations made by InSAR and GPS studies. The ultimate goal is the creation of a numerical model which is consistent with a large amount of geophysical data and can be used to better constrain the geometry and geophysical properties of the APMB as well as to understand why uplift rates at the surface above it have decreased since the mid-2000s.

We find that only an APMB with a maximum thickness of 13 to 19 km and a corresponding density contrast to the surrounding host rock of 100 to 200 kg/m3 satisfies both, tomography and bouguer data. Furthermore, results of early geodynamic models suggest that the observed surface deformation can be reproduced by the buoyancy effect of the APMB alone.



Misfit between the forward modelled bouguer anomaly and the observed anomaly for a range of APMB thicknesses and $\Delta\rho$. Result of 6000 models (4000 initial + 2000 through neighborhood algorithm) within in the 3D parameter space projected onto the two most influencial parameters (depth being less influencial).

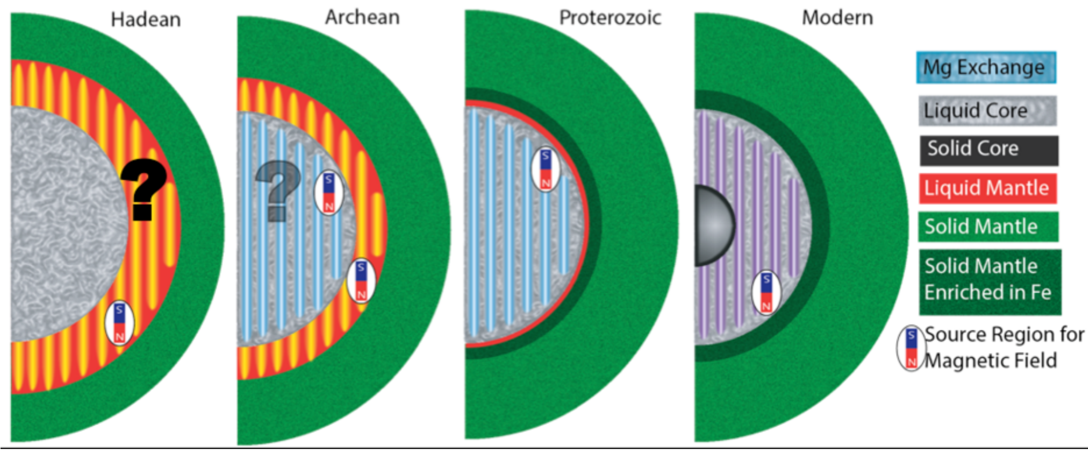
Thermal and magnetic evolution of a basal magma ocean

- Dave Stegman
  Scripps Institution of Oceanography, UC San Diego
  dstegman@ucsd.edu
- Nic Blanc
  Scripps Institution of Oceanography, UC San Diego
- Leah Ziegler
  Oregon State University, CEOAS

Paleomagnetic evidence suggests Earth maintained a magnetic field since 3.2Ga [1], and claims exist for even as early as 4.2Ga [2]. However, revised values for the thermal conductivity of Fe at core conditions [3] pose considerable challenges for conventional mechanisms of generating a dynamo over Earth's history as the larger adiabatic heat flows imply rapid secular cooling, a young (i.e. 500 Myr) inner core, and thermal evolution models with supersolidus mantle temperatures [4]. This has lead to proposals for alternative dynamo sources including a dynamo generated in a long-lived basal magma ocean (BMO) [5], and compositional buoyancy driven by exsolution of Mg [6,7] or Si [8] from the core into the mantle.

It has been proposed that following the Moon-forming impact, the Earth becomes molten and as such high T (>5000K), Mg and/or Si can partition into the metallic core and replace 3% of the core's mass. After sufficient secular cooling of the core, Mg will precipitate and provide a compositional power source for a core dynamo. The exchange coefficients measured in diamond anvil cell experiments were across an interface between large, well-mixed reservoirs of liquid metal and liquid silicate [6]. Thus, these results are only applicable to scenarios in which a liquid core is exchanging with a molten silicate mantle, such as the proposed basal magma ocean [9]. Thermal evolution models that appeal to these exsolution mechanisms require a basal magma ocean in order to be internally consistent with the reported exchange rates. Further, previous exchange rates were reported assuming a pyrolitic mantle composition for the liquid silicate [6]. However, the strength of Mg-exsolution is unlikely to be able to power a dynamo within the first 500 Myr of Earth's history, and therefore the most likely candidate for explaining any possible magnetic field generation during this time would be a field generated within the BMO. Recent studies indicate the electrical conductivity of liquid silicates at high temperatures are semi-conductive and probably sufficient to allow for dynamo generation.

We present a model of the thermal evolution of a basal magma ocean under conditions of a cooling mantle. We adopt an adiabatic gradient within the BMO as 1 K/km and a melting curve appropriate for bridgemanite with a parameterized melting point depression due to concentration of Fe and other impurities as the BMO solidifies. We show the evolution of the sources and sinks of entropy, including the Ohmic dissipation used as indication of magnetic field generation, for a variety of scenarios adapted for the early Earth.



Possible sources of dynamo generation over Earth history (left to right). Hadean: BMOD only; Archean: BMOD combined with Mg-X; Proterozoic: Mg-X and core cooling; Modern: Inner core growth

Effects of asthenospheric drag on subduction dynamics using 2D numerical models

- Lior Suchoy
  Department of Earth Science and Engineering, Imperial College of London, South Kensington Campus, London, UK
  l.suchoy17@imperial.ac.uk

- Benjamin Maunder
  Department of Earth Science and Engineering, Imperial College of London, South Kensington Campus, London, UK

- Saskia Goes
  Department of Earth Science and Engineering, Imperial College of London, South Kensington Campus, London, UK

It is well established that plate motions on Earth are largely driven by the pull of subducting slabs. Among resistive forces, drag at the base of the lithosphere has been proposed to be minor because of the lack of correlation between plate size and velocity. However, analytical calculations of drag indicate it may be of the same order of magnitude as slab pull for large plates such as the Pacific.

To achieve a relatively low contribution of drag, previous numerical models have lowered the asthenosphere to lithosphere viscosity ratio by either decreasing the former or increasing the later. A low drag has also been shown to affect trench mobility, allowing for instances of trench advance, which are observed for about 20% of the trenches on Earth.

In this study, we test and re-evaluate these ideas using 2D numerical thermo-mechanical models of subduction in Fluidity, a finite element modelling code with adaptive gridding for viscous flow.

We compare the behaviour of short and long plates for a range of asthenospheric viscosities and plate strengths. We find that a lower viscosity asthenosphere can indeed reduce trench retreat and is correlated with periods of modest amounts of trench advance.

However, we find that any combination of asthenosphere and plate viscosity that produces realistic subduction behaviour does not remove the dependence on plate size. Moreover, any trench advance periods observed are linked to a non-Earthlike forward roll of the slab at the 660 km discontinuity.

We therefore propose that drag does not play a significant role in allowing trench advance on Earth. Nevertheless, drag significantly buffers slab pull in large plates. Since slab age and plate size tend to increase together in nature, this would mask the effects of plate size on plate velocity. This co-dependency between plate velocity, age and length should be considered when modelling such systems.

A coupled petrological-geodynamical model for magma storage and migration in the upper crust

- Baolu Sun
  Institute of Geosciences, Johannes Gutenberg University of Mainz, Mainz 55128, Germany
  State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China baolusun@uni-mainz.de

- Boris Kaus
  Institute of Geosciences, Johannes Gutenberg University of Mainz, Mainz 55128, Germany

- Lisa Rummel
  Institute of Geosciences, Johannes Gutenberg University of Mainz, Mainz 55128, Germany

- Andrea Piccolo
  Institute of Geosciences, Johannes Gutenberg University of Mainz, Mainz 55128, Germany

- Liang Zhao
  State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

The origin, occurrence and evolution of granite have been a long-standing debate within the geosciences, and is fundamental to our comprehension of the formation and differentiation of continental crust. Here we designed a coupled petrological and geodynamical model using Perple_X and LaMEM, a parallel 3D numerical code which can be used to model various thermomechanical geodynamical processes in lithosphere and mantle, to investigate the dynamics of a mid-crustal magma chamber to which pulses of magmatic melt from the mantle are added. Our results demonstrate that multiple pulsing plays a crucial role for magma migration in a homogeneous tectonic background. We also explore the magmatic chamber dynamic by incorporating melting reactions into the simulations.

Strength and effective elastic thickness variations of the Australian plate: a combination of temperature and compositional changes

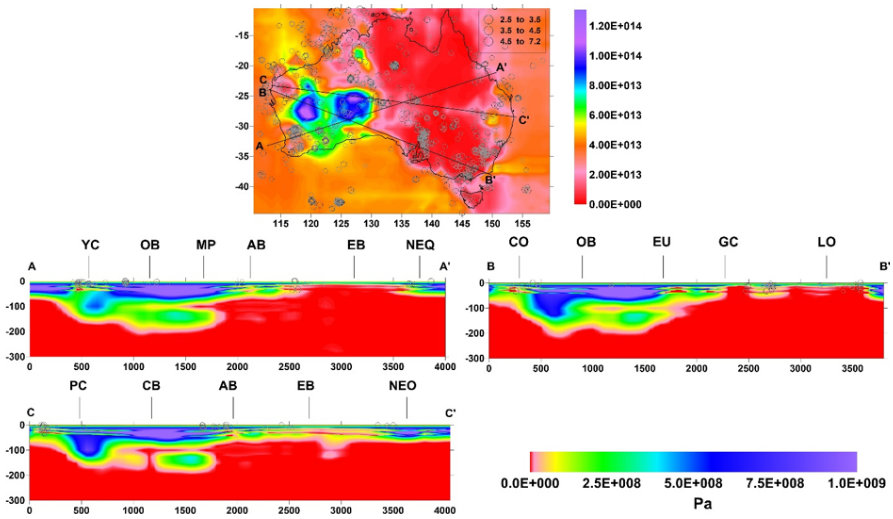
- Magdala Tesauro
  Department of Mathematics and Geosciences University of Trieste, Italy
  Department of Earth Sciences, University of Utrecht, Utrecht, Netherlands
  mtesauro@units.it

- Mikhail K. Kaban
  German Research Centre for Geosciences (GFZ) Potsdam, Germany
  Schmidt Institute of Physics of the Earth, Moscow

- Alexey G. Petrunin
  German Research Centre for Geosciences (GFZ) Potsdam, Germany
  Schmidt Institute of Physics of the Earth, Moscow

- Alan Aitken
  University of Western Australia

The Australian plate is composed of several terranes from Archean in the west to Phanerozoic in the east and has a long and complex tectonic history. The crust and upper mantle of Australia have been deeply investigated in the last two decades using a variety of geophysical methods. In this study, we discern temperature and compositional variations of the Australian upper mantle, by applying an iterative technique, which jointly interprets seismic tomography (AuSRem model, http://rses.anu.edu.au/seismology/AuSREM/index.php) and gravity data. The results obtained show that the Precambrian West and North Australian Craton (WAC and NAC) each possess thick, relatively cool, lithosphere that has depleted composition (Mg# > 90). The depletion is stronger in the older WAC than in the younger NAC. Substantially hotter and less dense lithosphere is observed in the eastern and southeastern margin of the continent, resolving the thermal perturbations due to Mesozoic and Cenozoic events. We used the surface heat flow values recently published and the crustal seismic velocity distribution from the AusREM model to estimate the heat generation and temperature distribution in the crust, assuming steady state conditions. The new crustal and upper mantle thermal model is used to estimate strength (Fig. 1) and effective elastic thickness (EET) distribution in the lithosphere. For this aim, we use crustal rheology variations based on the seismic velocity distribution, considering that low velocities reflect more sialic composition and weak rheology compared to the crust characterized by high velocities. Furthermore, we used strain rate values obtained from a global mantle flow model constrained by seismic and gravity data. We observe a strong relation between the strength and EET variability with the temperature distribution with the more rigid areas localized in the WAC. On the other hand, the crustal rheology and strain rate variations tend to enhance and decrease the effect of temperature on the plate rigidity, respectively.



Integrated strength distribution (Pa m) in the lithosphere and strength distribution (Pa) along three cross-sections, estimated using crustal rheology variations, based on seismic velocity distribution, and strain rate values obtained from a global mantle flow. Grey circles show earthquakes location.

Reconstruction of the structure and tectonic evolution of the cratonic lithosphere of the Congo Basin using geophysical data and 3D numerical models

- Francesca Maddaloni
  Department of Mathematics and Geosciences University of Trieste, Italy
  francesca.maddaloni@phd.units.it
- Damien Delvaux
  Royal museum of central Africa, Tervuren, Belgium
- Jessica Munch
  Institute of Geophysics, ETH Zürich, Zurich, Switzerland
- Magdala Tesauro
  Department of Mathematics and Geosciences University of Trieste, Italy
  Department of Earth Sciences, University of Utrecht, Utrecht, Netherlands
- Taras Gerya
  Institute of Geophysics, ETH Zürich, Zurich, Switzerland
- Carla Braitenberg
  Department of Mathematics and Geosciences, University of Trieste, Trieste, Italy

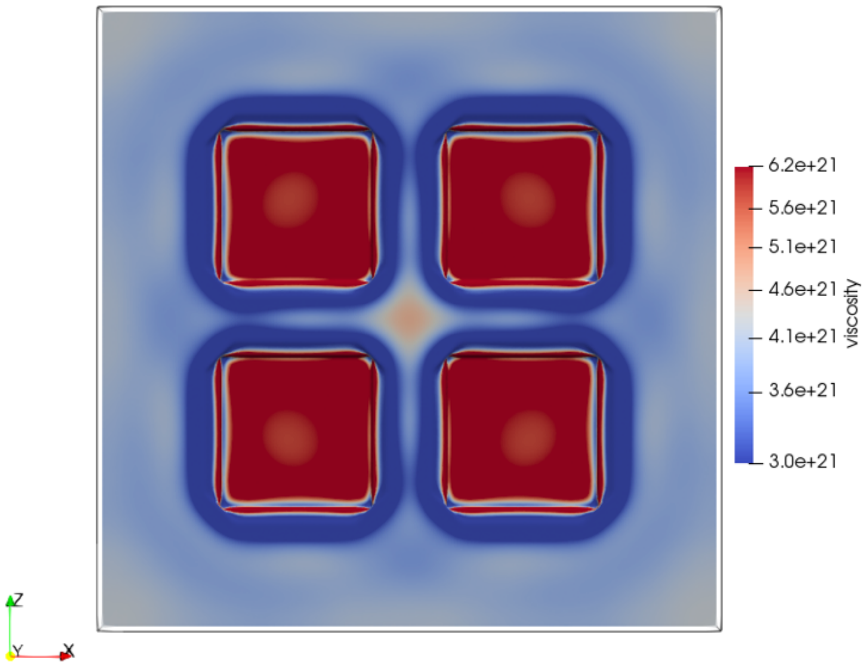
The Congo Basin (CB) straddles the equator in central Africa and occupies a large part of the Congo Craton ($\sim$ 1.2million km2), covering approximately 10% of the continent [1]. It contains up to 9 km of sedimentary rocks from Mesoproterozoic until Quaternary age. The formation of the CB started with a rifting phase during the amalgamation of the Rodinia supercontinent (1.2 Gyr) and evolved through the following post-rift thermal subsidence phase. Since Cretaceous, the CB is subjected to an intraplate compressional setting due to ridge-push forces [2].

The aim of this study is to simulate the mechanisms of formation and evolution of the Congo basin. For this purpose, we have first interpreted the seismic reflection profiles and well logs data located inside the central area of the CB (Cuvette Central). The results were successively compared with those obtained from the analysis of the relationship between topography and Bouguer anomalies (residual gravity data). In this way, we could identify the areas characterized by negative residuals, corresponding to large thickness of low density sediments and positive residuals, indicating the presence of mafic intrusions, likely occurred during the rift phases. Afterwards, we performed 3D numerical models using I3ELVIS code [3], in order to simulate the movements of the four cratonic blocks composing the Congo shield, during the initial rift phases (Fig. 1). We applied extensional stress in two orthogonal directions, to test the hypothesis of the formation of a multi extensional rift in a cratonic area. We performed the numerical simulations for different geometry configurations, thicknesses of the cratonic blocks, and physical parameters (e.g., temperature and rheology), in order to get the best agreement with the results obtained from the previous analysis.

[1] Kadima, E., Delvaux, D., Sebagenzi, S.N., Tack, L., Kabeya, S.M., (2011), Structure and geological history of the Congo Basin: an integrated interpretation of gravity, magnetic and reflection seismic data, Basin Research, 23, 5, October 2011 pp. 499 – 527, 10.1111/j.1365-2117.2011.00500.x

[2] De Wit, M.J., Stankiewicz, Jacek, Reeves, C.V., (2008), 399, 412, Restoring Pan-African-Brasiliano connections: more Gondwana control, less Trans-Atlantic corruption, 294, 10.1144/SP294.20, Geological Society, London, Special Publications.

[3] Gerya, T., Introduction to numerical geodynamic modelling, Cambridge University Press. T. Gerya 2009.



Example of numerical model displaying lateral viscosity variations (Pa s) at the base of the lithosphere at the time step 460 Myr. The experiment has been conducted dividing the area into four cratonic blocks of size 1000 km x 1000 km, subjected to multi-extensional stresses into two orthogonal directions (N-S and E-W). The vertical size of the cratonic blocks and of the area off-cratons is 250 and 200 km, respectively. The Moho depth is located at a depth of 35 km.

Impact of ferropericlase elongation on lower mantle rheology.

- Marcel Thielmann
  Bavarian Geoinstitute, University of Bayreuth
  marcel.thielmann@uni-bayreuth.de

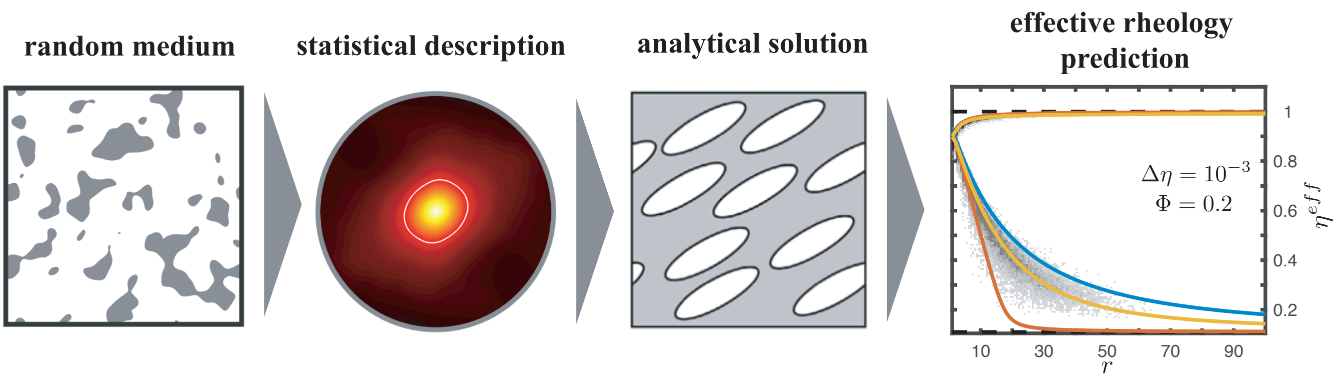
- Gregor J. Golabek
  Bavarian Geoinstitute, University of Bayreuth

- Hauke Marquardt
  Department of Earth Science, University of Oxford

Rocks in the Earth's lower mantle are not homogeneous, but consist of the mineralogical phases bridgmanite and ferropericlase exhibiting different rheological properties. When deformed, these heterogeneous rocks therefore also exhibit heterogeneous deformation, which depends on the rheological contrast between the different phases and their distribution within the rock. The effective properties of such heterogeneous mixtures have received a significant amount of attention in the past, but it has not yet been possible to link random weak phase topologies to the effective rock rheology.

Here we use a numerical approach to gain insight into the relationship between phase distribution topology and the effective rheology/ deformation of two-phase rocks. To this end, we prescribe the distribution of weak phases is using random fields and deform the resulting structures in pure shear. The usage of random fields allows us to prescribe a certain topology of the weak phase and to investigate its effect on bulk properties. Adding a weak phase has several effects: First, the internal strain rate, stress and pressure fields become strongly heterogeneous, thus resulting in at times unexpected behavior and localization of deformation. Second, the bulk rock is weakened. The amount of weakening strongly depends on the topology of the weak phase as well as on its rheology. We performed a large number of simulations for different viscosity contrasts, volume fractions and weak phase topologies to obtain the desired amount of data needed for statistical analysis of bulk rock deformation properties. We then link the statistical properties of the weak phase distribution to the effective rheology using an analytical solution.

Results show that the usage of appropriate statistical descriptors together with analytical solutions for simplified weak phase topologies makes it possible to capture the impact of a randomly distributed weak phase and to predict the effective anisotropic rheology of a ferropericlase-bridgmanite mixture.



Workflow scheme to obtain effective viscosity predictions for random heterogeneous media.

Recovering Coulomb angle-oriented shear bands in numerical visco-plastic geodynamical models

- C. Thieulot
  Department of Earth Sciences, Faculty of Geosciences, Utrecht University, the Netherlands.
  c.thieulot@uu.nl

- J. Naliboff
  Department of Earth and Planetary Sciences, University of California, Davis, CA 95616, USA.

- T. Heister
  Mathematical Sciences, Clemson University, O-110 Martin Hall, Clemson, SC 29634-0975, USA.

The vast majority of long-term tectonic and mantle dynamics codes now rely on thermo-mechanical approaches that include highly nonlinear elasto-visco-plastic rheologies. In nearly all cases, plasticity is implemented using a Drucker-Prager (or similar) yield function in combination with a 'viscosity rescaling method' to ensure viscous stresses never exceed the yield function. Despite decades of use, this approach remains problematic and exhibits numerous unwanted features: 1) the angle of the recovered shear bands is not stable and only recovers laboratory values at sufficiently high resolutions; 2) the width of the shear bands is very resolution-dependent; 3) pressure-dependent yield functions often exhibit poor scaling behavior (Spiegelman et al., G3, 2016).

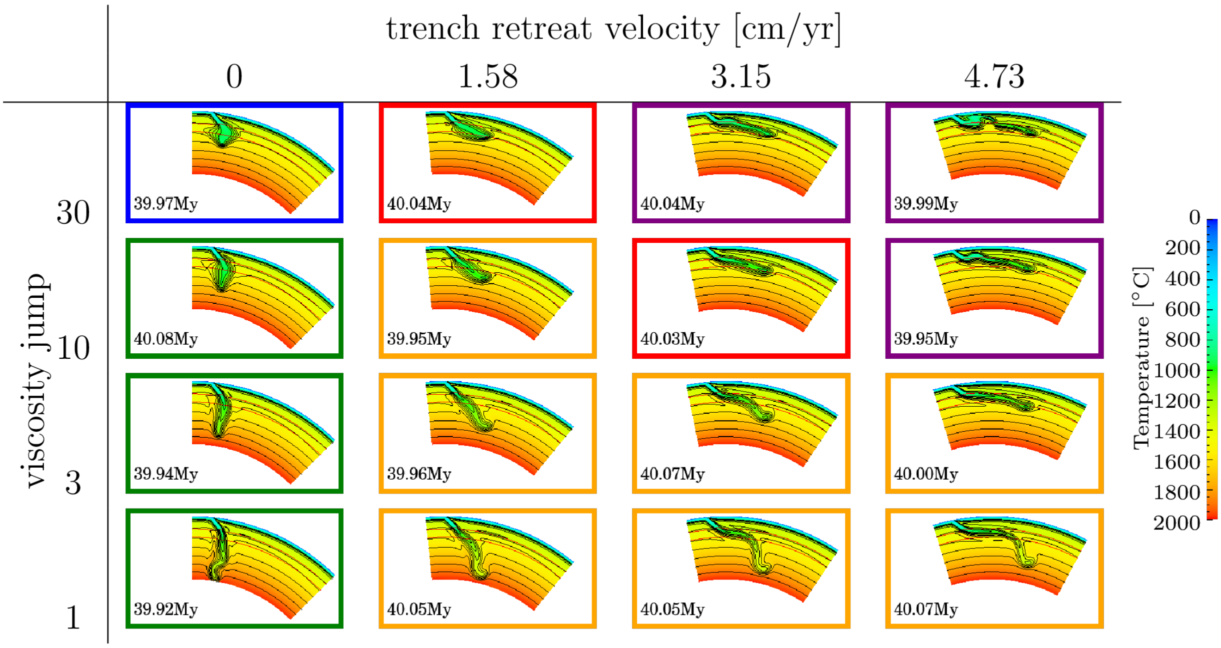
To address these issues, we have recently implemented a slightly modified form of the associative plasticity formulation of Choi & Petersen (Tectonophysics 657, 2015) with the mantle and lithospheric dynamics code ASPECT (Heister et al., GJI 210, 2017). Although the shear band width remains mesh-dependent, this implementation recovers the expected shear band angles in simple brick experiments (Lemiale, PEPI 171, 2008; Kaus, Tectonophysics 484, 2010; Glerum, Solid Earth 9, 2018) independent of the grid spacing.

We will present these results obtained with ASPECT using the Adaptive Mesh Refinement capabilities of the code for both compression and extension brick experiments, as well as additional geodynamic applications.

2-D numerical simulations on formation and descent of stagnant slabs: Important roles of trench migration and its temporal change

- Mana Tsuchida
  Geodynamics Research Center, Ehime University, Matsuyama, Japan
  tsuchida@sci.ehime-u.ac.jp
- Masanori Kameyama
  Geodynamics Research Center, Ehime University, Matsuyama, Japan

We conducted numerical simulations of thermal convection of highly viscous fluids in a 2-D cylindrical geometry, in order to study what mechanisms control the dynamic behaviors of subducting slabs such as the formation of "stagnant slabs" in the mantle transition zone (MTZ) and their descent into the lower mantle. Two series of experiments are performed here, by varying the history of migrating motion of "trench" where the slab of cold fluids descends from the top surface. In the first series of experiments, we carried out calculations where the migration rate of the trench is assumed to be constant with time, together with systematically varying the velocities of subducting slabs and trench migration, the Clapeyron slope at around 660 km depth, and the viscosity jump between the upper and lower mantle. Our model successfully reproduces the diverse morphology of subducting slabs. In particular, as is summarized in Figure 1, the behaviors of slabs around MTZ can be classified into five types depending on the delicate combinations of varying parameters: Penetrating (P), Accumulating (A), Floating (F), Long-term Stagnation (LS), and Short-term Stagnation (SS). In the second series of experiments, we take into account the temporal changes in the rate of trench retreat, by imposing its step-like change with time. We found that a sudden stop of trench retreat makes the already-formed stagnant slabs (LS and SS in the first series of our experiment) start to collapse into the lower mantle. A careful inspection of their dynamic behaviors shows that the style and course of the descent strongly depend on the slab shapes at the time instance of the sudden stop of the trench retreat. The results of our experiments suggest that the formation and descent of stagnant slabs are strongly related to the trench retreat, particularly through its temporal changes. In other words, the variations in the shapes of subducting slabs in nature, including those observed in Northeast Japan, Izu-Bonin, Mariana, Tonga, and Java subduction zones, are most likely to reflect the difference in the history of trench migration.



Snapshots of the distributions of temperature (T) at around 40 My after the initiation of subduction for cases with different values of the trench retreat velocity and viscosity jump. The Clapeyron slope and the plate convergence velocity are set to be -1 MPa/K and 7.88 cm/yr for all cases in this figure, respectively. The color scale for T is shown at the right side of figure. The frame colors correspond to five slab shape type: P (green), A (blue), F (purple), LS (red), SS (orange).

Mapping mantle flow beneath migrating mid-ocean ridges with analogue models

- Loes van Dam
  University of Rhode Island, Graduate School of Oceanography
  loesvd16@my.uri.edu

- Chris Kincaid
  University of Rhode Island, Graduate School of Oceanography

Analogue models of mantle flow at migrating mid-ocean ridges reveal the importance of taking realistic plate motions into account. We use a set of counter-rotating belts suspended from a drive system to simulate the effects of various spreading and migration rates on mantle flow in a large reservoir of glucose syrup. This viscous fluid is commonly used in analogue experiments to represent the upper mantle. DSLR cameras image beads and whiskers that are seeded throughout the reservoir to indicate general flow pathlines and shear flow directions, and the resulting images are processed with a particle tracking velocimetry (PTV) software system. The relationships we derive highlight the three-dimensional nature of mantle flow and upwelling. High migration rates relative to spreading rates cause increasing degrees of lateral transport. Experiments with oblique ridge migration reveal that a three-dimensional understanding of mantle flow is critical and that material transport from the leading plate becomes convoluted around transform offsets. Geochemical data and seismic anisotropy measurements should therefore be interpreted in terms of realistic plate motions and associated geodynamic models.

Constraining Grain Boundary Diffusion within the Earth's Lower Mantle

- Jac van Driel
- John Brodholt
- David Dobson

Diffusion creep is widely acknowledged as a fundamental process defining lower mantle viscosity. It is comprised of both lattice and grain boundary diffusive events. And, while significant progress has been made in constraining the self-diffusion rates through crystalline structures, far less is known about the nature of grain boundary diffusion at lower mantle conditions. Representing the largest interconnected defect structure, grain boundaries are of intrinsic mechanical significance, allowing for both fast diffusion pathways and impurity accumulation.

Before diffusivity can be calculated, the most stable atomic arrangements of an interface at a given P-T condition must first be established. Here a fully ab-initio random structure search has been applied to construct a library of low energy interfacial structures, enabling variation in both the atomistic configuration and local chemistry alike. The construction of such a library provides a means of understanding trends in interfacial energies and volumes as a function of pressure and chemistry.

A select number of low energy interfaces are then subjected to large scale molecular dynamics calculations. In which the interfacial diffusivity is found through combining the species specific means squared displacement and the kubo-green relation.

By following this approach and referring to known lattice diffusivities, an expression for a grain size dependant viscosity between pressures 20-140 GPa and grain-sizes between 10-1000 microns has been estimated. Results from this study have allowed us place constraints on the mantle grainsize and relative slab strength.

Wet Grain Boundaries of the Earth's Lower Mantle

- Jac van Driel
- John Brodholt
- David Dobson
- Josh Muir

The incorporation of water into lower mantle phases has been suggest to influence large scale dynamics of Earth's interior through hydraulic weakening. While much as has been speculated about the various anhydrous and hydrous lower mantle phases, little is known about the partitioning of hydrogen between the crystalline lattice and the surrounding network of grain boundaries.

This study establishes partition coefficients for protonic defects between grain boundaries and MgSiO3 Bridgmanite. Exploring pressures of 25-125 GPa and temperatures of 1000-4000K, all formation enthalpies are calculated through plane wave density functional theory as implemented by VASP. Utilising low energy interfaces of MgSiO3 Bridgmanite interfaces as predicted in a recent study, it is found that formation enthalpies for hydrogen partitioning can be up 4eV lower than the lattice. Even when considering configuration entropy, it was found that hydrogen preferentially segregates onto the grain boundary.

Results show that at grain sizes smaller that 0.1mm, interfaces will act as the dominant sink for protonic defects. However at larger grain sizes, the majority of the total water will be incorporated into the lattice interior. While large grainsizes will result in interfaces no longer acting as the dominant sink, grain boundaries themselves will maintain high concentrations of protonic defects; replacing up to 10% of available magnesium sites. In conjuncture with such high concentrations of protonic defects, a significantly enhancement grain boundary diffusivity is expected.

On the way improving melt extraction mechanism by dyking in a two-phase flow approach for melt ascending in continental crust

- Herbert Wallner
  Institut für Geowissenschaften, Goethe University, Frankfurt a.M., Germany
  wallner@geophysik.uni-frankfurt.de

- Harro Schmeling
  Institut für Geowissenschaften, Goethe University, Frankfurt a.M., Germany

The physics of melting and melt ascent within the continental crust is important for understanding magmatic systems with its various processes contributing to the crust's structural and compositional evolution.

We apply a thermo-mechanical-compositional two-phase flow formulation based on conservation equations of mass, momentum, energy, and composition for solid and melt. Full compaction of the solid matrix, melting, melt segregation, and freezing is included. The rheology is non-linear visco-plastic using power law parameters of quartzite and Byerlee's Law for plasticity. For melting a simplified binary melting model is utilized. Meta-greywacke serves as the initial rock type for solidus and liquidus definitions. Melt mobility depends on the viscosity of the melt and the permeability of the partially molten rock; they essentially determine the Retention number.

Plutonism and melt ascent in the crust, can be modelled by this physics as shown by Schmeling et al. 2019. However, observations show additional fast melt transport mechanisms acting on a short time scale. These symptomatically cannot be handled numerically by the same approach due to the big difference of time-step length of several orders.

Extraction of melt and its intrusion in a given emplacement level or extrusion to the surface is a widely used practice to replace fast melt transport. We use a parametrization of three critical parameters where vertically connected partially molten zones serve as source region. The source regions undergo compaction, inducing under-pressure attracting ambient melt. In a higher, colder crustal level the emplaced melt dilatates the matrix, and usually freezes immediately; heating and an increase of enrichment occurs. Such approaches locally violate mass and momentum equations more or less, and, more importantly, magma is redistributed at ad-hoc positions. Argumentation for intrusion levels are low constraint and do not follow the idea of self-consistency.

The most obvious fast magma transport mechanism through the subsolidus region is dyking. Our aim is the combination of two-phase flow physics and consistently draining the melt from the top of the partially molten regions, emplace the fast transported magma volumes and feed them back complying conservation laws. The fast dyking event occurs within a time step of the slow viscous flow. Dyking can be subdivided in the nucleationor generation, the propagation in an elastic medium exposed to regional stresses, and stagnation of dykes. Preliminary partial solutions exist, but will be improved by advanced methods. Implementation is in progress; last results will be presented.

[1] Schmeling, H., G. Marquart, R. Weinberg, and H. Wallner (2019), Modelling melting and melt segregation by two-phase flow: new insights into the dynamics of magmatic systems in the continental crust, *Geophysical Journal International, 217(1)*, 422-450.

The Himalaya from mantle to biosphere

- Alexander Webb
  U Hong Kong (Hong Kong S.A.R. China)
  aagwebb@hku.hk

- Laurent Husson
  ISTerre Grenoble (France)

- Fabien Condamine
  U Montpellier (France)

- Ryan McKenzie
  U Hong Kong (Hong Kong S.A.R. China)

- Peter Clift
  Louisiana State U (USA)

- Anne Replumaz
  ISTerre Grenoble (France)

- Tianyi Shen
  China U Geosciences Wuhan (China)

- Pieter van der Beek
  ISTerre Grenoble (France)

- Pierre Sepulchre
  CNRS-LSCE (France)

Most Himalayan mountain-building models consider the orogenic evolution in two-dimensional, cross sectional view. Here we show that the three-dimensional evolution of Himalayan mantle processes correlates well with Himalayan crustal deformation throughout Oligocene and Miocene time. The mantle processes inferred from seismic tomography and south Tibetan magmatism include underthrusting of India beneath Tibet until ∼30 Ma, delamination and relative rollback of the Indian slab to a steep orientation beneath the northern Himalaya by ∼25 Ma, tearing off of the slab from the eastern and western ends of the range to the east-central Himalaya from ∼25 Ma to ∼13 Ma, and renewed underthrusting following slab breakoff. Correlative crustal deformation records include: (1) a shift in metamorphic processes in the Himalayan core at ∼25 Ma; (2) cessation of motion along the South Tibet fault (marking the top of the Himalayan crystalline core) is progressively younger from ∼25 Ma in the western Himalaya to ∼13 Ma in the east-central Himalaya; and (3) concomitant younging of rapid exhumation of the Himalayan core from west to the east-central Himalaya from ∼25 Ma to ∼13 Ma. We therefore offer a three-dimensional model of the solid Earth system which shows that crustal mountain building processes are largely guided by mantle kinematics. In this model, the Himalayan sole thrust steepens during relative slab rollback, and thus deep crustal accretion at depth accelerates to maintain critical taper, resulting in a deep duplex system developing between the sole thrust and the South Tibet fault. This duplex system shuts off progressively as slab detachment migrates along the strike of the Himalaya, the Himalayan sole thrust shallows in response, and the locus of accretion migrates forward to lessen the orogenic taper.

This new model includes dynamic topography showing a rise in the range crest across the early and middle Miocene which correlates with the intensifying south Asian monsoon. Recent modeling by other researchers suggest a linear causality: increasing topography produces monsoon intensity in this system. Therefore, our model postulates a new mechanism by which mantle dynamics can lead to climatic change. In turn, topographic and climatic change can lead directly to environmental and ecological change. Our preliminary explorations suggest that the timing of changes in all these systems may be correlated in Oligocene and Miocene time. Such correlation may be ultimately suggestive of a bottom-up causality, from mantle processes to biodiversification. Future work will explore this potential causality and concomitant feedback mechanisms.

Observed residual depth anomalies, shear wave velocity, basaltic magmatism and mantle convection at rifted margins

- Nicky White
  Bullard Laboratories, Department of Earth Sciences, Madingley Rise, Madingley Road, Cambridge, CB3 0EZ
  njw10@cam.ac.uk

The success of rifting models often conditions the way in which we think about the large-scale structure of deep-water margins. For example, generation of subsidence and/or uplift is usually linked to the isostatic interplay of crustal and lithospheric thinning, which are ultimately controlled by horizontal plate motions. Despite this success, there is growing evidence that both vertical movements and heatflow anomalies at these margins can be influenced by sub-plate processes. It is generally agreed that convective circulation of the Earth's mantle maintains plate motion. However, we know little about the spatial and temporal details of this circulation. It is reasonable to expect that this circulation pattern generates and maintains dynamic (i.e. transient) topography, as well as affecting heatflow, at the Earth's surface. On the continents, small dynamic topographic signals are difficult to measure because the density structure of the crust and lithosphere is poorly known. More rapid progress can be made by exploiting our quantitative understanding of the thermal evolution of oceanic lithosphere. Seismic reflection and legacy seismic wide-angle profiles have been used to measure residual depth anomalies worldwide. Positive and negative deviations from the global age-depth curve are common along deep-water margins and have amplitudes of +/- 1 km and wavelengths of 100-10000 km. Spherical harmonic analysis of these observations shows that the results of computational models that calculate dynamic topography from the distribution of mantle mass anomalies are substantially incorrect. However, observed residual depth anomalies are consistent with long-wavelength gravity anomalies and with upper mantle seismic tomographic anomalies. Along the West African margin, a series of broad structural domes straddle the continental shelf. Uplifted marine terraces, offshore stratigraphic geometries, and fluvial drainage networks suggest that these gigantic features mostly grew in Neogene times and influenced regional heatflow. Along the northwest shelf of Australia, oceanic depth anomalies show that a broad depression intersects the coastline. Here, we observe rapid post-Miocene subsidence which is recorded by a dramatic switch from aggradation to progradation within a buried coral reef. This switch caused organic-rich source rocks at depth to enter the hydrocarbon window and charge overlying structural traps. In the North Atlantic Ocean, buried ephemeral landscapes have recently been mapped on three-dimensional seismic surveys. Their existence implies that rapid (i.e. 1 million year) transient uplift events occurred during Cenozoic times. We attribute these vertical movements to periodic fluctuations within the Icelandic plume. These three examples suggest that mantle convection plays a significant, and hitherto underestimated, role in moderating vertical movements and stratigraphic architecture at deep-water margins.

The evolution and distribution of recycled oceanic crust in the Earth's mantle: Insight from geodynamic models

- Jun Yan
  Institute of Geophysics, ETH Zurich, Zurich, Switzerland
  jun.yan@erdw.ethz.ch
- Maxim D. Ballmer
  Institute of Geophysics, ETH Zurich, Zurich, Switzerland
- Paul J. Tackley
  Institute of Geophysics, ETH Zurich, Zurich, Switzerland

A better understanding of the compositional structure of the Earth's mantle is needed to place the geochemical record of surface rocks into the context of Earth accretion and evolution. Cosmochemical constraints imply that lower-mantle rocks may be enriched in silicon relative to upper-mantle pyrolite, whereas geophysical observations tend to support whole-mantle convection and mixing. To resolve this discrepancy, it has been suggested that mid-ocean ridge basalt (MORB) of recycled oceanic crust segregates from harzburgite to be accumulated in the mantle transition zone (MTZ) and/or the lower mantle. However, the key parameters that control MORB segregation and accumulation remain poorly constrained. Here, we use global-scale 2D thermochemical convection models to investigate the influence of mantle-viscosity profile, plate tectonics and bulk composition on the evolution and distribution of chemical heterogeneity. In particular, we focus on the accumulation of subducted MORB/harzburgite in/beneath the MTZ. Our models robustly predict that, for all cases with Earth-like tectonics, a MORB-enriched reservoir is formed in the MTZ, and a corresponding harzburgite-enriched reservoir is formed just beneath the MTZ. This result is largely independent of the mantle viscosity profile, and explained by a balance between delivery and removal of MORB/harzburgite through deep-rooted plumes and subducted slabs. In turn, the amount of MORB accumulated above the core mantle boundary (CMB) strongly depends on the mantle-viscosity profile: lower-mantle viscosity directly affects the efficiency of MORB segregation (and entrainment) near the CMB; upper-mantle viscosity indirectly affects entrainment through its control on the thickness of subducted slabs. Our models further show that the enhancement of MORB and harzburgite in and beneath the MTZ, respectively, are laterally variable, ranging from 30% to 50% basalt fraction, and from 40% to 80% harzburgite enrichment relative to pyrolite. The resulting compositional mantle layering is associated with a subadiabatic potential-temperature gradient across the MTZ. These predictions can be potentially tested using seismic observations. Finally, the composition of the bulk-silicate Earth may be shifted relative to that of upper-mantle pyrolite if indeed significant reservoirs of MORB exist in the MTZ and lower mantle. Our results suggest that the segregation of MORB from harzburgite can act to filter mantle heterogeneity in order to sustain a layered distribution of mantle heterogeneity, even in the presence of whole-mantle convection.

Mantle dynamics in the Tibet

- Jianfeng Yang
  Dipartimento di Geoscienze, Università di Padova, 35131 Padova, Italy
  jianfeng.yang@unipd.it

- Manuele Faccenda
  Dipartimento di Geoscienze, Università di Padova, 35131 Padova, Italy

The deformation processes, e.g., formation of large-scale strike-slip faults, high plateaus, and the mechanisms during continental collision remain incompletely understood. India collided into Tibet since ∼50 Ma ago, is a natural laboratory to study lithospheric deformation. It is proposed that the mantle flow shapes surface deformation, is the major driving force of buoyant Indian subduction. However, the mantle dynamics beneath Tibet is not well known. Seismic anisotropy is a proxy of mantle deformation, exhibiting complex patterns in Tibet and Indochina regions. Explanations of combining seismic anisotropy and geodesy data often result in conflicting conclusions, indicating a missing mechanism in the dynamics. Here we use large-scale 3-D visco-elasto-plastic numerical models to investigate the mantle dynamics in the Tibet region. Our preliminary results show that Indochina block rotates towards southeast with retreating Burma slab. The dynamics are strongly dependent on the shape of Greater India and crustal rheology. The synthetic SKS exhibits a rotation direction along eastern Himalayan syntaxis, which is generally consistent with the observations, except in Yunnan region, where SKS shows W-E fast direction. Many large-scale strike-slip faults that probably accommodates deformation are missing due to limited resolution, which should be improved in the future study.

Subduction initiation in the Eastern Margin of the Caroline Plate

- Lulu Zhang
  Ocean College, Zhejiang University, Zhoushan, China
  11734005@zju.edu.cn

- Chun-Feng Li
  Ocean College, Zhejiang University, Zhoushan, China

- Sergio Zlotnik
  LaCaN, Universitat Politècnica de Catalunya, BarcelonaTech, Barcelona, Spain

The Caroline Plate in the western Pacific has a complex tectonic setting and history. Its interaction with neighboring plates, namely the Pacific, Philippines, Indo-Australian and Bismarck plates, is diverse, involving troughs, trenches, rises and ridges. Its eastern boundary, the Mussau Trench, shows evidence of convergence between Caroline and Pacific Plates. The polarity of the convergence changes from the Pacific underthrusting in the northern segment to the Caroline Plate subduction underneath the Pacific in the southern part. The Mussau Trench exhibits an unusual configuration that the new, hot and therefore buoyant Caroline lithosphere is starting to subduct underneath the old, thick, cold and dense Pacific plate, which might be explained by the strong rigidity of the old Pacific plate. This incipient subduction caused a convergence of about 10 km of crustal shortening during ~ 1 Ma.

In this work we describe the Mussau trench system and study it by means of numerical simulations. We aim to understand i) subduction initiation process, ii) conditions under which a polarity reversal might arise. We find that the lithospheric scale fault which dipping toward old plate as a weak zone promotes the young plate subducting underneath the old one in compression environment. Preliminary results favor that the Mussau subduction started in a compressional environment with a strong control by preexisting fractures.