Plate Tectonics on a Convective Mantle: From Crystal-Scale Processes to Global Data and Models

Fourth Crystal2Plate Workshop

27-31 January, 2013

Villa Clythia - Fréjus, FRANCE

Crystal2Plate Fourth Workshop
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27-31 January, 2013

Draft Agenda

	DAY 1 Sunday 27 January	DAY 2 Monday 28 January
	Arrival & registration ------------------- **Welcome cocktail and Dinner** 7 pm	The large-scale picture 9:00am-12:45pm *Lunch* 3pm - 7:00pm
DAY 3 Tuesday 29 January	**DAY 4 Wednesday 30 January**	**DAY 5 Thursday 31 January**
Strain localization… 9:00am-12:45pm *Lunch* Posters and lectures 3pm - 7:30pm	Mantle convection and surface processes 9:00am-12:45pm *Lunch* Poster session 3:30pm - 7pm	And the deep mantle? 9:00am-11:30pm Closing Discussion 11:30am -12:00pm *Lunch* Departure 2pm

Participants list

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Logistics information

Our venue for the event

Villa Clythia
2754 rue Henri Giraud
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France
Telephone: +33 (0)4 94 83 66 06
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frejus@caes.cnrs.fr
http://www.caes.cnrs.fr/vacances/nos-villages/la-villa-clythia

How to get to Villa Clythia

By train: TGV to Saint Raphaël (3 km – 2 miles) and bus to Fréjus/Valescure (line 3). Click here for bus timetable http://www.agglo-frejus-saintraphael.fr/images/bus/Ligne3_HIVER_2012.pdf. Get off at Villa Clythia stop.

By car: Michelin road maps n° 84 and n° 245. A8 leave Fréjus, head for Cannes (N7 and N98). Click here for a map http://www.caes.cnrs.fr/vacances/nos-villages/la-villa-clythia/plan-dacces-villa-clythia-1.pdf - **GPS**: 43°N 26' 42.1" 6° E 46' 5.0"

By plane: The closest airport is Nice (70 km – 45 miles).

Airport transfers will be organized for those who need it for arrivals on Sunday afternoon and again for departures on Thursday 31 January afternoon. Let us know if you need this service.

Accommodation details	
Villa Clythia	Villa Clythia 2754 rue Henri Giraud 83600 Fréjus France Telephone : +33 (0)4 94 83 66 06 Fax: +33 (0)4 94 95 67 22 frejus@caes.cnrs.fr http://www.caes.cnrs.fr/vacances/nos-villages/la-villa-clythia Accommodation costs are covered directly by the organiser. *Reservations will be made from Sunday 27 through Thursday 31 January 2013 (4 nights)*
Expenses reimbursement	
	Except for invited speakers, participants should MAKE their OWN TRAVEL ARRANGEMENTS and their travel expenses are to be covered by their main host institution.
Meeting Details	
Workshop location	Villa Clythia 2754 rue Henri Giraud 83600 Fréjus Telephone : +33 (0)4 94 83 66 06 Fax: +33 (0)4 94 95 67 22 frejus@caes.cnrs.fr http://www.caes.cnrs.fr/vacances/nos-villages/la-villa-clythia
Contact Meeting Organisation	Andrea Tommasi +33 (0) 4 67 14 49 12 – Mobile: +33 (0) 6 77 29 25 39 - deia@gm.univ-montp2.fr Nathalie Modjeska +33 (0) 4 67 14 37 43 – Mobile: +33 (0) 6 25 45 32 37 crystal2plate@gm.univ-montp2.fr
Material to bring with you	Students should bring a poster to present their science (A0 portrait)
Group event	**Sunday 27 January 2013 – 7pm Dinner at Villa Clythia**

4th WORKSHOP AGENDA

Day 1 – Sunday 27 January, 2013

19h00	**Ice-Breaker**	**Cocktail & Group dinner** for all participants at Villa Clythia

Day 2 – Monday 28 January, 2013

The large-scale picture

Time	Item	Description
9:00 – 9:15	**Introduction**	Opening by **Andrea Tommasi**
9:15 – 10:15	**Lecture**	**Convection with plate tectonics in the laboratory** by **Anne Davaille** (FAST, Orsay – F)
10:15– 10:45	**Break**	**Coffee break**
10:45 – 12:15	**Talks**	**Presentations by 3 C2P fellows** (30 minutes each): • "On the generation of supercontinent cycles from mantle convection with self-consistent plate tectonics and mobile continents" **Tobias Rolf** (ETH Zurich, CH) • "Dynamics of free subduction from 3-D boundary-element modeling" **by Zhonghai Li and N. Ribe** (FAST, Orsay, F) • "Mantle flow in regions of complex tectonics: insights from Indonesia" **by Jenny Di Leo** (Bristol University, UK)
12:30	**Lunch**	**Dining room**
15:00 – 16:30	**Posters**	**Poster session** (with coffee served at 4pm)
16:30 – 17:30	**Lecture**	**Geochemical constraints on the mantle convection** by **Manuel Moreira** (IPGP, Paris, F).
17:30 – 19:00	**Talks**	**Presentations by C2P fellows** (30 minutes each): • "Rising and stopping of thermal plumes in a yield stress fluid" **by Anna Massmeyer** (FAST, F) • "Partial melting and lithosphere erosion atop mantle plumes" **by Roberto Agrusta** (UM2, Montpellier F) • "Geochemical probing of the Cape Verde Plume" **by Katherine Adena and Tim Elliott** (Bristol University, UK)

Day 3 – Tuesday 29 January, 2013

Strain localization: Micro-structural evolution, shear heating and interactions with melts

Time	Item	Description
9:00 – 10:00	**Lecture**	**Strain localization controlled by damage and pinning in the mantle** by **Yanick Ricard** (Univ. Lyon, F)
10:00 – 10:45	**Lecture**	**Micro-structural evolution in experiments and nature: Does steady-state deformation exist?** by **Ben Holtzman** (Lamont Obs. NY, USA)
10:45 – 11:15	**Break**	**Coffee break**
11:15 – 12:30	**Talks**	**Presentations by C2P fellows** (30 minutes each) **+ 15 min discussion**: • "Breaking the lid: how to self-consistently create shear zones in the lithosphere" by **Marcel Thielmann** (ETH Zurich, CH) • "Thermo-mechanical evolution of the sublithospheric mantle in a (trans) tensional environment" by **Erwin Frets and <u>Carlos Garrido</u>** (CSIC, Granada, Spain).
12:45	**Lunch**	**Dining room**
15:00 – 16:30	**Posters**	**Poster session** (with coffee served at 4pm)
16:30 – 17:30	**Lecture**	**Magma transport in the mantle and the relations with deformation at various scales** by **Laurent Montesi** (Univ. Maryland, USA).
17:30 – 18:30	**Talks**	**Presentations by C2P fellows** (30 minutes each): • "Outcrop-based evidence for feedbacks between melt and deformation in the shallow mantle" **by Kate Higgie** (UM2, Montpellier , F) • "2D modelling of self-consistent spontaneous intra-oceanic subduction initiation triggered by porous fluid" **By Diana Dymkova and <u>T. Gerya</u>** (ETH Zurich, CH)
18:30 – 19:30	**Lecture**	**Seismological constraints on the nature of the asthenosphere** by **Hitoshi Kawakatsu** (Univ. Tokyo, J)

Day 4 – Wednesday 30 January, 2013

Continents deformation and mantle convection

Time	Item	Description
9:00 – 10:00	**Lecture**	**Mantle convection and surface processes** by **Alessandro Forte** (UQAM, Montréal, Canada)
10:00 – 10:30	**Break**	**Coffee break**
10:30 – 11:30	**Talks**	**Presentations by C2P fellows** (30 minutes each): • "Coupled lithosphere-mantle dynamics and surface responses: insights from modeling" **by Flora Bajolet** (UniRoma 3, Rome, I). • "Shear velocity structure of the Tyrrhenian region in relation to volcanism and tectonics" by **Sonja Greve** & **H. Paulssen** (Univ. Utrecht, NL)
11:30 – 12:30	**Lecture**	**Surface tectonics and mantle flow in the Mediterranean** by **Laurent Jolivet** (Univ. Orléans, F)
12:45	**Lunch**	**Dining Room**
15:30 – 19:00	**Posters**	**Poster session with 2 min short presentations**

Day 5 – Thursday 31 January, 2013

And the deep mantle?

Time	Item	Description
9:00 – 10:00	**Lecture**	**Deformation processes in the deep mantle** by **Patrick Cordier** (Univ. Lille, F)
10:00 – 10:30	**Break**	**Coffee break**
10:30 – 11:30	**Lecture**	**Mantle Dynamics in Super-Earths: Post-Perovskite Rheology and Self-Regulation of Viscosity** by **Paul Tackley** (ETH Zurich)
11:30 – 12:00	**Conclusion**	Closing discussion: **Main challenges for future research**
12:00	**Lunch**	**Dining room**
14:00	**Departure**	

Poster abstracts for Fourth Crystal2Plate Workshop
Plate Tectonics on a Convective Mantle: From Crystal-Scale Processes to Global Data and Models

Mr. Roberto AGRUSTA - *Université Montpellier 2, Montpellier, France*

Partial melting and lithosphere erosion atop mantle plumes

Roberto Agrusta
Géosciences Montpellier, Université de Montpellier 2 & CNRS, Place E. Bataillon, 34095 Montpellier, France.

Mantle plumes are traditionally proposed to play an important role in lithosphere erosion. Seismic images beneath Hawaii and Cape Verde show a lithosphere-asthenosphere-boundary (LAB) up to 50 km shallower than the surroundings. However, numerical models show that unless the plate is stationary the thermo-mechanical erosion of the lithosphere does not exceed 30 km.

We use 2D petrological-thermo-mechanical numerical models based on a finite-difference method on a staggered grid and marker in cell method to study the role of partial melting on the plume-lithosphere interaction. A homogeneous peridotite composition with a Newtonian temperature- and pressure-dependent viscosity is used to simulate both the plate and the convective mantle. A constant velocity, ranging from 5 to 12.5 cm/yr, is imposed at the top of the plate. Plumes are created by imposing a thermal anomaly of 150 to 350 K on a 50 km wide domain at the base of the model (700 km depth); the plate right above the thermal anomaly is 40 Myr old. Partial melting is modeled using batch-melting solidus and liquidus in anhydrous conditions. We model the progressive depletion of peridotite and its effect on partial melting by assuming that the melting degree only strictly increases through time. Melt is accumulated until a porosity threshold is reached and the melt in excess is then extracted. The rheology of the partially molten peridotite is determined using viscous constitutive relationship based on a contiguity model, which enables to take into account the effects of grain-scale melt distribution. Above a threshold of 1%, melt is instantaneously extracted. The density varies as a function of partial melting degree and extraction.

We analyze the kinematics of the plume as it impacts a moving plate, the dynamics of time dependent small-scale convection (SSC) instabilities developing in the low-viscosity layer formed by spreading of hot plume material at the lithosphere base, and the resulting thermal rejuvenation of the lithosphere. The onset time and the vigor of SSC and, hence, the new equilibrium thermal state of the lithosphere atop the plume wake depends on the Rayleigh number (Ra) in the unstable layer at the base of the lithosphere, which is controlled by the temperature anomaly and rheology in the plume-fed layer. For vigorous, hot plumes, SSC onset times do not depend on plate velocity. For more sluggish plumes, SSC onset times decrease with increasing plate velocity. This behavior is explained by differences in the thermal structure of the lithosphere, due to variations in the spreading behavior of the plume material at the lithosphere base. Reduction of the viscosity in partial molten areas and decrease in density of the depleted residuum enhance the vigor of small-scale convection in the plume-fed low-viscosity layer at the lithosphere base, leading to more effective erosion of the base of the lithosphere.

Ms. Flora BAJOLET - *UNIROMA 3, Rome, Italy.*

Coupled lithosphere-mantle dynamics and surface responses: insights from modeling

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The present work investigates the formation of curved ranges and syntaxes with scaled laboratory experiments. We simulated the subduction and collision between a continental upper plate and a subducting plate composed of an oceanic lithosphere and a continental indenter comparable to India-Asia configuration. The experiments reveal that the shape of the range (concave, straight or convex) and development of syntaxes are controlled by the trench viscosity, the buoyancy number (F_b) of the upper plate (i.e. thickness and viscosity) and the boundary conditions. Four end-members regimes of the indentation process can be defined depending on the range shape and dynamics of the upper plate. The curvature of the range is convex (toward the subducting plate) with syntaxes for a low viscosity trench and concave without syntaxes for a high viscosity. Convex curvature and syntaxes form by overthrusting of upper plate material on the subducting plate, faster at the center than at the extremities. They are associated with a rather flat slab (underthrusting) during continental collision. A thick and weak upper plate (high F_b) leads to gravity collapse that increases the amplitude of the curvature and lateral escape, similar to the late evolution of the Himalaya-Tibet system. In contrast, low F_b experiments show less pronounced curvatures associated to thickening comparable to the early stages of India-Asia collision. Important lateral decoupling on the sides of the indenter enhances the indentation and produces sharper syntaxes.

Ms Virginie BAPTISTE ***- Université Montpellier 2, Montpellier, France***

Seismic properties of the lithospheric mantle beneath the Kaapvaal craton, South Africa

Virginie Baptiste and Andréa Tommasi

Petrophysical data for cratonic xenoliths is important for constraining the interpretation of the thermal structure and composition of the mantle from seismological data. Here, we present calculated seismic properties of 42 mantle xenoliths from 9 kimberlitic pipes in the Kaapvaal Craton, taking into account their crystal preferred orientations, modal and chemical compositions (olivine mg# in particular) and their equilibrium pressures and temperatures.

As seismic waves average elastic properties at scales several orders of magnitude larger than an individual xenolith, these data has been used to construct a model vertical section representative for the cratonic mantle between 70 and 190 km, by averaging the individual samples properties over depth intervals of 20km, which allows estimating the variation of the seismic anisotropy and velocities with depth.

The fastest P-wave propagation direction is always close to olivine [100] axes maximum, which in most samples, except for some high-temperature mylonites, parallels the lineation. The fast split shear wave (S_1) is always polarized in a plane containing the propagation direction and the lineation. However, changes in olivine CPO symmetry result in variations in the seismic anisotropy patterns. Maximum anisotropy values range between 2.5 and 10.2% for P-waves azimuthal anisotropy (AVp) and between 2.7 and 8% for S-waves polarization anisotropy (AVs). Anisotropy intensity shows a positive covariance with the olivine CPO strength and the olivine content.

Variations in olivine composition (Fe depletion or enrichment) have a notable effect on the calculated density and seismic velocities. An increase in olivine Mg# decreases the rock density and S-waves velocity (Vs). Increase in orthopyroxene content tends to decrease the Vp and Vp/Vs ratio. Both variations are partially correlated, since the most refractory peridotites are often orthopyroxene-rich. Finally, garnet enrichment results in increase of whole-rock density, P-waves velocity and Vp/Vs ratio.

The conjugate effects of the pressure, temperature, and composition lead to an increase of density and a decrease of Vs with depth. The maximum P-waves anisotropy in a depth interval varies between 4.5 and 7.9%. The maximum S-waves polarization anisotropy is comprised between 3.7 and 5.8%. These anisotropies result for an anisotropic layer of 180 km where the foliation is horizontal, in delay times that are slightly higher than those measured from SKS splitting in the Kaapvaal.

Mr. Mickael BONNIN - *Université Nice, Nice, France*

Numerical modelling of the upper mantle anisotropy beneath a migrating strike-slip plate boundary: the San Andreas Fault system

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We performed forward modelling of seismic anisotropy beneath a migrating strike-slip plate boundary to: (1) test if such a geodynamic context might explain teleseismic shear-wave splitting data in the vicinity of the central part of the San Andreas Fault, and (2) constrain the power of such data to unravel vertical and lateral variations in deformation patterns in the upper mantle. The modelling involves five steps: (1) thermo-mechanical modelling, using a finite-element code, of the deformation field, (2) viscoplastic self-consistent modelling of the resulting olivine and pyroxene crystal preferred orientations, (3) calculation of the elastic tensors for different domains of the finite elements (FE) model, (4) forward modelling of seismic wave propagation through the model using ray theory, finite-frequency theory, and a full wave approach, and (5) performing splitting measurements on the synthetic seismograms. *SKS* splitting data in central California are best fitted by a model with a hotter geotherm within 60 km of the plate boundary accounting for the opening of an asthenospheric window due to the northward migration of the Mendocino Triple Junction. The westward motion of the plate boundary cannot however explain the rotation of fast polarisations east of the San Andreas Fault in central California. Comparison between modelled and measured individual shear-wave splitting also implies that the homogeneity of the 2-layer models accounting for the observations in the vicinity of the San Andreas Fault indicates a sharp transition between lithospheric and asthenospheric deformations beneath this plate boundary. The ability of different synthetic approaches to localize horizontally and vertically the plate boundary-related deformation differs significantly. Splitting data on ray theory synthetics closely follow variations in olivine crystal preferred orientations in the model. In contrast, splitting analysis on full-wave synthetics, which should be more representative of actual long period *SKS* waves, results in smooth lateral variations of the anisotropy; the location and width of the plate boundary may only be retrieved by comparing fast polarisation profiles obtained using a multichannel analysis on waves with different periods.

Mr. Nestor CERPA-GILVONIO - *Université Nice, Nice, France*

A simplified fictitious domain method for fluid / solid interaction

Nestor Cerpa, Muriel Gerbault and Riad Hassani
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Introduction

A wide variety of geodynamical problems involve a mechanical system where a competent body is embedded in a more deformable medium (e.g., the flow of a ductile matrix around a rigid inclusion, the motion of a subducting slab in the Earth's mantle). Such problems, that can be viewed as belonging to the field of fluid/solid interaction, are generally difficult to tackle numerically, particularly when the shape affected by the immersed body is geometrically complex (e.g., Gibert et al. 2012) and, of course when the surrounding medium undergoes large deformation.

Several techniques are used, among them the particles in-cell method (e.g. Gerya and Yuen, 2003), unstructured conforming remeshing (Bonnardot et al., 2008), the Potential theory approach (Morra and Regenauer-Lieb, 2006) or Euler-Lagrange formulations. We present here an alternative strategy based on a simplified variant of a class of techniques known as *fictitious domain method or immersed boundary method* which appeared in the 90's in the engineering community (e.g. Glowinsky, 1995, Lee, 2008). These methods overcome the need of meshes that fit exactly the interface between the solid and fluid domains. Preliminary results showing the potentialities of this method will be presented in the context of a subducting slab.

Basic principle of the method

To simplify the presentation we assume here that the immersed body $S \subset \mathbb{R}^3$ is a rigid body moving with a given velocity u_s and that $F \subset \mathbb{R}^3$ is the domain occupied by the surrounding material (a fluid for example) for which the sought velocity field u satisfies the linear problem

$$L(u) = f \quad \text{in } F, \qquad u = \bar{u} \quad \text{on } \Gamma_1, \qquad \nabla u \cdot n = g \quad \text{on } \Gamma_2, \tag{1}$$

where $\Gamma_1 \cup \Gamma_2 = \partial F$, n is the outward unit normal and L is a differential operator (Stokes operator for example). Moreover, we consider the adherence condition between the two domains:

$$u = u_s \quad \text{on} \quad \partial S. \tag{2}$$

The main idea behind the fictitious domain methods is to solve the problem in the geometrically simpler domain $\Omega = S \cup F$ and to enforce the condition (2) on the immersed interface ∂S by using different techniques. Suppose that we have discretized this problem in Ω (without the effect of the body *S*) by a finite element method resulting in the algebraic linear system

$$\boldsymbol{AU} = \boldsymbol{F}_0 \tag{3}$$

where $\boldsymbol{U} \in \mathbb{R}^{3N}$ is the vector of nodal unknowns, $\boldsymbol{F}_0 \in \mathbb{R}^{3N}$ is the load vector, $\boldsymbol{A}$ is a $3N \times 3N$ matrix and N is the number of nodes. To fulfill the condition (2), a forcing load $F(q)$ is added in the right hand side of (3) where the unknown parameter q can be interpreted as a source term.
As we are interested not only by rigid motion of S, we choose here a least-square approach to enforce condition (2): $x_1, \ldots, x_n$ being a discretization of ∂S, find the source vector $\boldsymbol{q} \in \mathbb{R}^{3n}$ minimizing

$$J(\boldsymbol{q}) = \tfrac{1}{2} \sum_{k=1}^{n} \| u(x_k) - u_s(x_k) \|^2 \tag{4}$$

where $u(x_k) = \sum_i \phi_i(x_k) U_i$ is the predicted velocity interpolated at the k^{th} control point, ϕ_i are the shape functions and the minimizer $\boldsymbol{q}^*$ is sough over the constraint $\boldsymbol{AU} = \boldsymbol{F}_0 + \boldsymbol{F}(\boldsymbol{q}^*)$. If punctual sources are considered, the solution of this optimization problem satisfies the following linear system:

$$\boldsymbol{M}\boldsymbol{q}^{*} = \boldsymbol{u}_s - \boldsymbol{u}_0 \qquad (5)$$

with $\boldsymbol{M} = \Phi \boldsymbol{A}^{-1}\Phi^{T}$, $\boldsymbol{u}_0 = \Phi \boldsymbol{A}^{-1}\boldsymbol{F}_0$, Φ is the $3n \times 3N$ matrix whose entries are the $\phi_i(x_k)$ values and the vector $\boldsymbol{u}_s \in \mathbb{R}^{3n}$ contains the velocities $u_s(x_k)$ at the control points.

A penalty variant

We also tried another technique where the condition (2) is enforced by penalty. On the discrete problem, it reads: find $\boldsymbol{U} \in \mathbb{R}^{3N}$ that minimizes

$$J_{\varepsilon}(\boldsymbol{U}) = \tfrac{1}{2}\boldsymbol{U}^{T}\boldsymbol{A}\boldsymbol{U} - \boldsymbol{U}^{T}\boldsymbol{F}_0 + \tfrac{1}{2\varepsilon}\|\Phi\boldsymbol{U} - \boldsymbol{u}_s\|^2 \qquad (6)$$

with $\varepsilon > 0$ being small enough. The solution satisfies

$$(\boldsymbol{A} + \tfrac{1}{\varepsilon}\Phi^{T}\Phi)\,\boldsymbol{U} = \boldsymbol{F}_0 + \tfrac{1}{\varepsilon}\Phi^{T}\boldsymbol{u}_s. \qquad (7)$$

The main drawback of this approach, compared with the former one, is that for a non-stationary problem we have to re-factorize the large matrix $\boldsymbol{A} + 1/\varepsilon\,\Phi^{T}\Phi$ at each time step since Φ is time-dependent. However, for a non-moving body S, this approach is less time-consuming.

Example of a solid / fluid interaction

To test our new method we reproduce the numerical experiment given in Bonnardot et al. (2008) consisting of an elastic plate immersed in a Stokes flow. We compare (figure 1) our calculation with the one presented in Bonnardot et al. (2008) where the coupling was done with the help of a standard remeshing technique.

(*a*) (*b*)

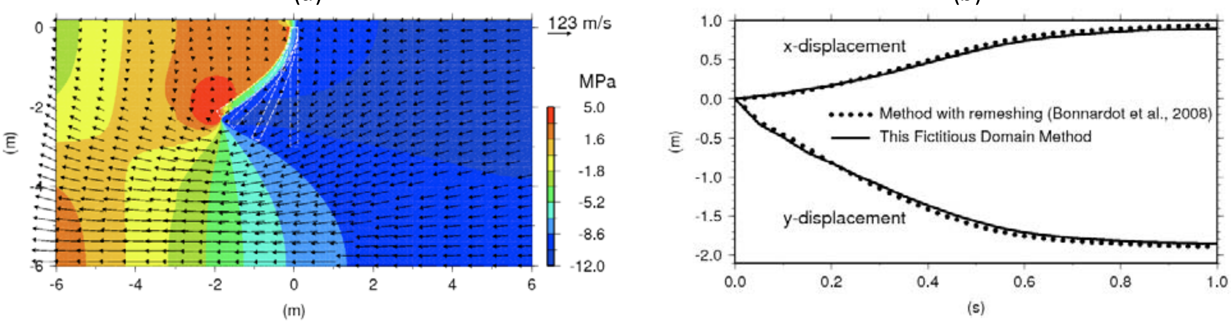

Figure 1: An elastic plate bended by the flow of a viscous fluid. At the right side, the inflow velocity is linearly increased during time until a value of 60 m/s is reached. The viscosity value is 10^5 Pa s. (a) Fluid pressure and velocity field (b) Time-displacement of the lower left corner and comparison with the result of Bonnardot et al. (2008).

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Mr. René CHAMBOREDON - ***Université Montpellier 2, Montpellier, France***

A petrographical and geochemical study of sulfides: new evidence for the origin of olivine in olivine-rich troctolites.

Two hypotheses are currently proposed for the origin of olivine in olivine-rich troctolites from slow-spreading ridges. The olivine may have crystallized in the crust from a slow-cooling magma or they may be inherited from a mantle peridotite. However, these hypotheses are based only on the analyses of silicate phases (olivine, plagioclase, pyroxene). Our study focuses on sulfide phases, which physical and chemical properties differ from those of silicates. We used a combination of a detailed petrographical study of magmatic sulfides armored in or in triple-junctions of olivine crystals, as well as in-situ electron microprobe (EMPA) and mass spectrometer (LA-ICP-MS) analyses of these sulfides. Their high I-PGE contents ($[Os]_n \approx 5.8$ ppm; $[Ir]_n \approx 4.2$ ppm; $[Ru]_n \approx 2.3$ ppm) and very low $(Pd/Ir)_n$ (~0.137) and $(Re/Os)_n$ (~0.427) indicate unambiguously that they are melting residues. Moreover, their HSE contents and fractionation patterns are very similar to those in abyssal peridotites. Their S/Se ratios (~2948) are also very close to the S/Se ratios of the Earth's mantle (~2800±200). Since sulfides are very reactive, they could not have preserved mantle-like characteristics if they were not themselves preserved in a refractory phase like olivine. Thus we infer that olivines in olivine-rich troctolites are residual minerals from a mantle which undergone consequent partial melting (10-20%).

Ms. Simona CHAVENA- ***University of UTRECHT, Utrecht, Netherlands***

Phosphorus in olivine from Italian potassium-rich lavas

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Phosphorus in igneous olivine is promising as a petrogenetic proxy and as a sensitive indicator of crystal growth histories. To explore its applicability in solving outstanding issues concerning Italian K-rich magmatism, we analyzed a collection of well-characterized Fo-rich olivine phenocrysts (Fo_{73}-Fo_{93}) hosting Mg-rich melt inclusions (MI) covering the low-medium K (L-MKS) and high-K (HKS) rock series that characterize the row of volcanic centres between the Roman Province and Vulture for minor and trace element contents by LA-ICP-MS. A subset was further analyzed by an electron microprobe to investigate intracrystal variations in phosphorus and associated elements in detail. The phosphorus contents of olivines range between 40 and 230 ppm, with M-LKS olivines containing generally less (<70 ppm) than HKS olivines (<130 ppm), except for Campi Flegrei where M-LKS olivines carry up to 230 ppm. The P content of olivine tends to increase with K_2O and P_2O_5 in MI. Regional systematics suggest that it signals variations in mantle source composition and/or mode of melt extraction. On the other hand, some M-LKS melts with similar P_2O_5 crystallized olivines with significantly different P contents, indicating that P in the melt is not the only control of uptake by olivines. Additional factors include growth rate and coupled substitutions. The olivines display zoning profiles in phosphorus as well as in Al, Cr, Ti, but without showing systematic coupling. Profiles in selected olivines show P depleted zones around MI, which questions the supposed immobility of this element in olivine.

Ms. Carole DENIS - *Université Montpellier 2, Montpellier, France*

EVIDENCE OF DEHYDRATION IN PERIDOTITES FROM EIFEL VOLCANIC FIELD AND ESTIMATES OF THE RATE OF MAGMA ASCENT

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From experimental studies, it is known that a significant part of the water of our planet may be in the form of hydrogen dissolved as point defects in nominally anhydrous minerals of Earth's mantle. Such hydrogen defects embedded in the mineral atomic structures are easily detectable using Fourier transform infrared spectrometry (FTIR) at low concentration levels (ppm). We report water contents in upper mantle minerals from peridotites transported by sodic olivine nephelinite–basanite suite lavas from three volcanoes Rockeskyllerkopf, Dreiser Weiher, and Meerfelder Maar in the Eifel volcanic field (West Germany). The water concentrations, obtained with FTIR, are ~ 6pmm, ~ 200 ppm and ~ 285 ppm for olivine, enstatite and diopside, respectively.

The water concentration in individual olivine grains is very heterogeneous; in contrast to water contents in pyroxenes, which are homogeneous. In addition, profiles using polarized infrared radiation across crystallographically oriented single-crystals of olivine reveal hydrogen depleted rims. These observations indicate that partial dehydration occurs during the ascent of the xenolith to the surface. Using experimentally obtained diffusion coefficients for hydrogen in olivine at high temperature, we estimate that the duration of the dehydration for the spinel-bearing xenoliths is limited to a few hours yielding rates of magma ascent from 3 ms^{-1} to 12 ms^{-1}. Our study suggests that the water content of the upper mantle based on measurements of mantle-derived peridotites is likely to underestimate the true water content of the equilibrated uppermost mantle, but water contents in pyroxens are a better proxy of concentration at depth.

Ms. Erika DI GIUSEPPE - *FAST, Orsay, France*

Dynamics of one-sided subduction: Insights from analog models in complex rheology fluids

Authors: E. Di Giuseppe, A. Davaille

The uniqueness of the Plate Tectonics involves two main ingredients : a planetary surface comprising a network of quasi-rigid moving 'plates', and an interior undergoing thermal convection. Mantle convection controls the cooling of the Earth, and hence, strongly influences its thermo-chemical evolution. Moreover, how the plates are built and recycled into its interior through the subduction process is still question of debate.

Understanding the link between these two processes is not only a fascinating problem of physics in its own right; it is also crucial to decipher the long-term evolution of our planet.

We report here new analog models of subduction by using a complex fluid, whose rheology varies from brittle to viscous when its solid volume fraction changes. So as an analogy to cooling from above, we dried the fluid from above. As the fluid dries at the surface, a thermo-chemical boundary layer develops and spontaneously subducts within the underlying convecting fluid. We systematically studied the dynamics of the process by varying the experimental parameters, i.e. humidity rate, temperature, fluid thickness, fluid concentration, resulting in a changing of the mantle flow. The entire process is monitored by means of cameras and balance.

Different regimes are observed depending on experimental conditions. Experiments demonstrate that our planet may not stay in the same regime throughout its life, but evolves through a suite of distinct regimes.

Ms. Jenny DI LEO - ***University of Bristol, Bristol, U.K.***

Mantle flow in regions of complex tectonics: insights from Indonesia

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Indonesia is arguably one of the tectonically most complex regions on Earth today due to its location at the junction of several major tectonic plates and its long history of collision and accretion. It is thus an ideal location to study the interaction between subducting plates and mantle convection. Seismic anisotropy can serve as a diagnostic tool for identifying various subsurface deformational processes, such as mantle flow, for example. Here, we present novel shear wave splitting results across the Indonesian region. Using three different shear phases (local S, SKS, and downgoing S) to improve spatial resolution of anisotropic fabrics allows us to distinguish several deformational features. For example, the block rotation history of Borneo is reflected in coast-parallel fast directions, which we attribute to fossil anisotropy. Furthermore, we are able to unravel the mantle flow pattern in the Sulawesi and Banda region: We detect toroidal flow around the Celebes Sea slab, oblique corner flow in the Banda wedge, and sub-slab mantle flow around the arcuate Banda slab. We present evidence for deep, sub-520 km anisotropy at the Java subduction zone. In the Sumatran backarc, we measure trench-perpendicular fast orientations, which we assume to be due to mantle flow beneath the overriding Eurasian plate. These observations will allow to test ideas of, for example, slab--mantle coupling in subduction regions.

Ms. Diana DYMKOVA ***- ETH, Zurich, CH.***

2D modelling of self-consistent spontaneous intra-oceanic subduction initiation triggered by porous fluid

Diana Dymkova, Taras Gerya

Numerical modelling of a porous flow has a wide range of applications in geosciences and industrial engineering. The purpose of our project is to implement complex porous flow process into geodynamical models of subduction and investigate the role of fluids on the process dynamic and development. As a result, our model suggests self-consistent explanation for the subduction initiation, which is a long standing open question of a central importance for the plate tectonic regime on Earth. Our results integrate fundamental aspects and observations within different disciplines such as oceanography, tectonics and geodynamics.

Although most of the presently active intra-oceanic subduction zones and initiated during the Cenozoic period, subduction initiation process remains poorly understood. Previous geodynamical models of subduction initiation assumed excessive weakening of tectonic plate boundaries which does not reconcile with laboratory rock strength measurements. The weakening was assumed to be caused by fluids present along tectonic fractures; however no self-consistent solid-fluid model of subduction initiation has been developed so far.

In our project we have developed new 2-dimensional numerical model of spontaneous intra-oceanic subduction initiation where solid rock deformation and fluid percolation are fully coupled. We demonstrate that although subduction fails to initiate under fluid-absent conditions, it can naturally start when porous fluid is present inside oceanic crust and along the plate boundaries. Fluid percolation is localised along spontaneously forming faults where high fluid pressure compensates lithostatic pressure, thus dramatically decreasing friction along the incipient subduction zone. Through the parametric study we conclude that the most important parameter for subduction initiation is the solid matrix permeability. Paradoxical at first, lowering the permeability indeed favours subduction initiation by maintaining high fluid pressure and thus decreasing friction along active faults.

Ms. Ria FISCHER- *ETH, Zurich, CH.*

Was plate tectonics different in a hotter Earth?
3D numerical modelling of Precambrian tectonics

Author: Ria Fischer

Plate tectonics is a global self-organising process driven by negative buoyancy at thermal boundary layers. Phanerozoic plate tectonics with its typical subduction and orogeny is relatively well understood and can be traced back in the geological records of the continents. Interpretations of geological, petrological and geochemical observations from Proterozoic and Archean orogenic belts however (e.g., Brown, 2007; Taylor and McLennan, 1995), suggest a different tectonic regime in the Precambrian. Precambrian tectonic complexes formed atop of hot mantle, remained hot and therefore mechanically extremely weak over protracted periods of deformation. The fundamental di
erence between Precambrian subduction and Phanerozoic subduction is therefore the upper-mantle temperature, which determines the strength of the upper mantle (Brun, 2002) and further collisional orogenesis (Burov and Yamato, 2008).
3D petrological{thermomechanical numerical modelling experiments of oceanic subduction at an active plate margin done with the nite difference multigrid solver I3ELVIS (Gerya and Yuen, 2007) at different upper-mantle temperatures show this different regimes. In the Precambrian the lithosphere shows very low internal strength and is strongly weakened by percolating melts and increased temperature due to higher radioactive heat production. Following Sizova et al. (2010), three different subduction regimes can be found. For upper-mantle temperatures < 175C above the present day value modern subduction style is found. At upper-mantle temperature 175 - 250C above present day value a "pre-subduction" regime emerges, where plates are weakened by melt percolation from the underlying hot upper-mantle. Instead of a stable one-sided subduction shallow underplating and buckling is observed. At > 250C above the present day value a "no-subduction" regime develops, where the underthrusting plate disintegrates into small deformable plate fragments.

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Mr. Erwin FRETS - *CSIC, Granada, Spain*

Thermo-mechanical evolution of the subcontinental lithospheric mantle in an extensional environment

Insights from the Beni Bousera peridotite massif
(Rif belt, Morocco)

Erwin Frets, Carlos J. Garrido & Andréa Tommasi

The mantle deformation processes that control the thinning and break-up of continental lithosphere remain poorly understood. Our knowledge is restricted to either lithospheric scale thermo-mechanical models —that use experimentally derived flow laws—, geophysical imaging and/or rare xenoliths from active continental rifts, such as the East African Rift System.

The originality of this work relies on the study of the two largest outcrops of diamond facies subcontinental lithospheric mantle in the world: the Beni Bousera and Ronda peridotite massifs in N Morocco and S Spain, respectively. The structures and petrologic and metamorphic zoning preserved in these massifs —implying a polybaric and polythermal evolution— provide a unique opportunity to investigate the thermo-mechanical evolution of thick subcontinental lithospheric mantle in extensional settings.

In this thesis we studied the deformation mechanisms in both peridotites and pyroxenites to constrain the modes of exhumation of subcontinental lithospheric mantle from garnet-, to spinel-, and finally, to plagioclase lherzolite facies conditions. We combined field mapping of tectono-metamorphic domains and structural mapping of ductile structures, microstructural analysis, crystal preferred orientations (CPO) measurements and conventional thermobarometric calculations and thermodynamic modeling (Perple_X) to unravel the pressure and temperature conditions of deformation. We showed that exhumation from garnet- to spinel lherzolite facies conditions was accommodated by fast shearing —in thermal disequilibrium— along a lithospheric scale transtensional shear zone. In this context, the petrological zoning and the large temperature gradient (ca. 100ºC/km) preserved in the Beni Bousera massif represent the mechanical juxtaposition of progressively deeper and hotter lithospheric levels at depths of ca. 60 km in the latest Oligocene (ca. 25 Ma). Final exhumation from spinel- to plagioclase facies lherzolite and emplacement into the crust is best recorded in the Ronda massif where it occurred by inversion and lithospheric scale folding of the highly attenuated continental lithosphere in a back-arc region, probably in relation with southward slab rollback and subsequent collision with the palaeo-Maghrebien passive margin in the early Miocene (21-23 Ma).

Ms. Candela GARCIA SANCHO - *University of UTRECHT, Utrecht, Netherlands*

Tractions from convective mantle flow modeling have been incorporated in a lithospheric model in which edge and lithospheric body forces are modeled explicitly for Eurasia. Resulting stresses were calculated in a homogeneous elastic thin shell. Here, we aim to constrain the evolution of lithospheric rheology at plate scale. With rock mechanical properties depending critically on temperature, pressure and composition, we need to combine geological province data (composition, mass density) with information about the thermal state of the lithosphere. To quantitatively constrain the rheological evolution of Eurasia, thus we need its thermal evolution above a convecting mantle with time-variable heat loss to the lithosphere. By combining stresses with estimates of lithospheric rheology, we evaluate the evolution of Eurasia's stress and strain fields and compare these key observations of intra-plate deformation and topography development.

Ms. Fanny GAREL – *Imperial College, London, U.K.*

Simulating subduction dynamics on a global scale: an adaptive-mesh numerical approach

working with Rhodri Davies, Huw Davies, Saskia Goes
(Imperial College London, Cardiff University)

The subduction of oceanic plates into the Earth's mantle is an important driving force for the surface dynamics of tectonic plates. Geophysical observations reveal a wide range of slab morphologies within the mantle transition zone, with slabs either stagnating at 660 km depth or sinking in the lower mantle. The multi-scale and intricate interactions of slab sinking through mineralogical phase transitions are currently poorly understood. I will present the first results of numerical simulations performed using the Fluidity software with a meshing automatically adapted on temperature and velocity gradients, thus allowing a high-resolution study of subduction dynamics on the whole mantle vertical domain.

The poster investigates the free-subduction of an isolated cold plate with the same rheology as the mantle around it (no compositional effects). The composite rheology takes into account diffusion and dislocation creeps, along with a stress-limiting rheology. Slab and mantle viscosities depend on temperature and strain rate, yielding a feedback between the slab dynamics and rheological state.

When the slab penetrates the lower mantle, a flow is induced in the whole mantle up to the core-mantle boundary at 3000 km depth. The treatment of the top interface as a free-surface or a free-slip boundary affects the slab deformation and subduction style (slab buckling or vertical sinking). The rheological parameters (yield strength, activation energies and volumes), as well as the initial slab geometry and the mode of subduction initiation, strongly affects the slab dynamics and its geometry when it interacts with the 660-km viscosity interface. This work provides first insights into the complexity of slab deformation the mantle transition zone, even without the additional thermal, buoyancy and deformation effects induced by mineralogical phases transitions that will be incorporated afterwards in the numerical model.

Mr. Neil GOULDING - *University of Bristol, Bristol, U.K.*

Analytical Parameterization of Self-Consistent Polycrystal Mechanics

Progressive deformation of upper mantle rocks via dislocation creep causes their constituent crystals to align preferentially, leading to elastic anisotropy that can be observed seismologically to constrain mantle flow patterns. Realizing this potential, however, requires a mechanical model for polycrystals that can predict how the individual crystals rotate in response to an imposed macroscopic deformation. Self-consistent models such as the second-order (SO) model of Ponte-Casteneda (2002) do this very well, but are too computationally expensive to be included in time-dependent numerical simulations of mantle convection. Accordingly, we have developed a new semi-analytical model that gives predictions indistinguishable from the SO model at a fraction (~ 0.0001) of the cost. We illustrate the approach for pure olivine polycrystals subject to different types of irrotational deformation (uniaxial compression, pure shear, etc.). We are currently working to extend the model to rotational deformations such as simple shear.

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Ductile strain localization in mantle pyroxenite by reaction enhanced softening

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The deformation of rocks in response to forces in Earth's interior is governed by rock rheology, which varies as a function of various factors including mineralogy, P-T, fluid content and chemistry, melt fraction, differential stress conditions and mineral grain size. The upper mantle consists predominantly of olivine and pyroxenes and it has been suggested that strain localization in the uppermost mantle occurs mainly due to grain-size-sensitive creep of dynamically recrystallized olivine. In contrast, pyroxenes are considered as strong minerals, at least in the dislocation creep regime. However, if the grain size of any phase becomes significantly smaller than that of olivine it can control strain localization. Synkinematic net-transfer metamorphic reactions can result in fine-grained reaction products promoting positive feedback between deformation and reaction, thus reaction-enhanced softening is a well known mechanism fostering ductile strain localization.

Here we report ductile strain localization in mantle pyroxenite from the spinel to plagioclase websterite transition in the Ronda Peridotite (southern Spain). Mapping shows that, in this domain, small-scale shear zones occurring at the base of the lithospheric section are systematically located within thin pyroxenite layers, suggesting that pyroxenite was locally weaker than the host peridotite. Strain localization in the studied samples is associated with a sudden decrease of grain size and increasing volume fractions of plagioclase and amphibole as a result of spinel to plagioclase phase transformation reaction that is also fostering hydrogen extraction ("dehydration") and hardening of clinopyroxene. Synkinematic net-transfer reaction, catalyzed by the presence of water-rich pore fluids, produced fine-grained, wet olivine and plagioclase, allowing weakening through onset of grain-size sensitive creep. Geothermobarometry and compositional zoning of constituent minerals suggest cooling from at least 1000 °C to 700 °C and decompression from 1.0 GPa to 0.5 GPa.

Ms. Kate HIGGIE ***- Université Montpellier 2, Montpellier, France***

Outcrop-based evidence for feedbacks between melt and deformation in the shallow mantle

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We analysed the interactions between melts and deformation in the upper mantle through detailed microstructural studies in two settings: a 100m section in the Moho Transition Zone (MTZ) of the Oman Ophiolite and plagioclase-rich lherzolites from the Lanzo massif (Alps). The MTZ section is characterized by a cm to m-scale layering; compositions range from dunites to olivine-gabbros. Parallelism between the layering and the foliation, diffuse layers limits, and alignment of mm-scale plagioclase-rich lenses in intermediate composition layers imply shear-controlled layering. All phases have crystal-preferred orientations (CPO), but olivine CPO varies depending on the layer composition. Layers with <70% olivine show strong [100] maxima parallel to the lineation (axial-[100] pattern). Layers with <50% olivine have [100] dispersed in the foliation and concentration of [010] normal to it (axial-[010] pattern). These changes occur repeatedly on the mm-scale, at the layers limits, providing strong evidence for deformation in presence of variable melt fractions. CPO in olivine-rich layers is consistent with high-temperature dislocation creep. Axial-[010] olivine CPO patterns imply transpression or sliding along preferentially-wetted (010) grain boundaries in melt-rich layers; they are accompanied by increased activity of [001] glide. Since the change in CPO symmetry is not associated with dispersion, instantaneous melt fractions must have remained <30-40%. The continuous variation in olivine CPO symmetry with decreasing olivine content implies therefore that the CPO depends on the strain cumulated in presence of melt rather than on the instantaneous melt fraction.

Plagioclase-rich lherzolites in Lanzo are characterized by an anastomozed network of plagioclase-rich layers, which locally grades into a diffuse cm-scale compositional layering. Olivine and orthopyroxene show evidence for deformation by dislocation creep under high temperature conditions: undulose extinction, subgrains or kinks, sutured grain boundaries, but plagioclase forms elongated aggregates with interstitial shapes. All major phases (except clinopyroxene) show clear CPO, independent of the layer composition. The olivine CPO has an orthorhombic symmetry, with [100] parallel to the lineation and [010] normal to the foliation (and to the layering), but [010] maxima are stronger than [100] ones. These olivine CPO are intermediate between the two patterns observed in the Oman MTZ, consistently with the less developed segregation in Lanzo.

Together these data imply that melts tend to concentrate in bands aligned in the shear plane, forming an anastomosed network that may grade with increasing shear into a planar layering. Instantaneous melt fractions remain below the solid matrix disruption threshold. They also show that deformation in presence of melt results in axial–[010] patterns and hence in a different seismic anisotropy. Shear-controlled compositional layering may create a mechanical anisotropy, with a directional reduction of the shear viscosity parallel to the bands.

Ms. Fatna KOURIM - *Université Montpellier 2, Montpellier, France*

Nature and Evolution of the lithospheric mantle beneath the HOggar swell (Algeria): a record from mantle xenoliths.

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The mantle xenoliths sampled by the Quaternary alkaline volcanics from the Tahalgha district (Central Hoggar) represent the subcontinental lithospheric mantle beneath the boundary between two major structural domains of the Tuareg Shield: the "Polycyclic Central Hoggar" to the East and the "Western Hoggar", or "Pharusian Belt", to the West. Samples were collected from volcanic centres located on both sides of the 4°10, a major lithospheric shear zone separating these two domains. Although showing substantial variations in their deformation microstructures, equilibrium temperatures, and modal and chemical compositions, the studied samples do not display systematic variations of these features across the 4°10. The observed variations rather record small-scale heterogeneities distributed throughout the whole studied area and mostly related to the asthenosphere-lithosphere interaction events associated with the evolution of the Hoggar swell, in the Cenozoic. These features include partial annealing of pre-existing deformation microstructures, post-deformation metasomatic reactions, and trace-element enrichment, coupled with heating from 750-900°C (low-temperature lherzolites) to 900-1150°C (intermediate-T lherzolites and high-T harzburgites and wehrlites). Detailed study of crystal preferred orientations coupled with petrographic observations indicates that melt percolation in Tahalgha lithospheric mantle is superimposed onto and older deformation event. Metasomatic enrichment in clinopyroxene and amphibole is often concentrated in veins aligned either parallel or at some angle to the foliation. Amphibole also occurs as isolated crystals, always associated with clinopyroxene and spinel. The modal enrichment in clinopyropxene and amphibole is associated with grain size reduction and some dispersion of olivine crystallographic orientations.

Trace element modelling confirms that the whole range of REE fractionation observed in the Tahalgha xenoliths may be accounted for by reactive porous flow involving a single stage of basaltic melt infiltration into a LREE-depleted protolith. The striking correlations between equilibrium temperatures and trace-element enrichments favor a scenario whereby the high-temperature peridotites record advective heat transport along melt conduits while the intermediate- and low-temperature lherzolites would represent more conductive heating of the host Mechanical Boundary Layer. This indicates that the lithosphere did not reach thermal equilibrium, suggesting that the inferred heating event was transient and rapidly erased by thermal relaxation down to the relatively low-temperature present-day geotherm.

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Comparison of continuous and discontinuous discretizations for the Stokes flow

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Finite element methods (FEM) of various types are widely used to solve incompressible flow problems in general and Stokes flow in particular. We present first results of a study comparing two numerical methods: the continuous Galerkin and the discontinuous Galerkin (DG) method. For this purpose a Matlab code was developed employing 2D Stokes flow in a model setup with known analytical solution. [2]

Nonlinearities of, e.g., the viscosity can lead to discontinuities in the velocity-pressure solution. Hence, using continuous approximations may result in avoidable inaccuracies. In contrast to the FEM, the DG method allows for discontinuities of velocity and pressure across interior mesh edges. This increases the number of degrees of freedom by a constant factor depending on the chosen element. A parameter is introduced to penalize the jumps in the velocity. The DG method provides the capability to locally adapt the polynomial degree of the shape functions. Moreover, it only needs communication between directly adjacent mesh cells, which makes it highly flexible and easy to parallelize.

The velocity and pressure errors of the methods are measured in the L1-norm [1]. Orders of convergence are determined and compared.

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Short and long-term folding and faulting of the folding of the lithosphere under compression

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In an extreme case, if the lithosphere were completely viscous, only folds would develop under shortening, provided there are viscosity contrasts among the layers. Without viscosity contrast, there would be only homogeneous thickening and the layers would remain horizontal. If, in contrast, the lithosphere were completely brittle, only faults would develop under shortening. In the case of a mixed behaviour (viscous at depth and brittle in the uppermost layer), but without viscosity contrast in the underlying viscous layers, we can expect that only faults form in the brittle layer, because the viscous layers would undergo homogeneous thickening only. Yet, the question is what happens in the most common case, i.e a rheologically stratified lithosphere, with, from top to bottom, a brittle layer atop two layers with different viscosity (lower in the bottom layer). What forms first? Folds, because there is a viscosity contrast, or faults because there is a brittle layer?

The problem was implemented using a three-layer model with a brittle top layer representing the upper crust or brittle lithosphere, a ductile intermediate layer, representing the lower crust or ductile lithosphere, and a lower and much ticker layer than the other two, representing the asthenosphere. Using widely accepted viscosity magnitudes and reasonable viscosity contrasts, 2D visco-elasto-plastic numerical modelling indicates that: (1) the oceanic lithosphere first buckles when the viscosity contrast ($\eta_{DL}/\eta_{BL} = \eta_R$) between ductile and brittle lithospheres is $\eta_R \geq 10$, and (2) the lithosphere first faults when $\eta_R \leq 0.01$. The model buckle wavelength is comparable to observations of buckling in the Central Indian Ocean.

We are also interested in studying the factors that control the evolution of faulting and folding of the lithosphere under compression. We use different configurations of viscosity, density and also study the effect of the friction angle on long-term runs of 2D visco-elasto-plastic numerical modelling. It indicates that: (1) if the viscosities of the top brittle layer and the intermediate ductile layer are equal, lithosphere undergoes homogeneous flattening; (2) similar viscosities between all the three layers inhibits deformation by buckling or faulting and the lithosphere undergoes almost or totally homogeneous thinning; (3) higher viscosity contrasts between the two top layers with higher viscosities in the ductile layer promotes buckling; (4) faulting is as stronger as higher is the contrast between viscosities of the brittle layer and the ductile layer when $\eta_{BL} > \eta_{DL}$; (5) faulting is strengthened by a small contrast between the viscosity of the asthenosphere and of the ductile layer; (6) a constant density profile promotes buckling or faulting; (7) using a density profile with different values for the different layers doesn't change the overall way of deformation, only its "intensity"; (8) the decrease of friction angle on a layer inhibit shear strain localization (brittle failure).

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Free Subduction Dynamics from 3-D Boundary-Element Modeling

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Motivated by the desire to understand the dynamics of free subduction, we carried out three-dimensional boundary-element numerical simulations of the creeping motion of a dense fluid sheet in another fluid with a different density and viscosity. The code employs specific Green's functions for Stokes flow in either (1) an infinite half-space below a traction-free surface or (2) a layer of finite depth above a rigid boundary. Instantaneous solutions in configuration (1) show that the sinking speed and transverse deformation rate of the slab are controlled by a dimensionless 'stiffness' parameter S that quantifies whether subduction is resisted primarily by the viscosity of the slab itself or by that of the ambient mantle. Instantaneous solutions in configuration (2) quantify the sinking speed modified by the presence of a lower rigid boundary. Using these results, we obtain scaling laws for the instantaneous sinking speed and transverse deformation rate of a subducting slab. Then the time-dependent solutions for slab rollback-induced poloidal and toroidal flow in configuration (2) are investigated with tracing particles, which demonstrate the mantle flow around both the tip and lateral edges of the slab to the mantle wedge. Finally the evolution of the slab's shape and its interaction with the rigid bottom boundary is investigated. A subduction regime diagram (retreating, folding, advancing) is proposed as a function of the mantle/plate thickness ratio and the plate/mantle viscosity contrast, which is in general agreement with the analog laboratory experiments.

Ms. Anna MASSMEYER - *FAST, Orsay, France*

Rising and stopping of thermal plumes in a yield stress fluid

Anna Massmeyer, Erika Di Giuseppe, Anne Davaille, Tobias Rolf, Paul Tackley

Due to the complex mechanical behaviour of the lithosphere, with solid as well as viscous properties, the process of emplacement of hot material in this region remains far from understood. In a ductile quasi-Newtonian matrix the intruding object generally forms a mushroom-shaped less viscous plume or a more viscous finger-shaped diapir. On the other hand dikes fracture and propagate through a solid matrix. But how does a thermal instability propagate in between those two end-members, i.e. in a fluid that exhibits viscous as well as elastic properties at the same time?

We answer this question by performing a combined laboratory and numerical study on the development of thermal plumes in a Herschel-Bulkley fluid. The laboratory fluid is an aqueous solution of Carbopol, a polymer gel suspension forming a continuous network of micrometric sponges. The fluid is shear thinning and presents a yield stress, whereby flow can only occur if the local stresses due to buoyancy exceed a critical value. Below this stress the fluid acts as an elastic solid.

The setup consists of a localized heat-source, placed in the center of a squared plexiglas tank. In the numerical simulations the rigid regions are replaced with an extremely viscous fluid, and therefore elasticity is neglected. We systematically studied the influence of the rheological parameters as well as the supplied heat. Depending on the ratio of the resulting buoyancy induced stress to the yield stress, three different regimes develop. By increasing the importance of the thermal buoyancy stress, the system passes from no convection to a small cell that convects confined around the heater. Two conditions need to be fulfilled to allow for a plume to develop: 1) the buoyancy induced stress needs to be sufficiently high compared to the yield stress and 2) the Bingham number *Bi* (comparing the yield stres to the viscous stresses) needs to be locally smaller than 1. As the plume rises it loses its buoyancy due to diffusion and convection slows down at the plume head. Therefore as soon as the buoyancy induced stress becomes too small compared to the yield stress, or as /Bi>1/, the plume halts and spreads under an unyielded, high viscosity region at the top of the box.

Experiments and simulations show that a plug flow develops inside the plume thermal anomaly, producing a rising finger-shape with strong shear zones confined along its edges. Those finger-shaped diapirs present a strong similarity with an off-axis diapir in Oman emplaced in a ridge context. This geological object, a few kilometers in diameter presents strong shear localization along its edges. Our fluid-dynamical analysis places strong constraints on the parameter range within which such an object may be emplaced, suggesting that a purely thermal anomaly could only be emplaced in a partially molten lithosphere (~100 kPa). However the yield stress of the surrounding matrix might be much higher (up to ~10 MPa), if the instability also exhibits a chemical density anomaly in addition to a thermal difference. Hence Herschel-Bulkley fluids, like Carbopol, might be good candidates to get new insights into the behaviour of "soft" geological systems like mid-ocean ridges.

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Deformation initiation and localization around inclusions

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Deformation localization along narrow zones of variable scales is a common feature in orogenic belts. In the upper crust, these faults normally produce gauges, whereas in the middle and lower crust, mylonites are the commonest products. Although there are a number of studies using different approaches that focused on the evolution of brittle fault zones, little is known about the initiation and localization of ductile shear zones. To fulfill this gap and gain some insights about the evolution of high temperature shear zones, we have been performing simple and pure shear experiments in marbles containing structural heterogeneities, coupled with microstructural analyses and crystallographic orientation mapping in the recovered samples. As starting material we have used cylindrical samples of coarse-grained Carrara marble containing one or two 1 mm thin artificially prepared sheets of fine-grained Solnhofen limestone. Samples were deformed in a Paterson-type gas deformation apparatus at 900°C temperature and confining pressures of 300 and 400 MPa. Three samples were deformed in axial compression at a bulk strain rate of 8x10−5 s−1to axial strains between 0.02 and 0.21 and 15 samples were twisted in torsion at a bulk shear strain rate of 2x10−4 s−1 to shear strains between 0.01 and 3.74.

Even at low strains, intense twinning of calcite is already observed in the calcite grains of Carrara marble juxtaposed to inclusion. The distance from the tip of the inclusion in which twinning is observed increases with increasing strain. Orientation of the twin planes may vary from parallel to normal to the tip of the inclusion, and with increasing strain there is a tendency of development of "twin conjugates". Together with twinning, subgrain boundaries are observed in this region, possibly followed by initial grain size reduction. In these experiments, strain is localized into narrow bands, which is demonstrated by misorientation maps showing the degree of internal lattice distortion of individual calcite crystals around the tip of the inclusion, reaching values from 3 to 10°, depending on the strain. The closest are those grains to the inclusion, the higher is the internal misorientation. The localization of strain extended into narrow, few mm long bands, and the degree of localization decays exponentially with increasing distance from the tip of the inclusion. Although weak, the initial development of crystallographic orientations along these process zones is evident and starts to be developed at very low strains, increasing in strength with increasing strain. The microstructural modifications observed at the tip of the inclusions are possibly caused by the stress concentration in this region. At higher strains in the pure shear experiments, deformation of grains is also observed in the lateral sides of the inclusions. The results demonstrate the importance of structural heterogeneities on the localization of deformation. More broadly, they demonstrate the microstructural modifications caused by stress concentrations causing "brittle" behavior at the tip of these inclusions.

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Detecting multiple mantle sources of K-rich melts in a single lava flow at Latera volcano, Central Italy

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Latera stratovolcano is situated near the boundary between the Roman and Tuscan Magmatic Provinces in Central Italy. Compositions of its ca. 0.29-0.15 Ma lavas range between leucite-bearing (HKS) and shoshonitic (SHO), the latter showing geochemical evidence for mixed-in lamproitic melt. Compositions of (near-) liquidus minerals (olivine, clinopyroxene, spinel), combined with major and trace-element contents of melt inclusions (MI) in Fo-rich olivines, show that the single Selva Del Lamone lava flow (SHO) hosts two different mantle-derived magmas: “traditional” SHO-I type and low-CaO, high-Na_2O SHO-II type with lamproitic affinity. The MI show an extreme Pb-isotopic diversity, each group being characterized by its own signature, so that the host lava appears to be a mixture of (at least) three distinct endmembers. The melts form arrays between MORB-like mantle and different crustal/sedimentary end-members including upper and lower continental material. Nearby HKS lavas are similar to their equivalents in the rest of the Roman Province. Mineral compositions are consistent with this diversity of primary melts. Our study demonstrates an extreme variation in the nature of vertically arranged mantle domains, presumably reflecting different subduction-related metasomatic imprints. Simultaneous melting can be explained by a heat pulse associated with rising hot asthenosphere through a wide open slab window.

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3D numerical modeling of India-Asia-like collision

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One of the most striking features of plate tectonics and lithospheric deformation is the India-Asia collision zone, which formed when the Indian continent collided with Eurasia, around 50 million years ago (*Royden et al., 2008*). The rise of the abnormally thick Tibetan plateau, the deformation at its Eastern and Western syntaxes, the transition from subduction to collision and uplift and the interaction of tectonics and climate are processes not fully understood.

Though various geophysical methods have been employed to shed light on the present structure of the Indian-Asian lithosphere, the driving mechanisms that uplifted the Tibetan plateau remain highly controversial and different hypotheses imply contradictory scenarios. Models for double crustal thickness include: wholescale underthrusting of Indian lithospheric mantle under Tibet (Argand model), distributed homogeneous shortening or the thin-sheet model (*England and Houseman, 1986*), slip-line field model to also explain extrusion of Eastern side of Tibet away from Indian indentor (*Tapponier and Molnar, 1976*) or lower crustal flow models for the exhumation of the Himalayan units and lateral spreading of the Tibetan plateau (*Royden et al., 1998, Beaumont et al., 2004*). The thin-sheet model has emerged as a more successful (or at least more widely used) model , but one of its major shortcomings is that it cannot simultaneously represent channel flow and gravitational collapse of the mantle lithosphere (*Lechmann et al., 2011*), since these mechanisms require the lithosphere to interact with the underlying mantle, or to have a vertically non-homogeneous rheology. Of those who favour a layered structure of the lithosphere beneath Tibet, some attribute the lack of substantial seismicity underneath the Moho as evidence that all the strength of the lithosphere resides in the upper crust and the mantle is weak – the crème brulée model (*Jackson, 2002*), while others point out that some processes can be well explained if the crust resides above a strong mantle lithosphere – the jelly sandwich model (*Burov and Watts, 2006, Royden et al., 2008*).

3D models are thus needed to investigate these hypotheses. However, fully 3D models of the dynamics of continent collision zones have only been developed very recently, and presently most research groups have relied on certain explicit assumptions for their codes. Here, we employ the parallel 3D code LaMEM (Lithosphere and Mantle Evolution Model), with a finite difference staggered grid solver, which is capable of simulating lithospheric deformation while simultaneously taking mantle flow and a free surface into account. We here report on first lithospheric and upper-mantle scale simulations in which the Indian lithosphere is indented into Asia.

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On the Generation of Supercontinent Cycles from Mantle Convection with Self-Consistent Plate Tectonics and Mobile Continents

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Kenorland, Columbia, Rodinia, *Pangaea*: there is some evidence in the geologic record that continental blocks have been assembled into a large landmass during some periods of Earth's history. These periods have been interrupted by continental break-up events and subsequent dispersal of the fragments. The alternation between assembled and dispersed continent configurations is often called the *supercontinent cycle*.

Plate reconstruction techniques allow us to look into Earth's tectonic history, but only for the last 200-250 Ma such that only the existence of the last supercontinent, *Pangaea*, is well documented. Especially for the presence of the first supercontinents there are only few constraints: one of them is the correlation of peaks in the production rate of continental crust (detected by analyzing the osmium decay system [1]) and the suggested assembly times of some of the listed supercontinents. These are derived e.g. from the argument that almost all cratons - that stabilized at a certain time - were located next to each other in *Pangaea*, which is very unlikely if they have not formed in a single continental block [2]. Further indications for supercontinents can be derived from palaeomagnetic data sets.

Supercontinents are thought to generate a large-scale thermal anomaly by insulation beneath them, which enhances melting processes and with that the growth of continental crust. This is supported by our simulations of mantle convection, which show a significant temperature increase of subcontinental mantle after the assembly of a supercontinent. However, although some progress has been made, the details of the dynamic origin of the *supercontinent cycle* are still not well understood. A fundamental question is if supercontinents appear periodically with an intrinsic period imposed by the convection of the underlying mantle or if they occur with a high degree of randomness?

To address this question we use here fully dynamic models of mantle convection that feature self-consistently generated plate-like behaviour and buoyant, rheologically distinct continents that drift over the surface, eventually colliding or splitting. In contrast to our previous models [3] the continents in this study consist of a rheologically strong interior surrounded by a weaker exterior. The former represent the Archaean cratons on Earth, which hardly deform and are thought be tectonically stable since > 2.5 Ga. The weak material represents the mobile belts from the Phanerozoic. In the present study we investigate in 2D and 3D numerical models how the properties of the mantle flow (yield strength of the lithosphere, mode of heating) control the occurrence of a *supercontinent cycle* and its periodicity. We show that a regular supercontinent cycle is unlikely. Strong variations between different cycles exist instead, that lead to significant fluctuations of the timescales of continent assembly and dispersal. Both timescales are dependent on the strength of the lithosphere, which thus controls the ratio of both timescales.

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Numerical modeling of dynamic topography and uplift rate, advection vs diffusion

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We study the evolution of the dynamic topography due to thermal anomalies in a set of numerical simulations of three-dimensional mantle convection. We show that the dynamic uplift rate may follow a Stokes behavior or a diffusion-dominated behavior depending on the magnitude and size of the thermal anomalies and on the viscosity. At low viscosity, advection dominates the flow, but at higher viscosity, heat diffusion becomes more important. In the first case, if advection dominates, a hot thermal anomaly may produce a positive uplift rate if the hot blob is sufficiently deep to move upward or a negative uplift rate if the anomaly deforms (diverging horizontally) below the bottom of the lithosphere. If diffusion dominates, a hot anomaly, generating a positive dynamic topography, tends to diminish in magnitude and then produces a negative uplift rate. Heat diffusion, often neglected in convection experiments going backward in time, can then be a very important parameter to consider.

To illustrate this result, we show the evolution of the dynamic topography in numerical simulations having thermal initial conditions computed from various tomographic models. We show that the resolution of the tomographic models influences strongly the ratio advection over diffusion, which strongly affect the uplift rate.

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Seismological insights into the structure of the Lesser Antilles Arc

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Due to an overall eastwards drift of the Caribbean plate of around 2cm/year relative to the Atlantic plate, the type of the subduction along the eastern part of the Caribbean changes. Compared to the simple subduction of the Atlantic plate in the east, the northern plate boundary zone is far more complex, predominantly characterised by a left-lateral east-west strike-slip motion that includes an oblique convergence of the Bahamas carbonate banks and a pull apart basin in the Mona Passage, the sea gate between Hispaniola and Puerto Rico. The island of Hispaniola is decoupled from the Caribbean plate, which leads to a second subduction zone south of Hispaniola where the Caribbean plate subducts beneath the Hispaniola micro plate. Strictly speaking, the arc only extends to the east of the island of Puerto Rico but since most of the northern Caribbean plate boundary zone is directly linked to it the results become more directly comparable. Fed by the Orinoco River the southern part of the Lesser Antilles is a sediment-rich subduction zone, which becomes sediment-poor towards the north as the sediments get blocked by several banks, including the accretionary prism containing the island of Barbados. Here we investigate the crustal and mantle structure variation along the Antilles Arc using measurements of seismic anisotropy and receiver functions. We use data from three component broadband stations that are located from the southern end of the arc to Hispaniola in the north.

Seismic anisotropy refers to directional variations in wave speeds and their polarisations. The observation of two independently propagating shear waves (splitting) is the least ambiguous indication of anisotropy. Such observations can be used to constrain mantle flow beneath subduction regions, offering insights into slab dynamics. We generally observed trench parallel orientations around the plate boundary. However, we see significant local deviations in the inferred flow pattern, for example, in the shallow mantle beneath the Mona Passage.

Significant variations in sediment load, petrology and volcanism are observed along the arc. We investigate whether there is any correlation with crustal structure using receiver functions to determine Moho depth and Vp/Vs ratio. The receiver functions are computed using the extended-time multitaper frequency domain cross-correlation receiver-function (ETMTRF) by Helffrich (2006). This method has the advantage of resistance to noise, which is helpful since most of the data around the arc will have been collected by stations close to the ocean, thus containing a large amount of noise. Our preliminary results show clear variations in these measurements. There are also regions where the Moho is not very sharp.

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Rifting and volcanism close to triple junctions: interactions between lithosphere break-up and mantle dynamics in an active oceanic rift

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Active rifts are inferred to grow and evolve as a response to asthenospheric mantle upwelling, whereas *passive rifts* develop as a response to lithosphere extension due to far field stresses. At triple plate junctions, both types of rifts can co-exist and interact in a complex way, producing a number of geological features like oceanic plateaus, tectonic structures and widespread volcanism.

The Azores volcanic islands in the North Atlantic have developed on both flanks of the Mid-Atlantic Ridge (MAR) near the triple junction (the Azores Triple Junction – ATJ) between the North America, the Eurasia, and the Nubia plates. The origin of volcanism is still debated. Many authors have proposed that the volcanism is induced by an active mantle plume, but the growth and the evolution of the islands during the late Quaternary has also been largely influenced by regional deformation, especially along the present eastern branch of the ATJ, the Terceira Rift (TR), an ultra-slow oceanic rift. Several islands have developed in and near the TR, i.e., from east to west, Santa Maria, S. Miguel, Terceira and Graciosa. The study of these islands is particularly interesting to try and understand the development of volcanic activity (continuous? by pulse?) in relation to the recent evolution of the TR.

We present a multidisciplinary study of the TR and the peculiar volcanism as a marker of the principal stages of melt production and regional tectonics. The approaches include geomorphological analyses from high-resolution DEM data to identify the main volcanic edifices and tectonic structures on the islands, fieldwork to study the various volcanic units and analyse fault kinematics, and high-precision K/Ar geochronology on target samples to constrain in time the main phases of growth and destruction. In addition, an analogue fluid dynamic approach is being used to model mantle and lithosphere interactions along a rift, and test whether the TR and the volcanism could have been initiated and developed in response to a buoyant mantle plume.

Geological data and analogue modelling should shed light on:
(1) how the TR evolved in space and time
(2) how lithospheric and asthenospheric processes control the development of volcanism near such triple junctions
(3) how the local and regional tectonic stresses have affected the morphology of the islands along the TR, e.g. by construction and gravitation destabilisation as graben, caldera and normal faults
(4) additional processes related to the intrinsic evolution of volcanoes (magma chamber evolution and creation of volcano-tectonic structures).

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Interactions between deformation and reactive melt percolation in the upper mantle: simple-shear deformation experiment at high pressure and temperature

(Soustelle V., Manthilake G., Walte, Frost D.)

This study consists of a series of simple shear deformation experiment by using a 6-ram multi-anvil apparatus at 2 GPa and 1150 ºC. The samples comprises a dunite aggregate mixed with 10% of Si-rich hydrous melt in chemical disequilibrium with the solid matrix. The samples were deformed at strain rates between $4x10^{-5}$ and $7x10^{-4}$ s^{-1}. The strain ranged from a γ of 0.3 to 1.5. The reaction between the melt and the olivine induces the precipitation of orthopyroxene and minor amounts of clinopyroxene.

The analysis of the melt pockets topology and orthopyroxene shape preferred orientation displays a clear difference between their directions of elongation. The melt pockets are mostly elongated or may form bands orientated at 45 to 75º counterclockwise from the shear plane at senestral shear, *i.e.* 0 to 30º to the compression axis. The orthopyroxene single crystal and aggregate long axis is parallel to the lineation defined by olivine elongation, which is orientated at 0 to 45º clockwise to the shear plane at senestral shear. In these two direction of melt pockets and orthopyroxene elongation, narrow bands composed by very fine grains (10 times smaller than the average grain size) are developed. Reactive melt percolation may then constitute an efficient mechanism for strain localization in the mantle.

Crystal preferred orientation (CPO) measurements on olivine show a maximum concentration of the [010] axes close to the normal of the shear plane. The [100] axes form a girdle close to the shear plane with one or two maxima concentrated normal or normal and parallel to the shear direction, respectively. The [001] axes display a maximum concentration, which becomes closer to the shear direction with the increasing of strain. Such CPO patterns may be explained by different processes: (1) deformation in the presence of high water contents that change the olivine dominant slip system; (2) a partitioning of the deformation between the narrow fine-grained bands elongated with the melt pockets and the orthopyroxenes, and the olivine matrix; and (3) olivine deformation dominated by diffusion creep, which is rate limited by interface reactions. Orthopyroxenes displays stronger CPO than olivines with the maximum concentration of the [001] axes close the shear direction, and a maximum concentration of the [100] and [010] axes close to the normal to the shear plane. This CPO pattern may result from the deformation of the orthopyroxene under relatively high water and Al contents.

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Viscoelastic convection with a free surface: Implications for subduction initiation

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The initiation of subduction on Earth is a yet unresolved question in geodynamics. It has been extensively investigated by many authors, but still remains poorly understood. It has been shown that it is rather difficult to initiate subduction in a stagnant lid regime . To obtain subduction zones, one needs to introduce either weak faults or a relatively low upper strength limit (the yield stress) to produce subduction-like features in numerical models. As an alternative to prescribed weak zones, lithospheric-scale models have also employed different weakening mechanisms to create lithospheric-scale shear zones.

In this study, we study the effect of a free surface upper boundary condition on bottom heated Rayleigh-Benard convection. The effect of a free surface on the lid stresses in stagnant lid convection is obvious: As the lid is allowed to bend under external forces, we may generate large bending forces which might help to break the stagnant lid. Using 2D viscoelastoplastic numerical models, we investigate the dependence of the lid stress on the Rayleigh number and the Deborah number. Results show that stresses in the lithosphere reach critical values when using a free surface boundary condition. Under such high stresses, subduction initiation is likely to occur.

In lithospheric-scale models of subduction initiation, three different boundary conditions are usually employed: constant velocity, constant strain rate and constant stress. Using the results from our convection simulations, we can put constraints on the applicability of the boundary conditions used in kinematically driven lithospheric-scale models.

Mr. Philip USHER - *University of Bristol, Bristol, U.K.*

Investigating two methods for measuring attenuation in microseismic data - the spectral ratio method and the instantaneous frequency method

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Attenuation is the loss of energy per wavelength of a seismic wave, however it is not commonly measured in microseimic data. Attenuation at such wavelengths (10's of meters) is probably dominated by a squirt flow mechanism (Chapman 2003), which is sensitive to the fluid and fracture properties of the rock. These are important to help understand how hydrocarbons are produced from tight unconventional reservoirs, which have been hydraulically fractured to increase the permeability.

The spectral ratio method is one of the more common ways of measuring attenuation (Tonn 1991, Dasgupta and Clark 1998). It does not require knowledge of the receiver response or geometrical response. It works in the frequency domain by comparing the spectra of two events. The log of the ratio of these two spectra is plotted against frequency (Fig. 1). The gradient of this graph is Δt^*. This is inversely proportional to Q, the quality factor. This method is affected by windowing of the events, sampling of the event, noise, and the amount of attenuation. These effects have been explored using synthetic spectra. This method also requires the attenuation to be approximately frequency independent over the frequency range. Using the synthetic spectra we can also look at what happens if this assumption is invalid.

The instantaneous frequency method (Ford et al 2012) uses the instantaneous amplitude and frequency of the trace. It tries to match the instantaneous frequency at peak instantaneous amplitude by applying an attenuation operator in the Fourier domain for different Δt^* values (Fig. 2). This method suffers from some of the same problems of sampling, windowing and noise, however it does not matter whether or not it is frequency dependent. These problems have been investigated using a synthetic wavelet.

The methods have been compared to show the advantages of each method and how this will affect the measurements of attenuation in microseismic data specifically the field data from Cotton Valley east Texas.

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Tonn, R. (1991). The Determination of the Seismic Quality Factor-Q From Vsp Data - a Comparison of Different Computational Methods. *Geophysical Prospecting*, *39*(1), 1–27.

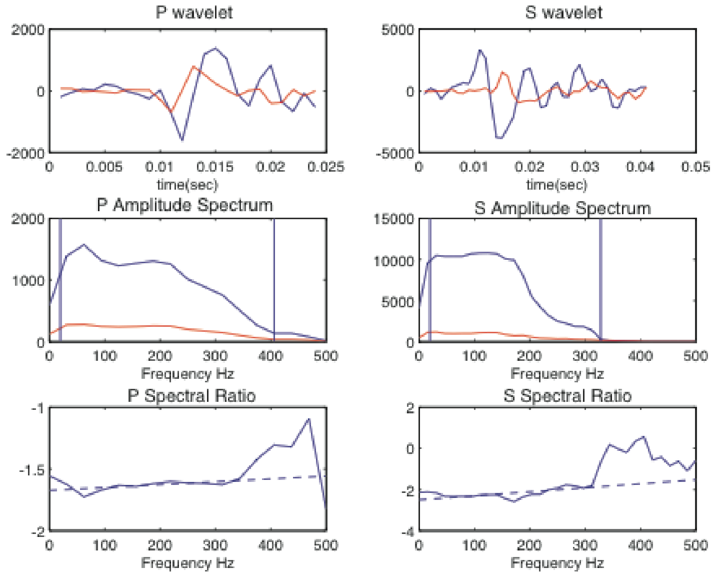

Fig. 1: Shows the spectral ratio method applied to a P and S wave (top left and right). The Fourier transform of these windowed wavelets (middle). The log spectral ratio with the straight-line fitting (bottom).

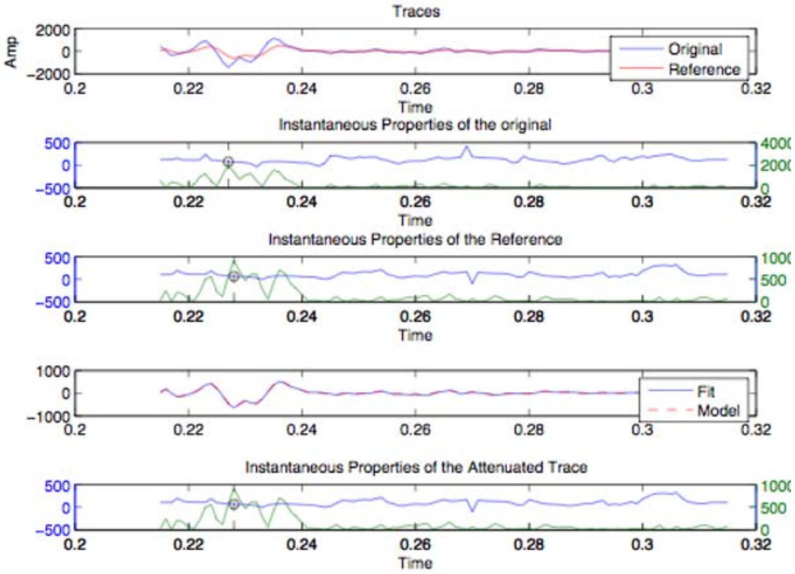

Fig. 2: Shows the instantaneous frequency method applied to two synthetic traces (1st line). The instantaneous properties of these traces (2nd and 3rd line). The attenuated trace to match the instantaneous frequency (4th line) and its instantaneous properties.

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Incorporating history dependence and texture in models of mantle convection

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Solid-state deformation processes permitting convection of Earth's rocky mantle necessarily lead to strong feedbacks between the deformation history and the instantaneous flow field. Mechanisms leading to the history dependence include the alignment of mineral grains with the attendant generation of elastic and rheological anisotropy, as well as processes operating at larger and smaller length scales (e.g. phase separation, grain size reduction, changes to the defect chemistry and dislocation multiplication and entanglement). Despite their sophistication, current models of mantle dynamics frequently ignore history dependent rheologies, and the feedback between deformation, grain size, crystal orientation, chemistry and viscosity. These processes have huge effects on viscosity: in the crust, they lead to the development of shear-zones and highly localised deformation, whilst, in the mantle, they are nearly always ignored.

Here we describe an approach intended to introduce the consequences of history dependence into models of whole-mantle convection. We make use of existing technology that exists in several convection codes: the ability to track markers, or particles, through the evolving flow field. Tracers have previously been used to track attributes such as the bulk chemical composition or trace element ratios. Our modification is to use this technology to track a description of the current state of the texture and microstructure (encompassing an orientation distribution function, grain size parameters and dislocation density) such that we can advance models of polycrystalline deformation for many particles alongside and in sync with models of mantle convection. Our approach is intended to be reasonably generic, coupling one of several mantle convection engines with a choice of polycrystalline deformation models, but the initial implementation uses the TERRA convection code (Baumgardner, *Stat. Phys.* 39:501-511, 1985; Davies and Davies, *EPSL* 278:50-54, 2009) to drive DRex (Kaminski et al. *Geophys. J. Int.* 158:744-752, 2004).

We note that there are several advantages of this coupled approach compared with post-processing stored strain histories. First, this approach opens the possibility of directly feeding data, such as the current local rheology, from the polycrystalline deformation model into the evolving convection simulation. Second, we allow the creation, merging, splitting and destruction of particles over time to help balance and reduce the computational work. Third, we automatically benefit from the parallelism and load balancing properties of the convection code. Finally, we remove the need to store potentially enormous volumes of data beyond the execution time of the model. One major disadvantage of this approach is the need to store large volumes of data associated with the present state of each particle. We currently overcome this by reducing the number of particles carrying information about texture and microstructure but intend to replace the crystal-by-crystal description with a novel compact and efficient method to describe the evolution of texture using structured basis functions. As well as outlining the approach, we will present key benchmark cases and initial results from our simulations focusing on texture development in the upper mantle.