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DAY 1

Session 1

ORALS

Strain-localization in convective systems: from the laboratory to planetary mantles

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Abstract

Strain-localization along plate boundaries is a characteristic feature of plate tectonics. However, the mechanisms able to produce strain localization are numerous and operating on various time and length-scales. So the exact process(es) that control plate boundary formation from convection of a viscous mantle remain debated, as well as the ingredients that should enter their mathematical representation in numerical modeling. Laboratory experiments, using analog fluids displaying controlled complex rheologies, from viscous to brittle, can give valuable constraints to the ongoing discussion.

Here, I shall focus on the formation of mid-ocean ridges. We used Ludox silica nanoparticles dispersions, whose mechanical properties vary from viscous to brittle with increasing particle content or salinity (Di Giuseppe et al, 2012). These dispersions allow independent variation of spreading velocity and mechanical structure of the plate while permitting detachment faults and axial fluid intrusion to occur. The shape of the ridge axis observed in the laboratory experiments is quite similar to the terrestrial case (fig.1, A-E). Morphologies of segmentation such as overlapping spreading centers, transform faults and rotating microplates are reproduced. Scaling laws based on fracture and fluid mechanics allow to predict the size, duration and abundances of theses features, as well as their conditions of existence on Earth (Sibrant et al, 2018; 2021). Varying the experimental fluids and conditions, we can also reach control parameters out of the range of the Earth to reproduce and explain extension morphologies encountered on Venus (fig.1F), or on icy satellites.

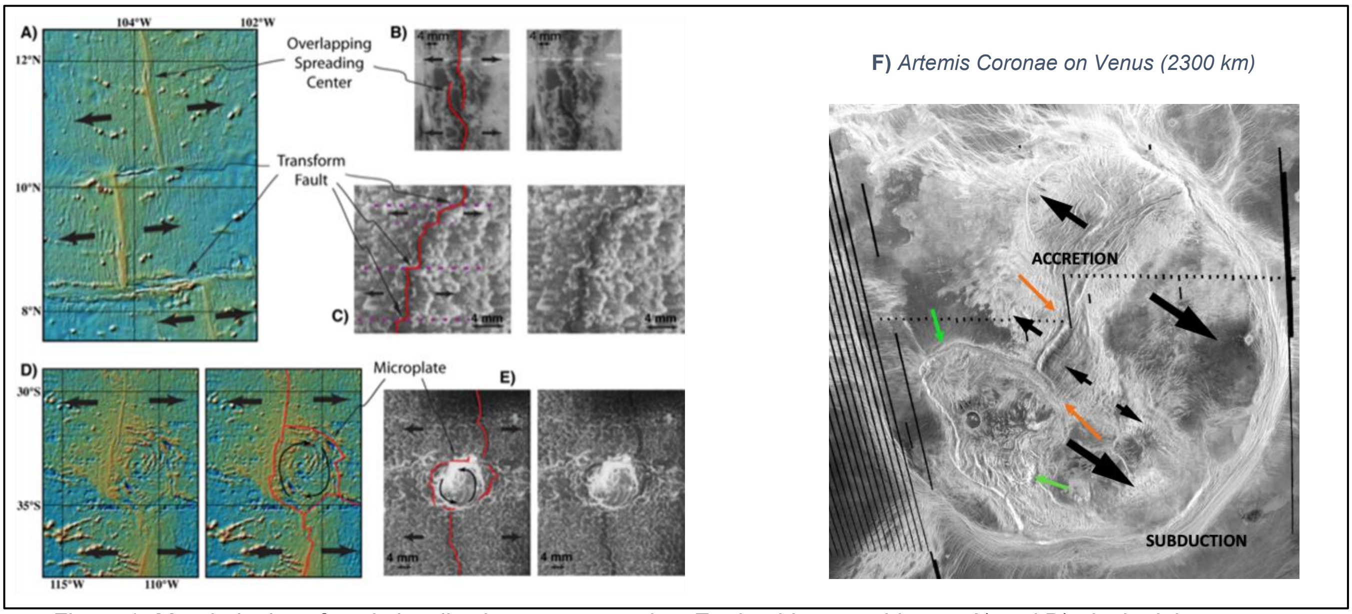

Figure 1: Morphologies of strain localization encountered on Earth mid-ocean ridges, - A) and D)-, in the laboratory experiments, -B),C) and E)-, and in Artemis Coronae on venus, -F-. On the bathymetric maps A) and D) drawn using http://www.marine- geo.org/rmbs/-, sea-floor depth increases from orange to blue. The accretion axis have been highlighted in red when needed. The black arrows show the direction of spreading. In Artemis (F), the green arrows indicate possible microplates, and the orange ones, possible transform faults.

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Sibrant A.R.L., Davaille A., Mittelstaedt E. (2021) Rheological control of the segmentation of the mid-ocean ridges: Laboratory experiments with extension initially perpendicular to the axis, Earth Planet. Sci. Lett., 557, 116706.

Impact of Rheology on Restraining Bend Evolution and Slip-Rate Variations: Insights from Analog Models

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Abstract
Crustal restraining bends evolve within a range of rock materials that exhibit different rheological properties. Material properties can impact fault system evolution. For example, analog models that use low cohesion granular materials like dry sand, which exhibits frictional-plastic behavior, to simulate crustal faulting generate a greater number of faults than models that use stronger and more cohesive materials like viscoelastic wet clay (Eisenstadt & Sims, 2005; Figure 1). Because slip rates along faults within a restraining bend system can change in response to the growth, linkage, and abandonment of faults, restraining bends that evolve within materials with differing rheological properties may produce differing slip-rate histories. We conduct experiments of restraining bends that use either dry sand or wet clay and compare the faulting histories and slip rates recorded at sites along individual faults. Both materials dynamically scale to the crust, and they represent two elements of rock behavior in the upper crust: frictional-plastic vs. viscoelastic (Eisenstadt & Sims, 2005). Due to these rheological differences as well as differences in the strength, cohesion and dilatancy, sand may reproduce some crustal fault processes more realistically than clay and vice versa.

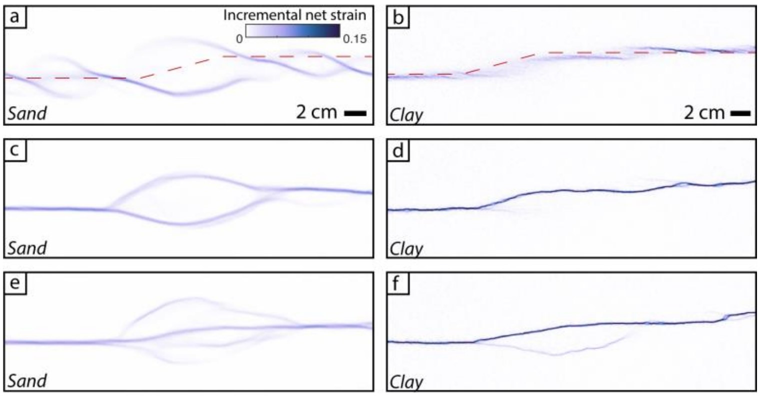

Figure 1 : Incremental net strain maps for the sand experiment at a) 8 mm, c) 25 mm, and e) 80 mm of basal plate displacement and for the clay experiment at b) 20 mm, d) 37 mm, and f) 79 mm of basal plate displacement. a & b) Red dashed line indicates basal plate velocity discontinuity location.

To demonstrate the material dependence of fault growth in restraining bends, we utilize a table-top split-box apparatus with a basal plate velocity discontinuity that includes a 15° bend with a 20 mm stepover. Stepper motors drive one half of the box to induce dextral faulting in the overlying sand or clay. A pair of overhead cameras capture stereoscopic images for the sand experiment and five overhead cameras capture images of the clay experiment that allow us to extract the complete (3D) incremental surface displacement fields, which we use to determine the surface strain as well as faulting and slip-rate histories.

The sand experiment produced a greater number of faults than the clay experiment; we attribute this first-order observation to the rheological differences between the materials causing deformation to localize into a major structure more quickly in the viscoelastic clay, which is more cohesive than the dry sand (Figure 1). In addition, the geometry of the echelon structures that formed early and the faulting sequence differed between the sand and clay experiments (Figure 1). While a single fault accommodated majority of the strain in the clay experiment, strain was more evenly partitioned amongst parallel fault segments in the sand experiment. Slip rates at some sites along faults in both the sand and clay experiments varied by more than 10% as the fault systems evolved. Due to more frequent fault reorganization within the sand experiment, slip rates recorded at sites along faults within the sand experiment exhibited larger temporal variations than recorded in the clay experiment. The experimental results demonstrate that analog crustal rheology can impact the temporal stability of the active fault geometry, strain partitioning and slip rates at sites along restraining bends.

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Controls on strain localisation in the crust during orogenesis

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Abstract
During the collision of continental crust, strain localises to accommodate convergence. The areas of the crust undergoing high strain is dependent on the rheology of the crust, which is controlled by geothermal gradients (Ellis, 1988; Vogt et al., 2017a), bulk composition (Chen et al., 2017; Piccolo et al., 2017; Vogt et al., 2017; Vogt et al., 2017a), internal friction angle (Ruh et al., 2012; Dal Zilio et al., 2020), as well as the convergence velocity (Vogt et al., 2017b; Vogt et al., 2017a). In this study, we utilise a 2D thermo-mechanical model to investigate how the crustal thickness, which results in changes in Moho temperature, and convergence velocity alter the areas of strain localisation in the crust.

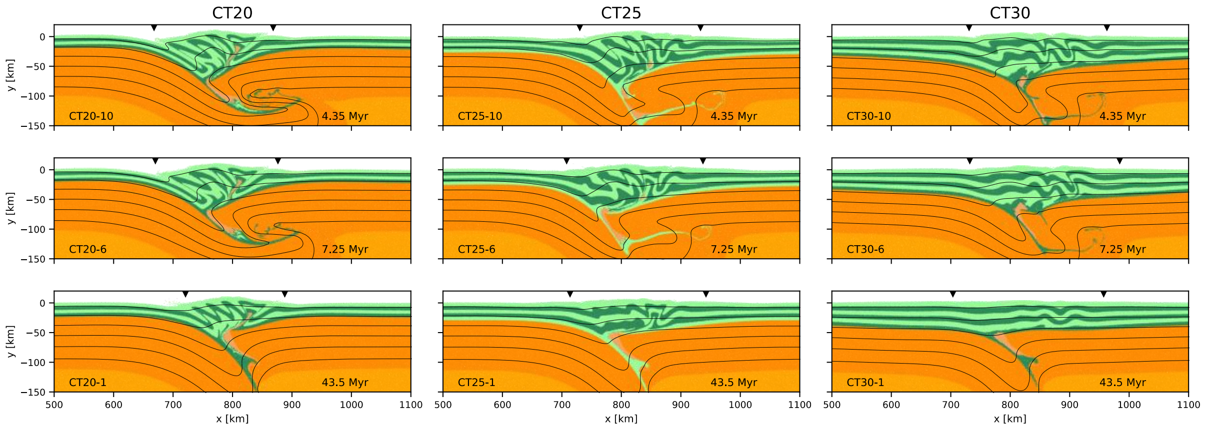

Figure 2: Final timestep of selected models showing the variations in structural style due to increasing convergence velocity (bottom-to-top) and crustal thickness (left-to-right).

Our results show that orogenic wedges with an initial uniform crustal thickness and converge velocity reach a steady state and can be characterised in to three categories, based on the geometry and internal structure: (1) Plastic wedges, characterised by high plastic strain localisation in the upper crust along shear zones, that results in stacking of the crust and shows no dependency on convergence velocity or temperature and are narrow and thick. (2) viscous wedges, characterised by folding of crust and diffuse deformation, with nominal plastic strain localisation, that are wide and thin and (3) visco-plastic wedges that show diffuse deformation in the lower crust and the development of high strain shear zones in the upper crust. The transition between these categories at a given Moho temperature is controlled by the convergence velocity: as it increases, the viscous wedges transition to visco-plastic and then to plastic. We propose a scaling for the critical velocities that control the transition between dominant deformation styles as a function of velocity and Moho temperature, for a given crustal rheology, which varies from cold, brittle crust that favours strain localisation along shear zones to warm, ductile crust that favours diffuse deformation close to the Moho.

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Laser-based acoustic imaging of analogue models

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Abstract

Since the 19th century pioneering work of Sir James Hall, physical analogue modelling has been proven a valuable method for the study of geological phenomena and has significantly contributed to understanding fundamental mechanisms of crust and lithosphere deformation. Traditionally, in such analogue scale models, structural deformation is monitored and quantified using top-view images or cross-sections, where the latter allow for portraying only the final state of internal deformation of the model. Monitoring the evolution of internal deformation while the experiment is running is a major challenge, and currently is possible only with X-ray scanning using medical-type CT scanners. These, however, put stringent limitations on size of the model and, thus, the possible geometric configurations related to different modelling setups.

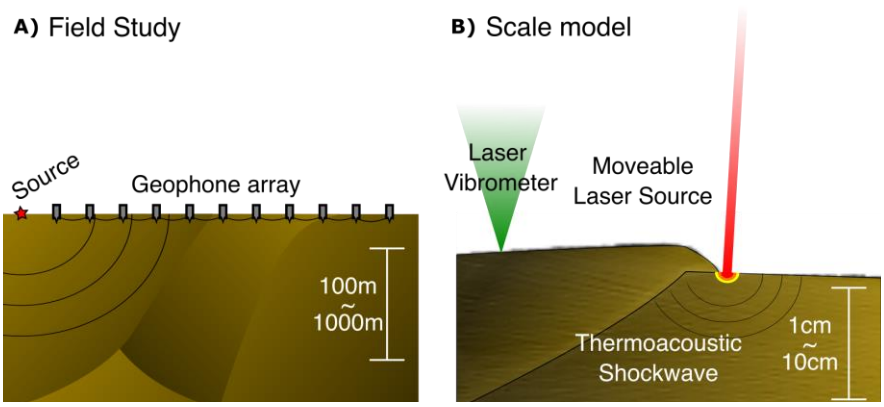

Figure 3 : Comparison between a field study setup and our lab setup

To tackle these limitations, we are developing a novel method to monitor internal deformation of analogue scale models using ultrasonic techniques. Similar to seismic studies used in the field, the analogue models can be imaged using sound waves (see Fig. 1). We developed a completely non-contact and non-invasive method, utilizing a laser Doppler vibrometer to detect the arrivals of seismic waves at the model surface. A laser pulse from a powerful pulsed laser acts as a point source and is used to introduce acoustic waves in the model. By moving the detector and source, acoustic data is recorded for a number of source-recorder combinations, allowing the reconstruction of the internal layering and structure along cross sections, as will be illustrated by the results of several tests with analogue models and other samples. By developing this technique, we provide novel tools to

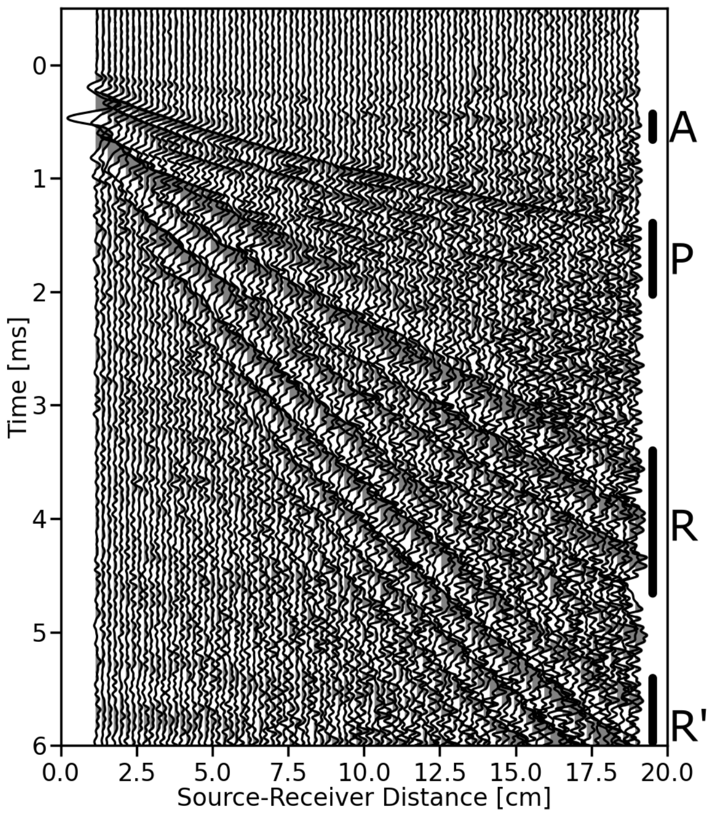

Figure 2 : Typical receiver-gather acquired on a uniform glass beads sample. The distance between two points is approximately 2 millimetres. Several seismic phases can be identified in the gather: The labels A, P, R, and R' indicate the wave in air, and the P-wave, first Rayleigh wave and second Rayleigh wave modes in the glass beads respectively.

characterize the acoustic behaviour of (sub)surface structures under well-controlled laboratory conditions with the aim of improving our understanding of waveforms and wave propagation in analogue models and earth materials in general.

As a demonstration, we monitor the velocity of both body and surface waves in an environment of changing temperature and humidity. It is shown that humidity and temperature variations in the laboratory environment have a large effect on acoustic velocities in granular material samples. An increase of humidity of 10% can lead to as much as a factor of two increase in surface wave velocity. We finally discuss future applications of the developed method by considering surface wave inversion for fault and stress monitoring during the deformation of a model.

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From microstructural heterogeneity to macro- and mesoscale shear zones: a recipe for strain localization on Earth

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Abstract
Strain localization is the rule rather than the exception in the lithosphere. Yet, modelling strain localization in the ductile field, which represents on average 90% of the lithosphere, remains a real challenge. Analysis of observations of ductile strain localization at various spatial scales in nature and experiments shows that heterogeneity in the mechanical behaviour is key for strain localization. This heterogeneity exists at all scales, in particular at small ones, and evolves in response to the mechanical fields. In the ERC RhEoVOLUTION, we posit that poor representation of this heterogeneity and its evolution during deformation is the locking point for generating strain localization in geodynamical models and examine how strain localization may arise in rocks deforming by ductile processes by associating a stochastic description of the mechanical properties of the medium with simple laws describing how these properties evolve in response to the resulting spatial variations in stress and strain rate.

Random variation in the rock mechanical properties (here, a strength variable describing a resistance to deform by dislocation creep) implemented in a stochastic manner in a FE model (random drawings from a truncated Gaussian distribution at fixed time intervals) produces, for simple boundary conditions and constant temperature, a strain rate field characterized by shear bands at 45° to the compression direction. The width of the shear bands is controlled by the size of the rheological heterogeneities. Their spacing results from the interactions between the perturbations in the strain field induced by the different heterogeneities; for a random distribution there are multiple wavelengths between 2-10 times the size of the heterogeneities. Yet this strain rate heterogeneity does not result in a change in the bulk mechanical behavior, which is well reproduced by simple homogenization schemes.

If the stochastically-described material property evolves as a function of the local work rate, strain localization may develop at scales significantly larger (at least 2 orders of magnitude) than the initial characteristic length scale of the rheological heterogeneity field. A few shear zones lengthen, coalesce, and widen, dominating the whole system, which reaches a new equilibrium. The intensity of strain localization (volume of the domain accommodating the localized deformation) depends mainly on the possible local softening. It does not depend on the initial heterogeneity field, which only controls the location of the shear bands. The evolution law controls the onset or not of strain localization and the kinetics of evolution of the system Stochastic time-varying descriptions of the rheology of rocks are therefore a powerful tool for investigating the feedbacks between physico-chemical processes changing the rocks rheology and their role on the development of strain localization at different scales.

POSTERS

Predicting Off-fault Deformation Using Convolutional Neural Networks Trained on Experimental Strike-Slip Faults

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Abstract
Surface offsets might not represent slip at seismogenic depths because at shallow depths, ruptures produce both slip and distributed off-fault deformation. Scaled physical experiments simulate off-fault deformation processes and provide direct observations of deformation partitioning. During strike-slip fault evolution, faults become more connected and more mature fault configurations accomodate greater proportion of the applied loading as localized slip (i.e., greater kinematic efficiency = slip rate/ applied velocity). More mature and through-going fault surfaces have greater kinematic efficiency, lesser off-fault deformation and limited shallow slip deficit. On the other hand, immature strike-slip faults with segmented and complex trace geometry produce greater off-fault deformation and larger shallow slip deficit. Laboratory experiments scaled to simulate crustal faulting provide both a wide range of active strike-slip fault configurations and associated off-fault deformation data.

Using experimental fault maps and kinematic efficiency data, we train and test a 2D Convolutional Neural Network (CNN) that can predict off-fault deformation of active strike-slip fault trace maps. Our approach follows that of Chaipornkaew et al. (2022) and in this study we expand upon that analysis in two ways. First, we implement a systematic grid search for optimal hyperparameters for the CNN training that minimize our custom loss function, which is also more strict than that used in Chaipornkaew et al. (2022). The second advancement is that this study trains on fault maps and kinematic efficiency data from two types of dry sand as well as wet kaolin experiments. By training the CNN on experimental strike-slip faults within both clay and sand with different loading rates and basal conditions, we simulate a wide range of material properties and conditions that may contribute to the evolution of fault geometry and off-fault deformation in the crust. For example, the variations in the dilatancy of sand upon shearing can produce very different fault geometry early in the strike-slip fault evolution (Visage et al., 2023). We train the CNN on experiments of wet kaolin run at UMass Amherst and experiments of both sedimented (via sieving) and poured sand run at CY Cergy Paris University (Lefevre et al., 2020; Visage et al., 2023).

First we train and evaluate the CNN separately on clay, sedimented sand and poured sand. Of the three materials, the CNN performs well on fault maps unseen during training for both wet kaolin (93% correct predictions) and poured sand (94% correct predictions). Even with a deeper CNN architecture the CNN trained on sedimented sand had lower accuracy in predicting kinematic efficiency than the other two materials (86%). We also assess kinematic efficiency predictions of the CNN trained on experiments on sedimented CV32 sand (UCP) to experiments with sedimented G12 sand from the GFZ Potsdam lab. Because different researchers use different techniques to delineate faults from off-fault deformation, we also test the capability of the trained CNNs to predict kinematic efficiency of maps unseen in training that were generated with different fault detection sensitivities. All of the trained CNNs correctly predict greater kinematic efficiency for fault maps generated with more sensitive detection schemes. Only the CNN trained on clay predicts kinematic efficiency correctly for >90% of the fault maps.

To further assess the potential predictive power of the CNN, we assess how well CNN trained on faults that grow in one rheology predict kinematic efficiency of fault maps from different rheology. Of the three trained CNN, the CNN trained on wet kaolin most correctly predicts off-fault deformation on fault maps generated in experiment using other materials. This suggests that the range of active fault configurations within clay experiments may correlate with those in the other experiments, especially the poured sand for which the clay predicts well. However, the poured sand does not predict well off-fault deformation of faults in clay. The limited range of active fault configurations in the poured sand experiment might not sufficiently encompass the range of active fault configurations produced in the clay experiments.

For a second assessment of the predictive power of the CNN we use the expeirmental trained CNN to predict kinematic efficiency for crustal fault maps. Growing records of satellite imagery before anda after earthquakes provide estimates of coseismic off-fault deformation but we have limited geologic data for long-term off-fault deformation. Here, we compare the predictions from experiment-trained CNN of all three materials with available crustal estimates of off-fault deformation along faults with variable maturity. The success of the CNN to estimate off-fault deformation provides a valuable approach for estimating shallow slip deficit along faults for which we do not yet have any geologic data to constrain off-fault deformation. This study demonstrates the strong potential for deep learning trained on experimentally produced faults for informing the strain partitioning of crustal faults and estimating potential shallow slip deficit due to geometric complexity.

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Impact of plate curvature and anisotropy on stress distribution and strain localization in a shortening lithosphere

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Abstract
The geometry of Earth's lithosphere resembles more a doubly curved shell than a flat plate. The mechanical properties of a shell can be fundamentally different to the properties of a plate. However, most numerical models studying lithosphere deformation do not implement this curvature. It is still unclear whether the shell-type geometry of the lithosphere has a significant impact on lithosphere deformation on the scale of up to a few 1000 kilometers. We present a comparison of numerical results of a shortening shell-type and plate-type lithosphere, and we investigate the importance of considering lithospheric shells by quantifying the spatio-temporal stress distribution. In addition, we present the effect of mechanical anisotropy for shell-type and plate-type shortening lithosphere models. Modeling an evolving anisotropy is physically motivated by material fabric development and can serve as a strain localization mechanism. Our numerical models are created with the two-dimensional state-of-the-art thermo-mechanical code MDoodz (Duretz et al. 2021). We consider a shortening lithosphere in an initially curved and in an initially rectangular geometry and calculate the spatio-temporal stress distribution inside the deforming lithosphere. We define an evolving anisotropy factor through finite strain evolution.

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Multi-scale modelling of subduction interface rheology

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Abstract

The composition and rheology of the subduction interface play a fundamental role in both the subduction dynamics and the deformation and topography of the overriding plate. Outcrop scale field observations have revealed that the interface is often compositionally and therefore rheologically heterogeneous. Since these heterogeneities cannot be easily resolved in large-scale geodynamic subduction models, we create meter-scale Finite Element models to determine the effect of heterogeneous rheologies on the bulk interface deformation. Our models comprise meter-scale blocks of continental affinity, encompassed within a quartz-rich matrix. We use the open-source particle-in-cell FEM code Underworld (Moresi et al., 2002; 2003) to create synthetic 2D visco-plastic models of the subduction interface that deform by simple shear. We study the effect of viscosity (constant, diffusion creep, dislocation creep) and coefficient of friction on the bulk deformation and stress distribution in the models, for large finite shear strains. By varying the percentage of block concentrations, temperature, and pressure, we mimic the trajectory of the blocks to higher depths along the interface. Using the same code we perform large-scale 2D buoyancy-driven subduction models, in which we vary the friction coefficient and the viscosity of the subduction interface, according to our small-scale models. We also test mixing laws (e.g. Tullis et al. 1991) to account for different percentages of blocks within the matrix. We finally investigate the long-term rheological evolution of the subduction zone and the deformation of the overriding plate with respect to the interface rheology. With this multi-scale approach, we gain insight into how the same rheology can affect deformation at different scales.

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Analogue modelling of negative inversion: an example from the Casino Basin, Northern Apennines, Italy

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Abstract

Negative inversion applies to tectonic basins formed in contractional environments that have undergone subsequent, late- or post-orogenic extension (Cooper & Williams, 1989). Under these conditions, synorogenic deposits occupying fault-bounded depressions are folded and uplifted during protracted compression and consequent erosion of their most elevated parts. The transition from orogenic compression to late- or post-orogenic extension is responsible for development of normal faults that may form ex-novo or reactivate pre-existing thrusts and reverse faults (Tari et al., 2023). Synorogenic deposits that have experienced the effects of negative inversion may therefore exhibit a variety of architectural and statal features recording the effects of the transition from compressional to extensional deformations.

The Casino Basin, located between the Montagnola Senese and Chianti Mts. Ridge in Southern Tucany, Italy, developed during the Miocene as part of the Northern Apennines mountain range that makes the backbone of the Italian Peninsula and whose evolution has long been proposed to result from negative inversion (Elter et al., 1975). This basin is considered part of the post-orogenic Neogene hinterland basin system of the chain, and it represents one of the easternmost ones. Despite a general good exposure condition of its fill deposits, the deep structure of the Casino Basin is still poorly constrained. As a consequence, the history of its development and evolution is still matter of debate and some, often contrasting interpretations have been proposed to explain its tectonic significance (e.g. Lazzarotto & Sandrelli, 1977), which is however classically ascribed to half-graben extensional tectonics. The results of new investigations carried out along the Basin in the framework of the CARG Project aimed at revising the geological mapping of the Italian territory at the 1:50.000 scale, coupled with interpretation of a seismic line to be acquired across the basin, will provide additional evidence to try to unravel the complex geometry and history of this interesting basin (Milaneschi et al., 2023).

Analogue modelling has long represented a useful tool in trying to reconstruct the origin of tectonic basins and in providing insights on their kinematic evolution. In this study we present the results of an experiment aimed at illustrating the geometry and history of the Casino Basin. The experiment was carried out reproducing the effects of negative inversion, from orogenic compression to late- or post-orogenic extension, at the expenses of a horizontal strata of dry sand layers whose thickness is scaled to the maximum estimated thickness of the tectonic basin fill, based on available surface data. The results from analogue modelling of negative inversion across a sequenced aimed at reproducing the features of the Casino Basin will provide useful tools to try to unravel its complex, controversial evolution. We expect that these data, integrated with information from ongoing field surveys and seismic line acquisition, processing and interpretation, will represent original elements to illustrate the history of development and evolution of this interesting, yet problematic basin, providing new constraints to the tectonic evolution of the hinterland of the Northern Apennines.

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Brittle-ductile mixed rheological behavior in subduction zones controlled by the strength contrast in heterogeneous materials.

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Abstract

From a geological point of view, deep deformation at the subduction plate interface in blueschist conditions, is often proposed to be accommodated by a "brittle" deformation of strong meter-scale mafic lenses embedded in ductily deformed weak metasediments. This brittle-ductile behavior is commonly proposed to explain transient slips, a geophysical signal characteristic of the transition between locked and creeping domains in active subduction zones. We propose here that such brittle-ductile rheological behavior is typical of the blueschist conditions, not only in tectonic mélanges but also in homogeneous oceanic metagabbros. We use microstructural observations of exhumed blueschist gabbros exposed in the Queyras massif (French-Italian Alps) to identify deformation mechanisms that may be associated with transient slip nucleation. We observe micro-fracturing of "strong" clinopyroxene porphyroclasts and the ductile deformation of a "weak" lawsonite-rich matrix. Lawsonite formed during the prograde deformation event from the destabilization of the plagioclase in blueschists conditions. The presence of lawsonite in the metamorphic matrix and glaucophane inside clinopyroxene microfractures suggests a significant hydration of the rocks during subduction and fluid overpressure.

Two-dimensional large strain simple shear numerical experiments are used to constrain the mechanical conditions for brittle deformation of strong clast inside a weak matrix. We run models at imposed velocity, constant temperature, depth and pore fluid pressure coefficient ranging between 10^{-13} s^{-1} to 10^{-11} s^{-1}, 280°C and 700°C; 25 km and 55 km; and 0.8 and 0.95. Our numerical results show three main types of behavior: 1. entirely brittle deformation (both matrix and clast) at low temperature; 2. ductile deformation of the matrix and very limited deformation of the clast that instead rigidly rotates during shear, at high temperature and 3. ductile deformation of the matrix and brittle deformation (micro-fracturing) of the clast for intermediate temperature. The rheology of this brittle-ductile material is controlled by the strength ratio between the yield plastic stress of the strong clast (e.g., a function of pressure and pore fluid pressure) and the dislocation creep ductile shear stress of the soft matrix (e.g., function of temperature). Our numerical models show that when the strength ratio is between 1 and 2, a rheological behavior is observed, with micro-fracturing of the strong clast and ductile creep of the matrix. For larger ratios, even if the clast is plastic, its internal deformation is very limited, yielding to an almost ductile deformation of the assemblage. This study therefore provides the mechanical conditions for having a mixed brittle-ductile rheological behavior. These conditions significantly differ from the theoretical rheological prediction (brittle-ductile transition in clast and matrix) and may be the key to a better understanding of the mechanics of transient slips.

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Thermomechanical numerical modelling and the impact of volumetric heating in compressional regimes

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Abstract

The development of a subduction zone encompasses a stage of strain localization and is epitomized by the growth of lithospheric-scale shear bands. Using numerical experiments, we investigate factors that promote or inhibit localization of deformation in brittle and ductile regimes in compression, especially the contributions of volumetric stresses and strains. We use a combination of power-law dislocation creep to model ductile deformation and the Drucker-Prager yield criterion along with a non-associative flow rule to model brittle failure. We first give a brief theoretical description of our constitutive update and present some benchmark tests using crustal-scale examples. Thereafter, we investigate lithospheric-scale deformation, where the model domain is subjected to steady-state compression, and contains an initial weak-zone on which localization can potentially nucleate. In solving the energy conservation problem, we incorporate a “heat source” term from the mechanical deformations which embodies the irreversible plastic work done by utilizing the full stress tensor instead of utilizing shear terms alone. We compare the feedbacks from shear heating alone with shear and volumetric terms used. This work term couples the energy equation to the constitutive description, and hence the stress balance, via the evolving temperature field. Finally we present the initial steps in an application to a key geodynamic problem, namely the deformation involved in intra-oceanic subduction initiation. We infer that inclined lithospheric-scale shear bands on which subduction can initiate are most likely to nucleate at the base of the lithosphere and propagate upward as heating proceeds.

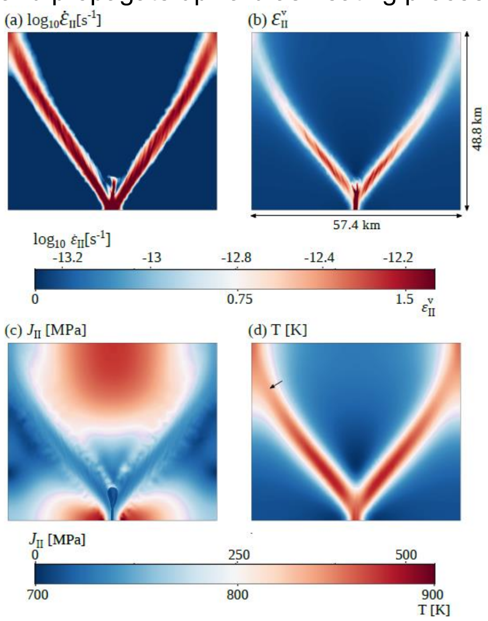

Figure 4 : Numerical benchmark tests of a viscoelastic rheology for a semi-circular weak inclusion in a homogenous medium. We compare results using our constitutive description with Duretz et al., 2014

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A brittle constitutive law for long-term tectonic modeling

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Adequate representations of brittle deformation (fracturing and faulting) are essential ingredients of long-term tectonic simulations. Most often, these rely on Mohr-Coulomb plasticity coupled with strain softening of cohesion and/or friction. This approach captures fundamental properties of brittle failure (e.g., pressure-dependence, possibility of spontaneous strain localization...), However, it also has important shortcomings such as a strong sensitivity to ad-hoc softening parameters, and the inability to capture the strain rate dependence and permanent weakening of elastic moduli that are typically associated with brittle yielding.

Here we design a new brittle constitutive law that captures key features of brittle deformation and can be straightforwardly implemented in standard geodynamic models. In our Sub-Critically-Altered Maxwell (SCAM) flow law, brittle failure begins with the accumulation of brittle damage, which represents the sub-critical lengthening of tensile micro-cracks prompted by slip on frictional shear defects. Damage progressively and permanently weakens the rock's elastic moduli, accounts for an effective brittle creep viscosity, and determines the onset of localization.

By incorporating a micromechanics-based model of stress-dependent crack growth and interaction, the SCAM framework accounts for the time-dependence of failure, the transition from distributed to localized inelastic deformation, as well as multi-phased brittle creep behavior. The model's micromechanical parameters are fully calibrated against rock deformation experiments in 0-D simulations, alleviating the need for ad-hoc softening parameters. This model calibration is validated by simulating laboratory experiments assuming 2-D plane strain deformation. Further, the model can be upscaled to simulate tectonic deformation of a 10-km thick brittle plate over millions of years. This produces features similar to field observations, such as the development of complex fault networks with power-law distributions of slip rates, and a subtle dependence of faulting styles on deformation rates.

Preexisting restraining bend and their impact on thrust propagation: insights from analogue models and the northern Tianshan foreland basin

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Abstract

Fold and thrust belt growth during mountain building typically happens through the propagation of deformation toward the foreland basin. As this deformation progresses, inherited faults in the foreland basement, like normal faults, can be reactivated and can control the distribution and characteristics of structures in the cover units (*Butler*, 1989; *Scisciani*, 2009). The dynamics of this structural inheritance depends on several parameters, such as the geometry and kinematics of basement faults, the *décollement* strength in the cover units, the intensity of surface processes, etc. (*Bonini et al.*, 2012; *Ferrer et al.*, 2023). In some cases, the inherited basement faults can be strike-slip faults. This is the case in the northern Tianshan foreland basin, where the trend of shallow Cenozoic thin-skinned thrusts is likely controlled by the underlying deeper Mesozoic strike-slip faults (*Peng et al., submitted*). For example, in the Gaoquan anticline, horizontal seismic slices illustrate that the location and lateral extent of the shallow thrust-related fold are associated to an underlying restraining bend (Figure 1a and 1b). Cross section from 3D seismic cube (Figure 1c) shows that this restraining bend is superimposed by a thin-skinned thrust that roots in an upper *décollement* layer (formation E2-3a). Kinematic analysis of Gaoquan structure (Figures 1d-f) illustrates that the deep restraining bend has been reactivated prior to the occurrence of the shallow thrust ramp. While the kinematic restoration appears feasible, the dynamic relationship between the reactivation of the deep restraining bend and the initiation of the thin-skinned thrust remains uncertain under compressional stress conditions.

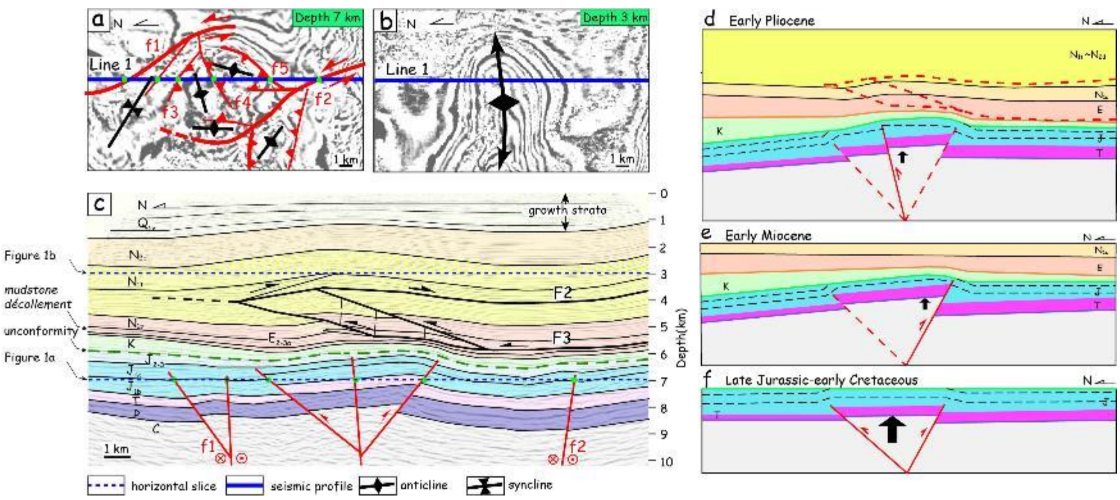

Figure 5 : Structural analysis of the Gaoquan anticline, northern Tianshan foreland basin. (a-b) 2D horizontal seismic slice extracted from a 3D seismic volume. A restraining bend geometry is observed on a deep horizontal slice (at 7km), whereas an E-W-trending fold is visible on a shallow horizontal slice (at 3km). (c) Interpreted 2-D N-S seismic line (Line 1) across Gaoquan. Horizontal seismic slice levels are indicated by blue stippled lines. (d) Restoration sequence of Gaoquan structure form early Cretaceous to early Pliocene. During the middle Miocene to

early Pliocene, the deep pop-up structure was active. (e) Between the Eocene and early Miocene, the deep steeply dipping fault zone was reactivated as a thick-skinned structure and then stopped. (f) The deep steeply dipping fault zone in the Jurassic is sealed with a Cretaceous unconformity (redraw after Peng et al., submitted).

We developed an experimental approach to unravel the kinematic and dynamic relationships between reactivated basement restraining bend and upper thrust and folds. We used a 120cm long and 80cm wide box in which we deformed a 10.5cm thick brittle-ductile upper unit (made of sand and PVC, silicone putty) that represents the upper crust, lying above a 1.5cm thick basal viscous layer (made of silicone putty) that represents a mid-lower crust level (Figure 2d). The scale between nature and model is about 1km ~ 1cm. The models underwent three tectonic phases:

- Phase 1: strike-slip deformation of a 5cm thick sand/PVC pile. No sedimentation. Relative displacement was 10cm. Relief of the restraining bend was completed erased at the end of this phase and three 5mm thick layers (one silicone and two sands) were deposited above the flattened topography.
- Phase 2: deposition of a 2cm thick sand pile without (Mod01) and with (Mod02) reactivation of restraining bend. Relative displacement was 8cm.
- Phase 3: model contraction (shortening by 9cm) with deposition of two syntectonic layers.

Boundary conditions applied to the model during strike-slip phases 1 and 2 are inspirited from Boussarsar, (2022). Shear velocities during phase 1 and 2, and shortening velocity during phase 3 was fixed at 2.0cm/h.

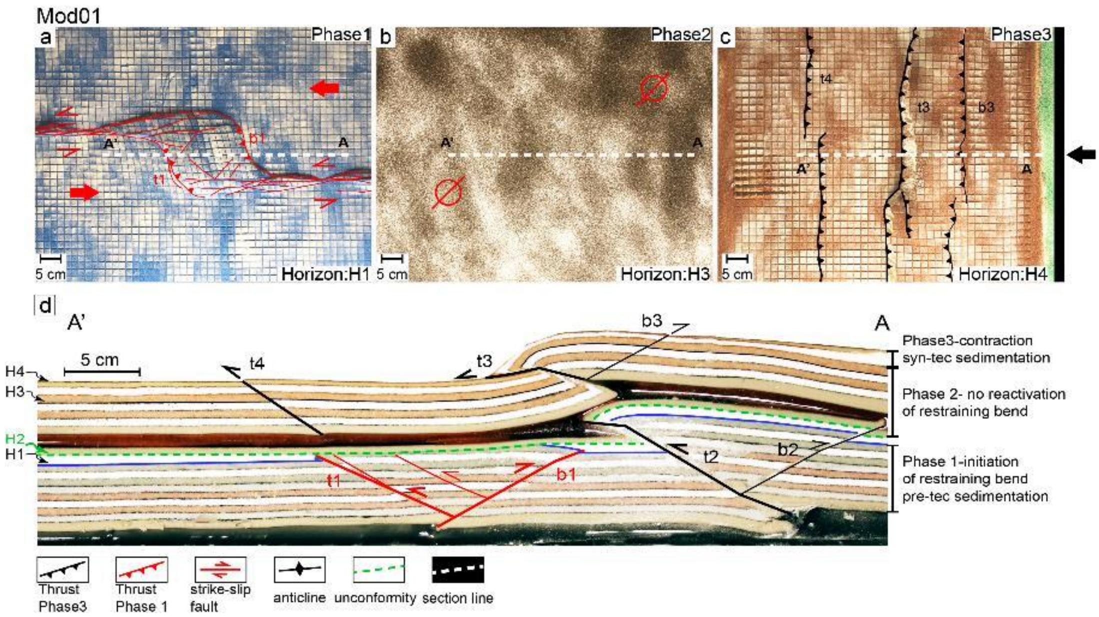

Figure 2 : Mod01 results. (a) End of phase 1 with the development of the restraining bend. (b) End of phase 2 where no strike slip deformation occurred during layer deposition. (c) Final stage after contraction of the model and addition of two syntectonic layers (brown top). (d) Final cross-section across the non-reactivated inherited restraining bend. "t" is forethrust, "b" is backthrust and numbers refer to the sequence of thrusting.

Mod01 accounts for the experiment where the pre-existing restraining bend was not reactivated during phase 2 (Figure 2b). Basement pop-up was neither reactivated during phase 3 (Figure 3d) since the overlying green unconformity level (H2) is flat. Most of the phase 3 shortening has been consumed by the thick-skinned thrust (t2) and transferred upward to the upper *décollement.* This resulted in the development of a shallow pop-up (t3-b3) and a long and fairly cylindrical thrust sheet (t4) detaching in the upper silicone level.

In contrast, Mod02 accounts for the experiment where the pre-existing restraining bend was reactivated during phase 2 (Figure 3b). This folded the upper silicone level and influences the localization of deformation during phase 3. Indeed, two thin-skinned thrusts t4 and b4 nucleated right above the restraining bend zone (Figure 3d), and their lateral extent was consistent with the width of the underlying restraining bend (Figure 3c).

Sequential restoration of the Mod02 final cross-section illustrates the reactivation of restraining bend during phase 2, which folded the upper *décollement* layer and the overlying units (Figures 3e and 3f), as evidenced by the fanning growth strata. During phase 2, about 1.0cm of shortening has been consumed by the pop-up. During phase 3, the contractional deformation was consumed by the thick-skinned thrust (t2, b2) and transferred into the shallow pop-up (t3, b3) and localized on thrusts t4 and b4. This consumed about 6cm shortening.

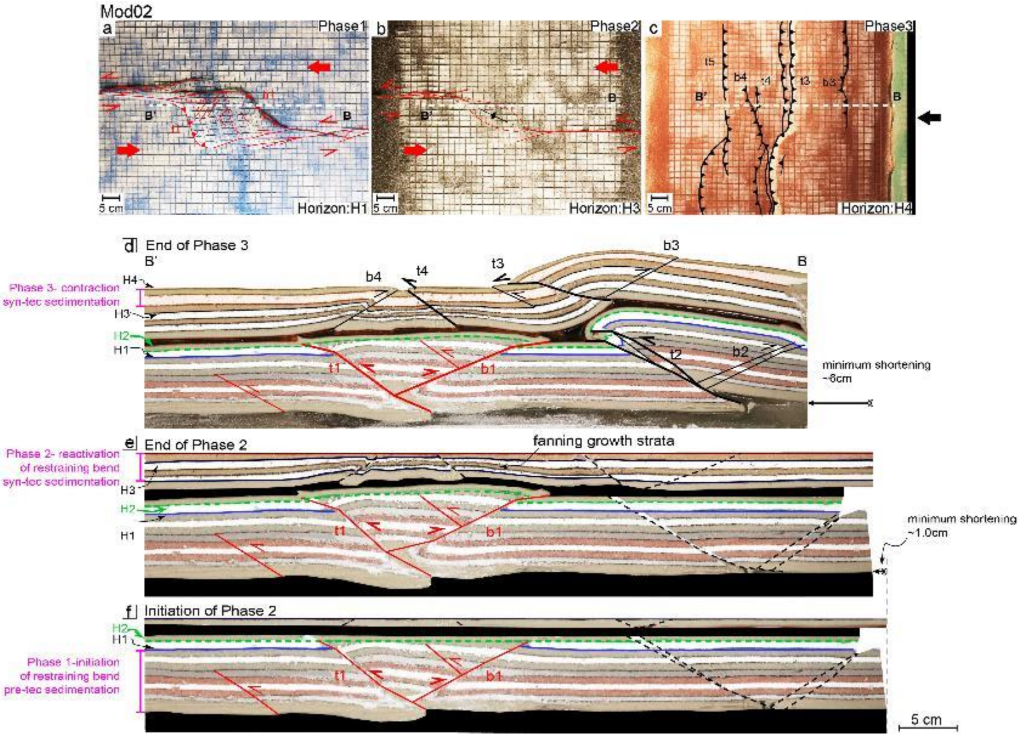

Figure 3. Mod02 results. (a) End of phase 1 with the development of the restraining bend. (b) End of phase 2 with syntectonic sedimentation coeval with strike-slip motion. (c) Final stage after contraction of the model and addition of two syntectonic layer (in brown). (d) Final cross-section across the reactivated inherited restraining bend. (e) Restoration at the end of phase 2 and (f) at initiation of phase 2.

In conclusion, our work illustrates how the reactivation of a pre-existing restraining bend inherited from an early strike-slip phase can influence the distribution of deformation during a latter fold-and-thrust belt development. In section view, the reactivation of a deep inherited restraining bend can fold an upper *décollement* layer which influences deformation localization during deformation propagation. In map view, the reactivated restraining bend zone would limit the lateral extent of the overlying thrust and related folds. In this way, our results provide explanations why the shallow Gaoquan anticline within the northern Tianshan foreland basin is localized right above the basement restraining bend. Additionally, this explains the constancy of the lateral extent of the shallow Gaoquan anticline and the underlying restraining bend zone. This kinematic and dynamic relationship between the basement restraining bend and upper thin-skinned thrust can be insightful for understanding the structural evolution of foreland basin that present wrench-thrust tectonic interaction.

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Smooth visco-plasticity model with tensile cap

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Abstract

Modeling tensile failure is essential to describe the mechanical behavior of rocks in geodynamically relevant contexts, such as dyke propagation. A common approach to tackle brittle deformation in different stress regimes within the framework of flow plasticity theory is an adaptation of multi-surface plasticity models. From an algorithmic point of view, it is necessary to enforce the continuity of the yield surface and the flow potential gradients (flow directions) around the intersection points in order to avoid the so-called corner regions. Many models that respect these constraints exist in the literature (e.g. Dolarevic & Ibrahimbegovic, 2007). However, a careful analysis of the yield surface map reveals that although continuity is enforced at the yield surface, it is not automatically guaranteed elsewhere in the stress space. Moreover, spurious elastic domains and singularity points may exist, which severely affects the convergence rate of the local stress iterations and can even cause divergence (Golchin et al., 2021). The discontinuity of the yield surface in the stress space requires a logically complex return mapping algorithm.

Here we present a relatively simple visco-plastic model of Perzina type that combines a linear Drucker-Prager shear failure envelope with a circular tensile cap. An appropriate formulation of the cap surface enforces dimensional consistency and continuity of both segments throughout the stress space (see Figure 1), resulting in a straightforward return mapping scheme. We discuss the implementation details, which include stress update, linearization, selection of primary variables for local stress iterations, and a robust initial guess. Application results are demonstrated.

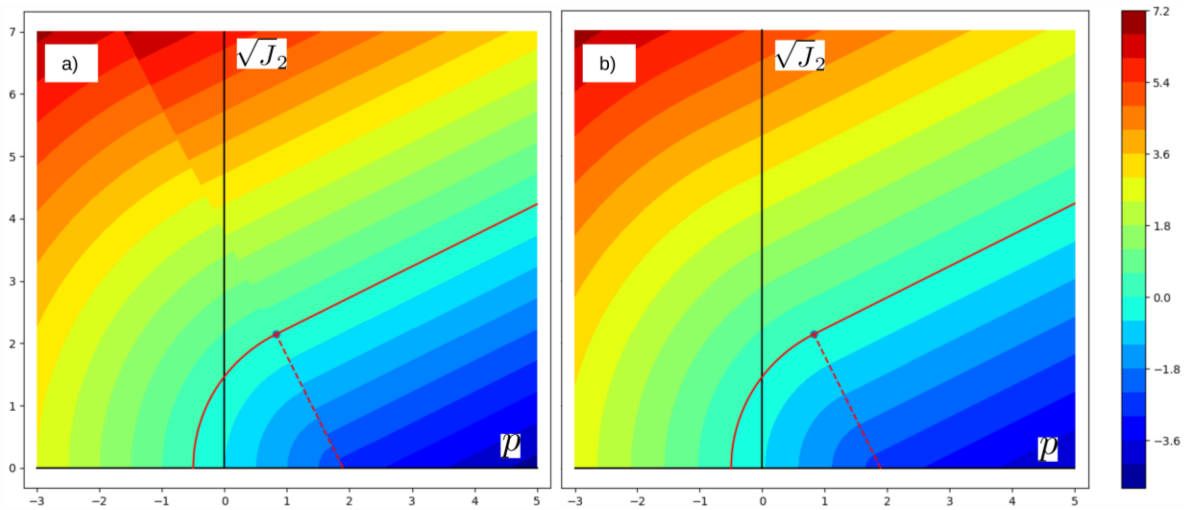

Figure 6 : Map of the yield surface consisting of Drucker-Prager shear failure envelop, and circular tensile cap. Dashed line shows the boundary between the yield functions in stress space; a) original discontinuous surface; b) continuous surface with scaled tensile cap.

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The impact of pre-existing weaknesses on strike-slip fault evolution: rupture maps from the 2019 Ridgecrest earthquake inspire scaled physical experiments

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Abstract
The Eastern California Shear Zone of California has hosted several historic earthquakes along complex networks of faults. The faults that hosted the 2019 Ridgecrest earthquake developed in a setting with pervasive pre-existing weaknesses within the shallow crust (e.g., Nevitt et al., 2023). The Mw 7.1 Ridgecrest Earthquake produced a complex rupture pattern along the mainshock fault that provides insights into the early development of strike-slip faults (Antoine et al., 2021; Milliner et al., 2021).
The northwest end of the Ridgecrest mainshock (Mw 7.1) rupture reactivated a series of left-lateral cross-faults that trend sub-perpendicular to the right-lateral mainshock without a through going dextral fault structure (Figure 1). This series of parallel left-lateral NE trending cross-faults have been interpreted to be older structures that reactivated in the Ridgecrest event (Antoine et al., 2021; Chen et al., 2020). Why did these NE trending older sinistral structures reactivate rather than initiating a new NW dextral structure that could more efficiently accommodate the coseismic strain? Understanding how the orientation of pre-existing cross-faults can influence the early evolution of strike-slip faults, strain localization, and the distribution of off-fault deformation over geologic times scales can inform future seismic hazards of regions with abundant cross-faults. We conduct laboratory experiments that simulate crustal deformation using wet kaolin (e.g., Cooke and van der Elst., 2021; Cooke et al., 2013; Reber et al., 2020) as a crustal analog and directly document the kinematics of early evolution of strike-slip fault systems with pre-existing cross faults. The experimental data augments field data that does not provide a complete record of the evolution of faulting patterns and only reveals the cumulative results of events.

We use wet kaolin as the analog material because it produces localized, easy to track faults that are long-lived and its non-zero cohesion allows the introduction of pre-cuts that can be reactivated under different loading conditions before the failure of the intact clay. (e.g., Cooke and van der Elst., 2021; Eisenstadt and Sims, 2025; Henza et al., 2010; Reber et al., 2020; Bonini et al., 2016). Furthermore, wet kaolin can simulate the off-fault relaxation behavior of the crust due to its viscoelastic properties (Cooke and van der Elst, 2012) and we can modify the shear strength by altering the water content to scale the experiments to the strength and length of the Earth's crust. By maintaining a water content of 60-65%, the shear strengths of wet kaolin are approximately 100-120 Pa (Hatem et al., 2017; Cooke et al., 2013; Hatem et al., 2015; Henza et al., 2010). Using the viscosity and strength scaling relationship between the wet kaolin and the crust, 1 min in the experiment is equivalent to 1.3 – 13 k.y in the crust and 1 cm within the wet kaolin scales to 1-2 km of the crust (Hatem et al., 2017; Elston et al., 2022).
We assess the evolution of pre-cut cross faults with a range of initial orientations at high angles to the applied right-lateral shear at loading rates of 0.5 mm/min. To create faults in the clay we incorporate the use of a new programmable plotter with an electric probe. A 1.5 cm wide elastic band between the plates creates a distributed shear basal condition. Throughout the experiment, we capture a series of images to calculate the incremental horizontal displacement field using Digital Image Correlation. Strain maps derived from displacement fields will reveal how slip localizes and varies in time and record how these oblique faults link, reorganize, or simply get abandoned depending on their orientation.
Experiments with pre-existing cross-faults oriented favorable to the applied dextral loading experience long-lived right-lateral slip and link and reorganize to form a mature throughgoing fault with low off fault deformation. In contrast, within clay experiments with pre-existing cross-faults initially oriented perpendicular to the right-lateral shear zone, cross-faults are reactivated with left-lateral slip (red on Figure 2) and eventually abandoned in favor of new dextral faults parallel to applied loading. Thus, these cross-faults have short periods of left-lateral slip before being overprinted by more favorable

oriented fault segments. These experiment results suggest that crustal regions with high angle pre-existing cross-faults can produce more complex active fault configurations with higher off-fault deformation than regions with lower angle cross-faults. These results are consistent with observations of the Ridgecrest rupture that shows greater off-fault deformation at the northwestern end (Antoine et al., Preprint). Furthermore, the short-lived nature of left-lateral slip along the cross-faults in the experiments suggests that the northwestern end of the Ridgecrest mainshock fault may be very young in its evolution. As this fault matures, we expect that linking right-lateral faults will develop.

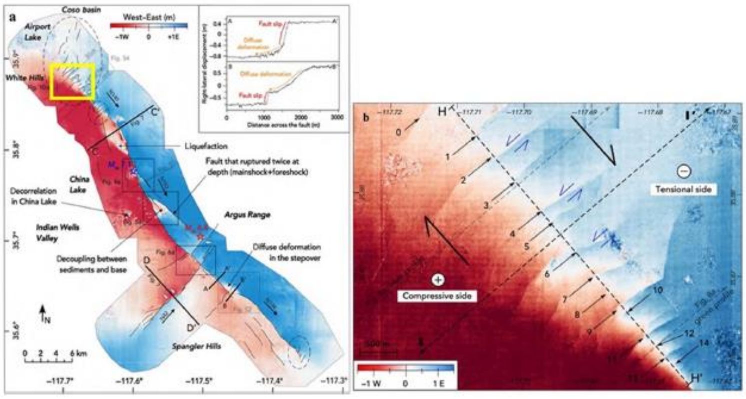

Figure 7. a) Ridgecrest's mainshock (epicenter marked by blue star) and foreshock (marked by red star) coseismic displacement map from Antoine et al. (2021). Transition to the Coso Basin on the northernmost section of the Mainshock highlighted by yellow box. b) Closer look of the northeast trending faults with left-lateral slip

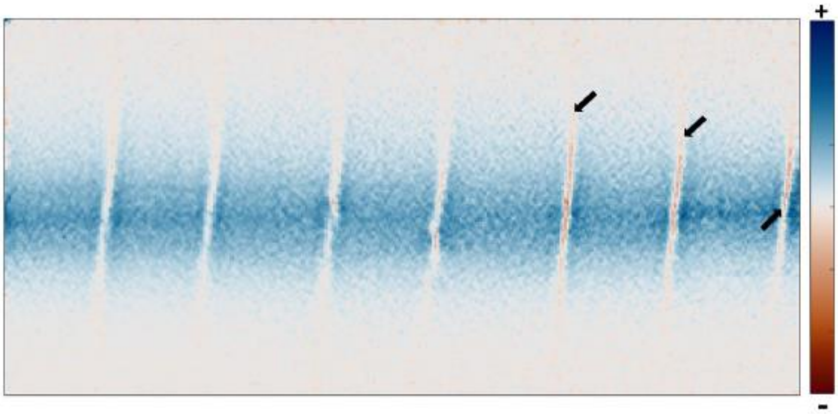

Figure 8 Vorticity map showing clear left-lateral slip (black arrows) along 90° oriented pre-cuts during early stage of dextral strike-slip. Note that pre-existing weaknesses disrupted right-lateral shear of the fault system and show left-lateral slip (red color)

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Surface stress reorientation controlling rift linkage structures: insights from analogue and numerical experiments

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Abstract

During continental rifting, individual rift segments propagate towards each other and eventually may interact by linkage. The propagation of adjacent rift segments causes notable reorientations of the stress field resulting in strong local deviations from the regional trend. Vice versa, such stress reorientations feedback on progressive deformation and thereby control rift interaction.

Here, we employ numerical and analogue experiments of continental rifting to investigate rift linkage and the role of stress reorientations during progressive deformation. Both experiment types consist of a crustal-scale two-layer setup where pre-existing linear heterogeneities are introduced using mechanical weak seeds. Various seed configurations were applied to investigate the effect of (i) two competing rift segments that propagate unilaterally, (ii) linkage of two opposingly propagating rift segments, and (iii) the combination of these configurations on stress re-orientation and rift linkage.

Both the analogue and numerical models show counter-intuitive rift deflection of two rift segments competing for linkage with an opposingly propagating segment (model types (i) and (iii); Fig. 1). These deflection patterns can be explained by means of stress analysis in numerical experiments showing that stress reorientation occurs locally and propagates across the model domain as rift segments propagate. Major local stress reorientations imply that faults and rift segment trends do not necessarily align perpendicularly to far-field extension directions but can deviate substantially from the latter. Our results imply that strain localisation and stress reorientation are closely linked, mutually influence each other and may be an important factor for rift deflection among competing rift segments as observed in nature.

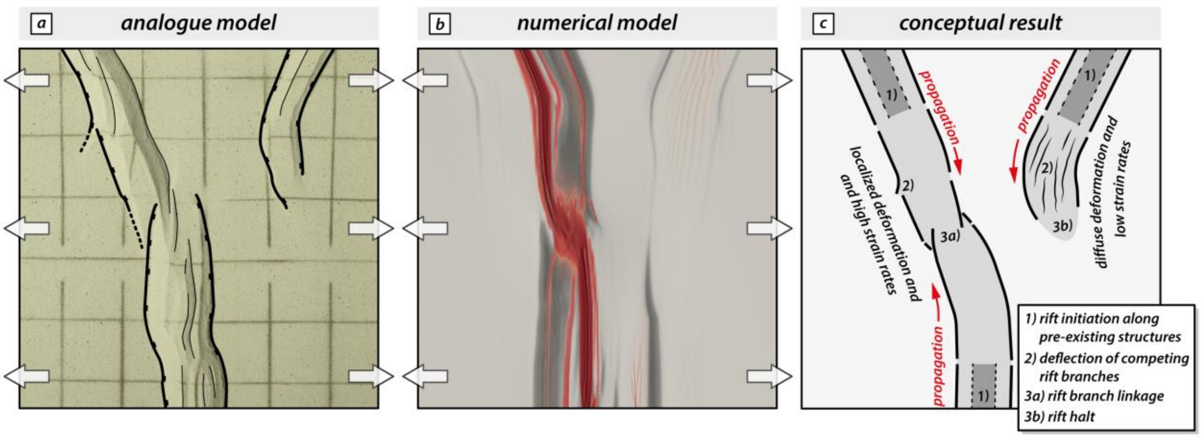

Figure 9: Geometric similarity of rift segment linkage, deflection of competing segments, and abandonment in analogue (a) and numerical models (b) and their conceptual interpretation (c).

Influence of Model Preparation on Strain Gradient towards Thrusts revealed by Magnetic Fabric Analysis

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Abstract
Strain is increasing towards localised shear zones/thrusts, which can be revealed by magnetic fabric analysis in analogue sandbox models (e.g. Schöfisch et al., 2022). Sieving and scarping layers of sand are commonly used to prepare analogue models. Both techniques have an influence on the rheology of sand layers and the development of the model (e.g. Lohrmann et al., 2003). The initial difference between scraped and sieved models lies in the packing of the sand grains. To quantify differences on grain scale, we apply magnetic fabric analysis to sieved and scraped models. Loose sand was mixed with magnetite (< 0.1vol%), which has the same grain size and similar subangular shape as the sand. The mixed material was sieved by a hand-held sieve in the "sieved" models. In contrast, the material was poured and scraped parallel to the shortening direction in the "scraped" models. After each modelling run, the sand was carefully wetted and small cubic samples (inner volume: 1.8 cm^3) were taken across the models for measuring the low-field anisotropy of magnetic susceptibility (AMS) with a MFK1-FA Kappabridge (Agico Inc.) with AC field strength of 200 A/m and frequency of 976 Hz. From the AMS measurements, the principal axes of susceptibility ($k_{max} \geq k_{int} \geq k_{min}$) derive and provide information about the bulk orientation of magnetite grains in a sample. Additionally, the degree of anisotropy (*Pj*) and the shape (*T*) of the resulting magnetic ellipsoid can be calculated, both useful to depict changes in strain (e.g. Borrdaile and Jackson, 2010, Parés, 2015).

The initial magnetic fabrics of the sieved and scraped models reflect distinct differences in grain alignment (Fig. 1a). The sieved model creates an initial fabric that is similar to a sedimentary fabric observed in nature (Parés, 2015). The magnetic lineation (orientation of k_{max} axes) is distributed parallel to bedding with a random declination. In contrast, the magnetic lineation is parallel to the scraping direction in an undeformed model prepared by pouring and scraping (Fig. 1a). Such oriented alignment of magnetic lineation can be similar to a flow fabric in sedimentary systems. The shape of anisotropy differs also between a scraped and sieved model. The samples of the scraped model show mainly a triaxial fabric, whereas mainly oblate fabric is analysed in the sieved model. The degree of anisotropy shows a wider range in values for the scraped model compared to the sieved model (Fig. 1b). Consequently, the grain orientation is initially different in models prepared by different techniques.

As known from previous experiments, a poured and scraped material is less compact compared to sieved material (e.g. Lohrmann et al., 2003). The difference in compaction has an influence on the accommodation of model shortening. That is also observed in models of this study, where a scraped model accommodates a relatively larger amount of layer-parallel shortening compared to a sieved model. The scraped model has to compensate for this difference by initial compaction. This compensation is also reflected by the changes in magnetic fabric. There is a decreasing gradient in degree of anisotropy with decreasing distance towards a thrust/hinterland (Fig. 1; Schöfisch et al., 2022), but this gradient differs between the scraped and sieved model. The scraped model also shows a larger scatter in degree of anisotropy compared to the sieved model (Fig. 1b). Moreover, a clustered set of magnetic lineation produced by scraping is overprinted differently compared to a random horizontal

orientation of magnetic lineation created by sieving (Fig. 1a). Consequently, the overprint from an initial fabric towards the hinterland/deformation front differs.

The deformation front is characterised by a thrust that shows a characteristic thrust-induced magnetic fabric with alignment of magnetic foliation (girdle distribution by k_{max} and k_{int}) parallel to the thrust surface (Fig. 1a). Such a thrust-induced fabric is distinct from the fabrics observed in the rest of a model. However, the thrust-induced fabric is similar in both sieved and scraped models. Also, the degree of anisotropy shows comparable means and low values along the thrusts of the scraped and sieved models (Fig. 1b).

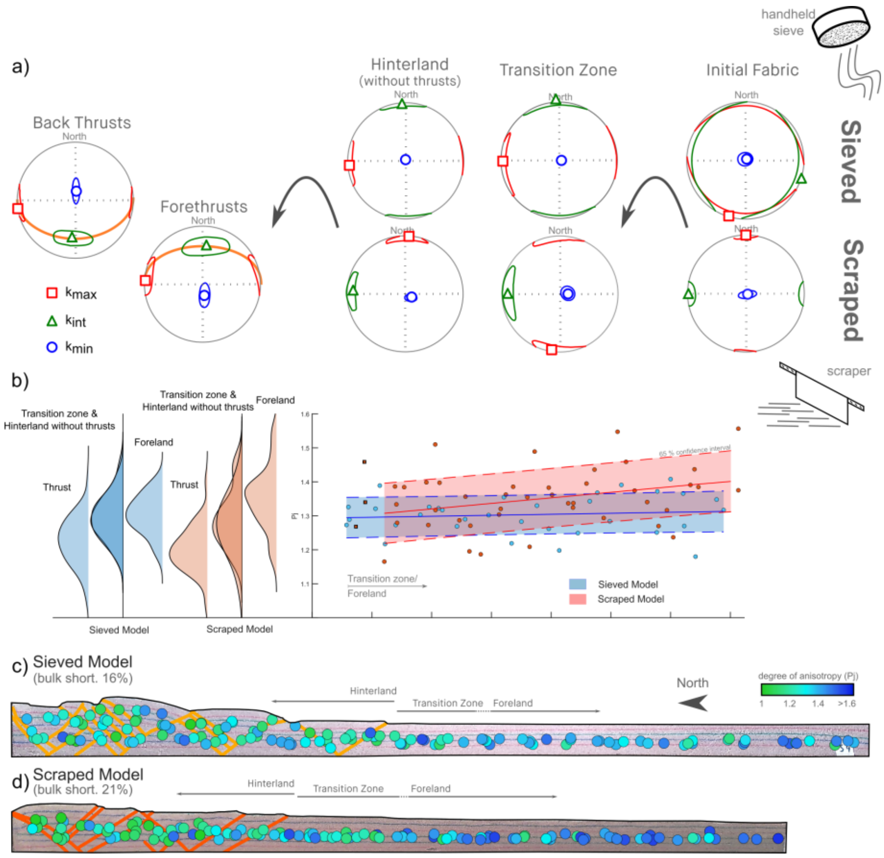

Figure 10 : Magnetic fabric development for sieved and scraped models. a) Schematic overview and development of principal axes distribution on lower-hemisphere equal-area stereographic projection. b) Development of degree of anisotropy (Pj) from foreland towards the hinterland as density distribution and plotted on representative section for c) sieved and d) scraped model.

In conclusion, the characteristic magnetic fabric along localised shear zones (i.e. thrusts) in analogue models is similar in scraped and sieved models (Fig. 1). However, between the models, the initial fabrics differ and different gradients in grain reorientation are observed towards a thrust. The initial differences in grain alignment, material packing and initial conditions of a model have a strong influence on model development and the gradients towards areas of localised strain.

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Influence of Gondwana structural inheritance on the rift architecture of the São Paulo Plateau, SE Brazil – Insights from analog modelling experiments

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Abstract

Interpretations based on geological and geophysical data assume that basement structural inheritance played a major role on rift initiation and propagation along the southeastern Brazilian margin. Pre-existing structures, such as shear zones, basement structural grain (ductile foliation) and intracontinental faults constitute lithospheric weak zones, where plates preferentially “break”. The southeastern Brazilian crystalline basement is comprised of a terrane mosaic, built during the Brasiliano-Pan African orogenic events leading to the final Gondwana amalgamation in the Cambrian. This terrane mosaic represents Precambrian paleo-plates separated by suture zones, lithospheric scale scars that influenced the rifting processes, more than 350 million years later in the Cretaceous. Among the Brazilian Cretaceous rift basins, Santos is the widest continental margin (c. 500 km), with the most prolific pre-salt oil fields. Its structural complexity includes the São Paulo Plateau (SPP), whose compositional nature is still a matter of debate. This complexity can be tied with the basement terranes. Onshore, the coastal Cabo Frio Terrane (CFT), a Paleoproterozoic continental crust, is interpreted as the Cambrian reworked margin of the Angola craton that remained in the South American Plate after rifting. The CFT suture zone, that separates it from the Neoproterozoic orogenic Ribeira Belt, continues offshore underneath the Santos Basin. Although it is a key structure to better understand the terranes of the SPP and rifting dynamics, its continuation through the SPP is still unknown. Studies connecting the basement grain to the rift architecture using analogue physical and numerical rifting models until now did not consider the terrane mosaic of SPP.

In this study, we designed analogue physical models that simulated rifting scenarios in distinct basement terrane mosaics with the objective of replicating the actual configuration of the SPP to propose a model for the Santos basin rifting process and the role of basement inheritance. The experiments were performed at the University of Bern Tectonic Modelling Lab and tested: (1) Two distinct hypotheses for the offshore prolongation of the CFT suture zone, based on reconstructions of Gondwana; (2) Two rifting phases in the same experiment with different combinations of divergence velocities (slow, fast and superfast rifting) and directions (E-W and NE-SW), and (3) Two distinct upper/lower (feldspar sand/silicone mix) crust thickness ratios.

Preliminary results show that: (1) The structures of the Santos Basin were well-replicated when using one of the hypotheses for the offshore continuation of the CTF suture, which suggests the importance of this pre-existing structure on the formation and structural orientation of the major pre-salt fields in this basin, whose basement would consist of the cratonic CFT; (2) The distribution of the deformation is more widespread when divergence velocities are slower. Therefore, the main structures of the rift are developed in phase 1 and only part of them are reactivated in phase 2 (closer to the spreading centre); (3) A thick upper crust (feldspar sand layer) favoured the interactions of two initially developed narrow rifts, which ultimately formed a single wide rift, with several intra-rift highs and lows.

The Early Cretaceous evolution of the Romanche Fracture Zone:

Insights from analogue model experiments

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Abstract

The Romanche oceanic transform is located in the Equatorial Atlantic. It has the largest offset on any mid-oceanic ridge worldwide (nearly 900 km) and formed as a result of rifting and drifting between the African and South American continents. Major transpressional fold-and-thrust belts occur along the margins of the Equatorial Atlantic and have been explained as the result of a two-phase evolution (Davison et al., 2016): (i) An early Aptian-age transtensional rift phase producing a series of E-W to ENE-WSW striking grabens along what is called the Romanche Fracture Zone, and (ii) a Late Albian transpressional phase, at a time when the African and South American continents were still in contact across a 500 km-long segment of the Romanche Fracture Zone, reactivating rift structures and producing transpressional fold-and-thrust belts.

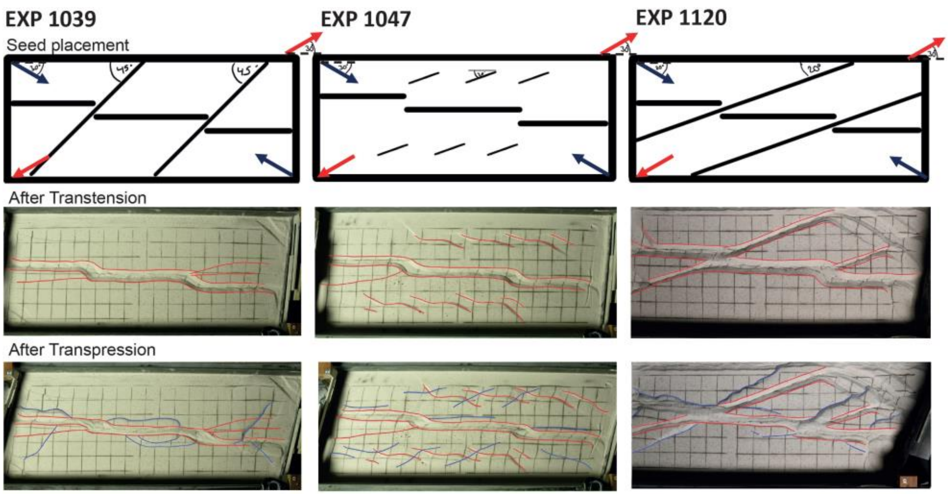

Figure 11: Initial set-ups of three selected models (upper row) and top views after the first phase of transtension (central row) and after the subsequent phase of transpression (lower row). Red arrows indicate oblique divergence direction, and dark blue angles oblique convergence direction. The horizonal seeds had the same position in all three models. The oblique seeds were placed at varying angles and lengths to determine their influence on the transpressional phase. Red lines: first-phase deformation structures; Blue lines: second-phase deformation structures.

In order to test this two-phase tectonic scenario, we performed a series of analogue model experiments in which we varied the directions of first-phase transtension and second-phase transpression, as well as the orientation of pre-existing weak crustal zones. Model results show that a major, E-W striking transtensional graben forms in all models during the first transtensional phase (Fig. 1., central row). The most important differences in strain occur during the second transpressional phase, where oblique seeds are activated at varying degrees creating or not creating fold-and-thrust belts. Oblique ENE-WSW striking fold-and-thrust belts on either side of the transtensional graben only appear, when pre-existing weak crustal zones, striking at about 50° to the convergence direction, are included in the model (Fig. 1, second and third panel in third row). Our model results indicate that also in nature, the presence of pre-existing weak crustal zones might have been a prerequisite in order to form the transpressional fold-and-thrust belts striking obliquely to the earlier formed transtensional grabens.

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1D and 2D numerical models of rapid ductile strain localization due to thermal runaway

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Strain localization is a crucial process for lithosphere and mantle deformation as it allows for the formation of faults and shear zones that enable plate tectonics. In the crust, strain localization usually occurs via brittle failure (i.e., breaking the rock). The deeper and/or hotter the setting, the less likely brittle failure becomes as the critical stress increases with the increasing overburden pressure while the temperature-dependent rheology of rocks limits the stresses that can be accumulated before being relaxed by slow, viscous flow.

Yet, we do observe fast and localized deformation (i.e., earthquakes) at depths of several hundred kilometers. These deep earthquakes either require local differential stresses of several Gigapascal (GPa) to trigger brittle failure or a different, ductile failure mechanism that significantly reduces rock strength while at the same time creating highly localized shear zones. Here, we investigate the feedback loop of visco-elastic deformation and shear heating to determine whether their combination can lead to a localized viscosity reduction and allow for fast slip.

We present a collection of 1D and 2D numerical codes written in the Julia language which use the pseudo-transient approach and graphical processing unit (GPU) computing to model the process of ductile localization and thermal runaway in a simple-shear setting. Our models employ a nonlinear, visco-elastic rheology, including grain-size-dependent diffusion creep, stress-dependent dislocation creep and low-temperature plasticity. We find that the combination of the aforementioned mechanisms is sufficient for deformation to localize on a small perturbation and then propagate through the model similar to a brittle rupture. Low-temperature plasticity acts as a critical stress-limiter at temperatures consistent with the core of subducting slabs. We are able to identify two non-dimensional scales that govern whether thermal runaway and rapid ductile strain localization occur in our models.

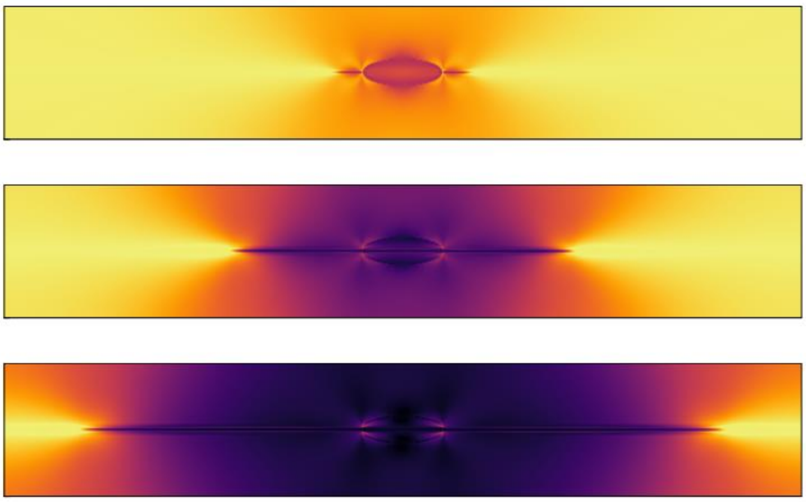

Figure 12 : Propagation of a thermal runaway-driven, ductile rupture in 2D.

Oblique continental rifting. Insights from 3-D forward coupled geodynamic-surface process modelling and application to the Equatorial passive margins formation

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Abstract
Continental rifting is often oblique to the rift axis or plate boundary, comprising many active rifts and mature rifted margins on Earth. Previous research has identified the role of vertical strike-slip and transform structures in oblique extension but has also shown that the initiation of long-distance syn-rift vertical strike-slip motion requires preexisting weaknesses. The Southern part of the Equatorial passive rifted conjugate margins is a typical example that exhibits orthogonal rift segments separating with transform faults with different lengths and orientation. We aim in this study to 1) understand the influence of these inherited weaknesses on the pattern of faulting, 2) to evaluate the consequences of oblique margin formation for rift related topography, and 3) to explore the interaction between tectonic and surface processes in the context of oblique rifting. We use most recent advances in 3-D forward geodynamic modeling coupled with surface processes. Preliminary results support the importance of inherited weak zones in shaping segmented oblique continental margins, with highly contrasting tectonic and subsidence histories in the orthogonal and transform segments. These results compare well with observations from the Equatorial passive rifted conjugate margins and provide insight into the factors that may drive the timing and magnitude of vertical motions and associated sediment flux.

The control of the pre-existing lithospheric weakness on forming the Cenozoic Altyn Tagh fault system, northern Tibetan Plateau: Insights from physical analog modeling under normal and high gravity conditions

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Abstract

The ~1600 km long sinistral Altyn Tagh fault system is one of the largest strike-slip faults on the Earth, and defines the northern boundary of the Tibetan Plateau that formed in response to the Cenozoic India – Eurasia collision. The central-east part of the Altyn Tagh fault system includes the lithospheric-scale South Altyn Tagh fault (SATF, an active sinistral strike-slip fault trace with a rate of ~10 mm/a), the North Altyn fault (NAF, a reverse-dominated fault forming part of the geographic boundary between the high Tibetan Plateau and low-lying Tarim Basin), and the triangular-shaped Altyn Mountain in between. How such complicated geometric and kinematic features form remains disputed. A compilation of regional tectonics reveals that the Altyn Tagh fault system developed upon some pre-existing weaknesses related to the accretion of small blocks onto the Eurasia during the Early Paleozoic. As such, we carried out an sandbox experimental study on both normal and high gravity conditions, together with PIV analysis, to investigate the influence of these pre-existing weaknesses on the geometric and kinematic features of the Altyn Tagh fault system. In the experiment, the rigid Tarim Basin and the relatively weak Tibetan Plateau contrast in the strength of the middle/lower crust and lithospheric mantle, but are consistent in strength of the upper crust. Our result under normal gravity indicates that jagged, rather than straight or multiple-branched, pre-existing lithospheric weaknesses are responsible to the formation of complex geometry and kinematics of the Altyn Tagh fault system, such as the triangular-shaped Altyn Shan, the younger formation of the central segment of ATF and the E-W-striking faults adjacent to the ATF. Experiments under high gravity (50g) by using a large centrifuge mechine generate similar but much simple result, and amplifies the impact of pre-existing weaknesses on the subsequent deformation. Our findings also have implications for the tectonic configuration of the block accretion in the northern Tibetan Plateau in the Early Paleozoic.

Modelling metamorphic transformations:

the case of the eclogitization process

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Abstract
Eclogitization is an important metamorphic reaction for the understanding of convergence zones dynamics (e.g. Kirby et al., 1996, Hacker et al., 2003; Austrheim, 1987). This transformation, that occurs between 1.5 and 2.0 GPa in both oceanic and continental lithosphere, leads to the formation of new phases whose properties greatly differ from those of the initial untransformed rock (gabbro in the oceanic case or granulite in the continental case). Eclogitization requires the introduction of fluids (e.g. Bras et al., 2021, Kaatz et al., 2023), leads to a significant increase in density (between 200 and 400 kg.m-3), and induces an important strength decrease (by one to two orders of magnitude). At the P-T conditions corresponding to this transformation, most rocks (gabbros or granulites), are expected to deform viscously. However, the recording of earthquakes at these conditions questions the role this transformation could have on the rheology of rocks at depth (e.g. Hetenyi et al., 2007; Shi et al., 2018). To understand the interactions between metamorphic transformation and deformation (Figure 1A), numerical modelling tools can be used, but require the implementation of (1) changes in density and therefore the use of a compressible code, (2) changes in viscosity, which can be significant, (3) consideration of fluids, and (4) the use of visco-elasto-plastic rheologies.

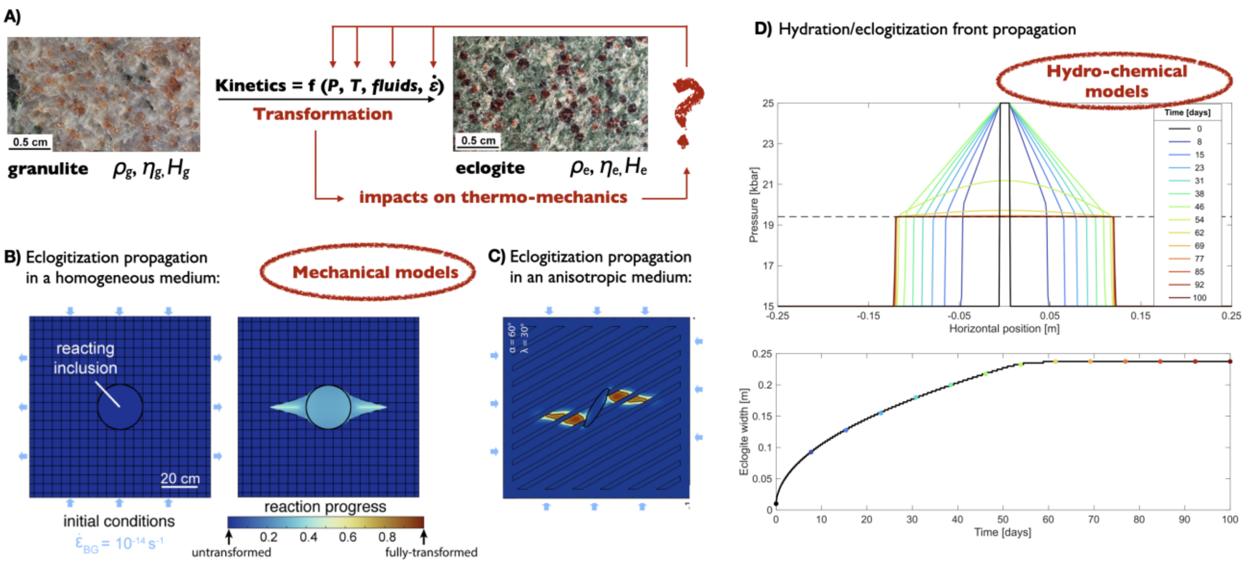

Figure 1 : A) Interaction between metamorphic transformation and deformation: here, on the case study of eclogitization (i.e. granulite => eclogite). B) example of mechanical model where propagation of the eclogitization in a homogeneous medium is driven by density change (after Yamato et al., 2022). C) Example of a model where eclogitization propagation is inhibited by the presence of un-reacting material layers. D) Example of a 1D hydro-chemical model showing the propagation of an eclogitization front (after Bras et al., 2023).

We here present a synthesis of the first results we have obtained through the study of this transformation, using various numerical modelling tools: 2D compressible visco-elasto-plastic mechanical models on the one hand, and hydro-chemical models on the other hand. These models enable us to isolate the various aspects of this eclogitization transformation. They show that:
(1) The drop in strength associated with the eclogitization process is probably transient,
(2) The effect of the change in density associated with this reaction is at least as important as the one associated with the strength decrease, and can play an important role in eclogitization propagation (Figure 1B, D)
(3) The anisotropy of the rock seems to play an important role in the propagation of the transformation (Figure 1C).
(4) The propagation of the eclogitization/hydration front within an initially dry rock is only allowed for densification reactions, that involve the creation of porosity (figure 1D).

In a second time, we will show how the coupling of these different aspects within 2D hydro-chemical-mechanical models enables us to study in greater detail the interactions between the transformation process and deformation, and how this affects the results presented above.

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Session 2

ORALS

Unraveling Complex Fault Slip Dynamics: Integrating Source Modeling, Energy Analysis, and Synthetic Observations

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Abstract
Over the last decades, observations of spatiotemporally complex slip events have multiplied. Beyond creep and fast ruptures, we now observe a continuum of transients energy release happening on fault systems, ranging from: slow slip events to LFEs and tremors. The majority of recent studies have interpreted these events by the variation of frictional behaviour along the fault plane.

Nonetheless, fault systems are observed to be geometrically complex in nature over different scales. In addition, recent studies have shown the effect of considering a fault volume or damage zone around a fault on the slip dynamics. We aim in this work to investigate the role of “realistic” fault geometry on the dynamics of slip events. For this we address the problem from three complementary perspectives: 1) forward source modeling; 2) we bridge the gap between source modeling and observations by generating synthetic surface records; 3) and finally we carefully analyze the energy budget variations that occur throughout the earthquake cycles.

In this framework, we consider a fault system which consists of a main self-similar rough fault, surrounded by a hierarchy of off-fault slip planes/fractures. All fractures are frictionally homogeneous (rate weakening) and can potentially undergo dynamic slip. We embed our 2D quasi-dynamic fault zone in a 3D elastic half-space and cover the free surface with a wide array of colocated broadband accelerometers and high rate GPS stations.

Our goal is to investigate the role of the “fault volume” in slip dynamics. We aim to understand how the deformation in the volume is accommodated by the off-fault damage zone and the main fault. What fraction of the “supplied” moment rate is hosted by the off-fault fractures during an earthquake cycle? We also try to understand how the different sequences of complex behavior that we observe on the fault plane are recorded on the stations. What are the different contributions of the main fault and off-fault fractures to the radiated signals recorded on the stations? And finally we study how the medium’s energy budget evolves throughout the earthquake cycles and evaluate the dissipative contribution of off-fault fractures to determine their energetic role during earthquake cycles.

3D Quasi-dynamic seismic cycles accelerated using Hierarchical Matrices: Role of complex fault geometry

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Abstract

Natural fault system has complex structures over a wide range of length scales. Multiple faults are activated during one single earthquake and control the earthquake initiation and termination. Both geological and geophysical studies indicate that the fault geometry complexities can have a first-order effect on spatiotemporal complex slip dynamics. We develop a 3D quasi-dynamic seismic cycle model with Hierarchical matrices to investigate how the complex geometry affects the slip dynamics. The calculation of elastic response due to slip is a matrix-vector multiplication, which can be accelerated by using hierarchical matrices and is easily multi-threaded. The computational complexity is reduced from the order of O(N^2) to O(NlogN). We did a series of benchmarking exercises including static crack benchmark and SEAS SCEC benchmark to verify our code. With this approach, we could analyze the fault communication through stress transfer in complex fault systems over multiple cycles. We applied this model on two parallel faults and investigated the stress interaction on two faults in 3D. We analyse how the overlap distance, distance between two faults, relative fault length and friction properties control the coexist of earthquake and slow slip event under spatial uniform rake weakening friction. We also plan to apply this model on real fault system and analyse synthetic signals to explain seismological and geodetic observations.

Scaled seismotectonic models of megathrust seismicity: recent progress and future perspective

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Abstract

Scaled seismotectonic models are valuable investigation tools in Earth Science, especially for modeling megathrust seismicity. Together with their capability of reproducing multiple seismic cycles in a few minutes duration experiment, they enable accurate tracking of surface deformation such as in a dense geodetic network extending homogeneously from a few hundred km inland up to the trench. These conditions represent a unique opportunity for compensating the temporally incomplete and spatially fragmented character of natural observations.

In this presentation I will show recent progress in analog modeling of megathrust earthquakes and future directions. First, I will focus on basic applications such as asperity synchronization and correspondence between interseismic locking and subsequent slip characteristics. Then, I will show how datasets produced by seismotectonic models represent perfect playgrounds for Machine Learning (ML) applications. In particular, I will show how ML can be used to predict the timing and size of laboratory earthquakes as well as the possibility to forecast future rupture characteristics using a computer vision framing. In the final part of this presentation, I will discuss how to export to nature lessons learned in the laboratory in terms of predictability. The paucity of observations from nature can be ideally overcome by physics-informed ML. To pave the way in this direction, I will show how to retrieve rate-and-state friction parameters that better explain the behavior and variability of analog seismic cycles by coupling the Simulated Annealing algorithm with quasi-dynamic numerical models.

Unraveling the earthquake potential of velocity-strengthening faults through fluid-induced poroelastic effects

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Abstract

Tectonic faults have long been classified as either stable or prone to seismic activity, based on their frictional behavior. However, recent findings challenge this conventional understanding by revealing that even nominally stable faults can undergo seismic slip when subjected to specific conditions. In this study, we present a fully coupled Hydro-Mechanical Earthquake Cycles (H-MECs) code (Dal Zilio et al., 2022), a novel numerical framework that integrates solid rock deformation, fluid flow, inertial wave-mediated dynamics, and rate-and-state friction in a poro-visco-elasto-plastic compressible medium. By accurately capturing the long- and short-time scales involved, H-MECs provides a valuable tool for understanding fault stability and the evolution of seismic and aseismic slip during fluid injection experiments. To investigate the influence of fluid injection on fault behavior, we design a 2D fault model that combines velocity-strengthening friction with dynamic weakening caused by rapid poroelastic effects, and we investigate the intricate interplay between pore-fluid pressure evolution, compaction and dilation in the gouge layer, and fault slip. Our model demonstrates that fluid injection significantly reduces the effective normal stress and frictional resistance along the fault, ultimately leading to failure. The onset of fault failure is governed by shear-induced poroelastic compaction and fluid pressurization, initiating a slow-slip transient originating from the injection point. As the slow-slip patch reaches a critical size, dynamic rupture is triggered, propagating beyond the region affected by the perturbed fluid pressure. Notably, our experiments reveal that under critically stressed conditions, the aseismic slip phase evolves rapidly in a matter of seconds, while at lower stress levels, it propagates gradually over hundreds of seconds. These findings provide a comprehensive explanation for various seismic phenomena, including the unexpected nucleation of dynamic rupture on velocity-strengthening faults and the transition from aseismic slow-slip to fast seismic slip induced by poroelastic compaction and fluid pressurization within the fault zone. Our results shed light on the complex response of tectonic faults to fluid injection and highlight the critical role of poroelastic effects in earthquake nucleation. By unraveling the hidden earthquake potential of velocity-strengthening faults, this study opens new avenues for understanding fault behavior and improving the safety of reservoir storage operations.

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Geomechanical modelling of injection-induced seismicity: the case study of the Muara Laboh geothermal plant

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Abstract
In this work, we study the induced seismicity recorded during an injection operation in the Muara Laboh geothermal plant. First, we analyze the seismic data and we find that the seismicity preferentially expands on a plane, suggesting the reactivation of a set of normal faults, at a characteristic speed of the order of km/day. Next, we use a 2D rate-and-state continuous fault model (e.g. Dublanchet, 2019) to better understand the physical mechanisms which control the induced seismicity underlying the real geothermal scenario. The model suggests that the rapid seismic migration observed can be explained by the interaction among asperities through the expansion of postseismic slip fronts. Also, it shows that the amount of seismicity generated by the cycle of injection in analysis is strongly controlled by the « natural » seismicity of the system, that is by the seismicity determined by the tectonic load charging the fault. This close correlation between natural and induced seismicity suggests that the injection in Muara Laboh principally stimulates critically stressed faults which release, on a shorter timescale, the seismicity determined by their natural seismic cycle. Finally, we also describe the Muara Laboh geothermal scenario with a simple 1D spring-slider model in order to unmask the fundamental time scales of the system. We show that the comparison of such time scales with the ones characterizing the injection cycle (periods of continuous injection vs periods of shut-in) determines the rate of seismicity observed at Muara Laboh.

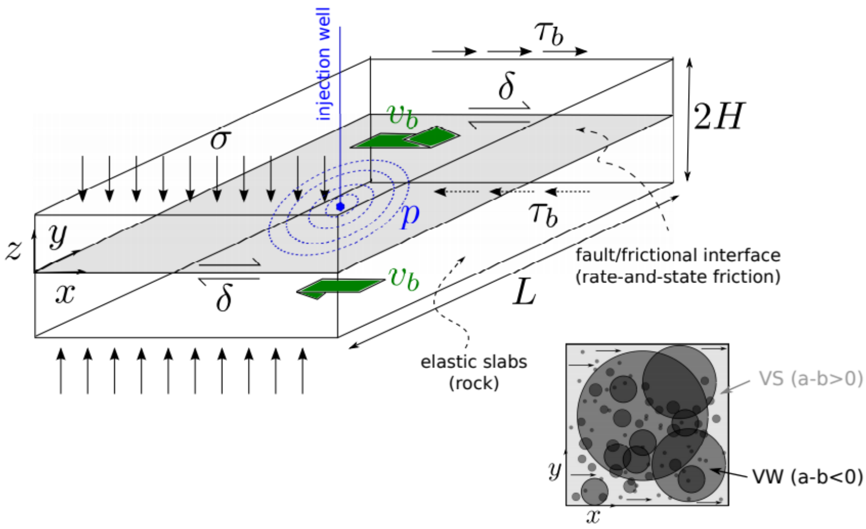

Figure 13 : Geomechanical model setup.

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Earthquake nucleation with stochastic normal stress heterogeneity

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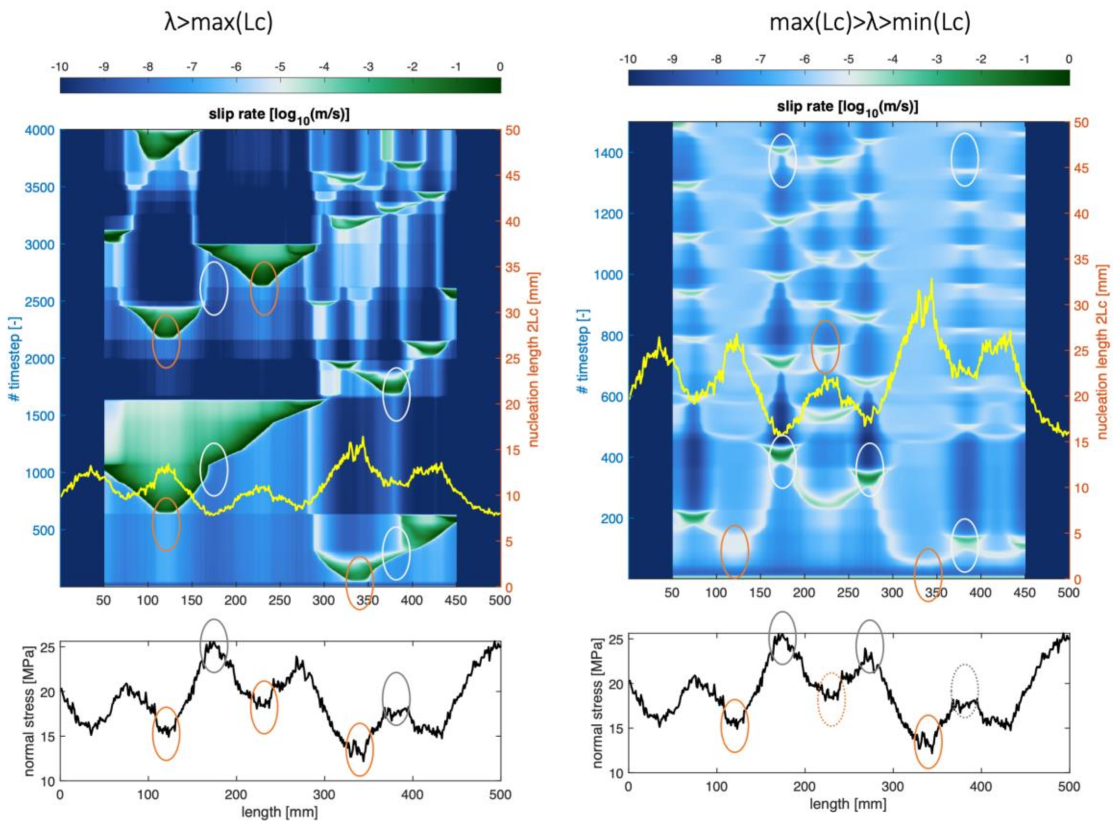
Abstract

A diverse spectrum of slip behaviors takes place prior to an earthquake and in between earthquakes, including foreshocks and slow slips. Laboratory, field and numerical studies suggest that fault heterogeneity plays an important role in this process. Variations in effective normal stress have been given a lot of attention thanks to the controlling role of normal stress on fault strength and fracture energy. While effective normal stress is mostly heterogeneous due to the fault geometry, variations in fluid pressure and offsets of faults across different lithologies play a key role as well, especially in induced seismicity.

Here, we present a stochastic numerical study on spatially heterogeneous normal stress and its influence on earthquake nucleation and the following earthquake cycles (Fig. 1). We find that the recurrence of full rupture events on heterogeneous faults has similar recurrence intervals compared to homogeneous faults with an averaged normal stress. However, on heterogeneous faults slow-slip events which rupture only local parts of the fault occur, which are more frequently observed when the amplitude and the wavelength of the heterogeneity are increased. When the wavelength (λ) is much smaller than the nucleation length (*Lc*), nucleation requires the failure of a coalition of asperities (locked patches), the total length of which reaches *Lc*. Thus, the fault property is homogenized at length scale *Lc*. When λ is larger than *Lc*, nucleation completes in one single asperity. In this case, the low stress regions (LSRs), which are weaker, fail first. The high stress regions (HSRs) become barriers but can be activated by the dynamic rupture to join the event. Or they can be activated and become the nucleation location of the next event. Interestingly, *Lc* is inversely proportional to the normal stress. Therefore, in the scenario where λ is between the *Lc* of the HSRs and LSRs, nucleation cannot complete in one LSR but has to be transferred to the neighboring HSR. In this case, an LSR is still activated first, but only through aseismic slips. The final nucleation takes place in HSRs. The creeping LSR becomes a barrier for rupture propagation in this case. These two scenarios correspond to two proposed end-member nucleation models: the "cascade" and the "pre-slip" models [1, 2]. We also observed results between the two end members, where the nucleation location alters between LSRs and HSRs per event, similar to what has been observed in laboratory experiments [1]. Our results demonstrate that only with normal stress heterogeneity, the interplay of the length scales already produces distinctly different nucleation locations and slip behaviors. The observation that nucleation does not always take place in the weakest region may contribute to earthquake forecasting.

Figure 14 : Two earthquake sequences with the same heterogeneous normal stress distribution but different Dc in rate-and-state friction. The HSR and LSR are labeled with orange and gray circles respectively, see the abstract for details.



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POSTERS

Fault zone complexity naturally produces the full slip spectrum: Insights from numerical models

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Abstract
In addition to regular earthquakes, observations of spatiotemporally complex slip events have multiplied over the last decades. These slip events range along different time scales: from creep , slow slip events to LFEs and tremors. At present, these events are generally interpreted by imposed frictional heterogeneities along the fault plane. However, fault systems are geometrically complex in nature over different scales. We aim in this work to investigate the role of “realistic” fault geometry on the dynamics of slip events. We consider a fault system in a 2D quasi-dynamic setting. The fault system consists of a main self-similar rough fault, surrounded by a dense network of off-fault fractures. All fractures are frictionally homogeneous (rate weakening) and can potentially undergo dynamic slip. We aim to understand how the deformation in the volume is accomodated by the off-fault damage zone and the main fault. By looking at the fraction of the “supplied” moment rate released by the off-fault fractures during an earthquake cycle we show that deformation localizes to the main fault plane during an earthquake rupture but de-localizes towards off-fault structures after the main rupture.

The influence of seamount subduction on megathrust seismicity: the interplay between geometry and friction

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Abstract
The influence of seamounts on megathrust seismicity has been widely recognized over the past years. Seamounts, with their distinctive topography, can influence interplate stress and facilitate the formation of a fracture network in the overriding plate. Additionally, subducting seamounts can control the accumulation of fluids and sediment porosity. However, the role of seamounts as barriers impeding rupture propagation or as triggers initiating earthquakes remains a topic of ongoing debate.

To better understand how the seismogenic behavior of the megathrust is influenced by the geometric and frictional heterogeneities associated with the subduction of a single seamount, we conducted a series of analog experiments. These experiments involved four different model configurations: a flat interface, a seamount with high friction, a seamount with low friction, and a localized patch characterized by low friction. By exploring these configurations, we aimed to analyze the combined and individual effects of geometry and friction on megathrust earthquakes.

The results of our study indicate that areas with low friction, regardless of whether they are flat or characterized by the seamount relief, contribute to a decrease in interplate seismic coupling. The presence of a geometric feature also reduces the seismic coupling and promotes segment ruptures, leading to the initiation of earthquakes on the flat region. The model featuring a low-friction patch exhibits the highest level of barrier efficiency, as the accumulated stress is preferentially released through small earthquakes. This behavior aligns well with natural scenarios where seamounts are known to promote fluid release or the development of fracture systems, hence microseismicity and slow slip events.

Earthquake rupture around stepovers in a brittle damage medium

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Abstract
Strike-slip fault systems consist of a variety of geometrical complexities like branches, kinks and step-overs. Especially, the presence of a step-over structure can strongly determine the final size of the earthquake rupture. Thus understanding the dynamics of a rupture through such a complexity is crucial for seismic hazard assessment. A few studies have looked at this within the context of a linear elastic medium. However, during an earthquake off-fault damage is generated, especially at the ends of a fault, that significantly changes the overall dynamics of a rupture. Using a micromechanical model, that accounts for crack growth and opening and its impact on the dynamic evolution of elastic moduli, we evaluate how dynamic off-fault damage can affect the capability of a rupture to navigate through step-over fault structures. We show that sometimes, accounting for this energy sink, off-damage suppress the ability of the rupture to jump from one fault to another. Whereas, in some specific cases, the dynamically created low-velocity zone may aid the rupture to jump on the secondary fault. Combing this numerical study with an analytical analysis we set the contours for a systematic approach useful for earthquake hazard assessments.

Poroelastic influence on rupture propagation across fault stepovers

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Abstract

The mechanics of earthquake rupture propagation across fault stepovers remain a pivotal area of study for earthquake dynamics research, directly influencing our understanding of earthquake physics and our ability to assess seismic hazards. Despite their significance, poroelastic effects — the two-way coupling between fluid and solid phases where changes in pore pressure from compressional or dilational strain due to fault slip — are rarely incorporated in simulations of earthquake ruptures involving parallel strike-slip faults with a stepover. Existing models primarily consider a one-way coupling, reducing pore pressure changes to disturbances in effective normal stress. Additionally, constraints on Skempton's coefficient *B* are sparse, and its conventional value of 0.8, potentially an upper limit, lacks comprehensive observational support. To address these gaps, we present a quasi-dynamic boundary element model capable of simulating 2D plane-strain earthquake cycles within a poroelastic effects, which causes clamping or unclamping of the fault (Figure 1). The model employs rate-and-state friction, with state evolution defined by the ageing law. Our aim is to accurately depict pore pressure changes driven by solid matrix compression or dilation due to fault slip and to delineate the resultant fluctuations of the effective normal stress within fault stepover regions. Furthermore, we investigate the influence of Biot's and Skempton's coefficients and stepover width on fault interactions within a porous, fluid-filled environment. Our findings provide novel insights into the role of poroelasticity in rupture dynamics within fault stepover systems, revealing how local structural intricacies can significantly dictate the overall fault rupture length.

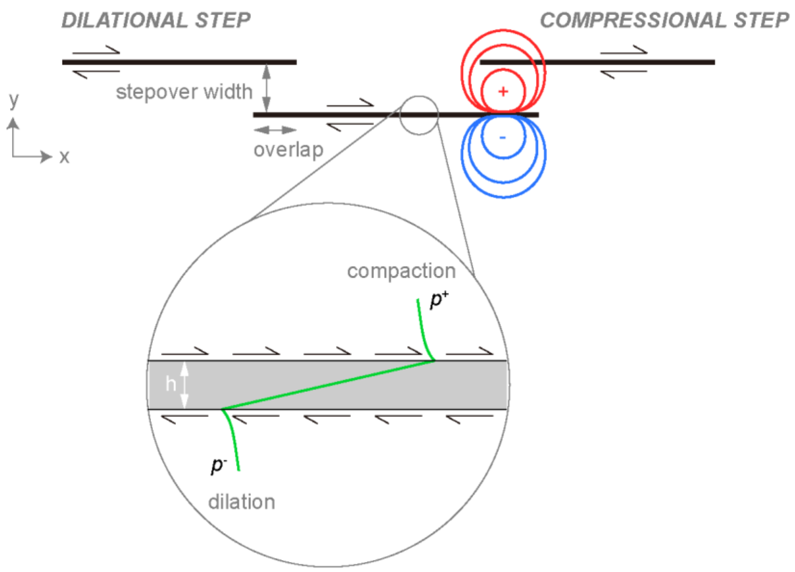

Figure 1: A sketch showing the fault stepovers and the pore pressure changes due to fault slip.

Seismic and aseismic slip driven by ascending fluids and overpressure pulses on faults

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Abstract
Fault zones have long been recognized as potential pathways for fluid migration. While it is debated whether all faults serve as conduits for fluids, there is compelling evidence to suggest that fluid pressure and transport properties play a crucial role in fault behavior. In this study, we present a newly-developed Hydro-Mechanical Earthquake Cycles (H-MECs) (Dal Zilio et al., 2022) model, which fully couples solid-fluid interactions, enabling a comprehensive investigation of poroelastic stresses and fluid flow in fault structures. Conventional earthquake cycle models often assume a constant effective normal stress and overlook the dynamic evolution of fluid pressure. By incorporating the two-way coupling of solid and fluid phases, our model addresses the limitations of previous models and provides a more realistic representation of fault behavior. In our 2-D antiplane strike-slip fault model, we introduce a poro-visco-elasto-plastic compressible medium with a strike-slip fault governed by rate- and state-dependent friction. We consider both slow tectonic loading and fast dynamic rupture, capturing a wide range of timescales from years to milliseconds. Additionally, we simulate the ascent of fluids along the seismogenic zone, mimicking metamorphic reactions as a source of fluid generation. The model incorporates a permeability evolution law, accounting for changes in fault slip and sealing processes over characteristic healing times. Our results demonstrate the significant influence of fluid overpressure and relative changes in fault strength on the occurrence of seismic and aseismic slip, as well as the timing, stress transfers, and other rupture properties of seismic events. During the late interseismic period, fluid overpressure builds up at the base of the seismogenic zone, weakening the fault and triggering slow-slip transients and small earthquakes. Overpressure pulses, facilitated by shorter healing times, promote the propagation of fluid-driven aseismic slip and its ascent through the seismogenic zone, leading to swarm seismicity. Long-term slow slip events are triggered when healing times are of the order of a few years, while fluid-driven aseismic slip can cause transient unlocking of the fault without seismic events for even longer healing times. Our H-MECs model, incorporating viscoelastic deformation and poroelasticity effects, brings earthquake cycle simulations closer to reality and provides greater consistency with experimental and geologic constraints on fault zone dynamics. By investigating the transient effects of fluids, we gain a deeper understanding of how fluid-solid interactions influence seismic and aseismic slip, thereby enhancing our ability to analyze fault behavior and earthquake occurrence.

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Seismic cycles observed through energy budget analysis

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Abstract
Recent studies show the importance of modeling tectonic faults systems as a volume hosting fracture damage that surrounds frictional faults. Off-fault fractures can actively participate in storing and releasing the potential energy buildup. They often go unstable, when the slip on the main fault accelerates, or decelerates, producing observed statistical distributions in the seismic catalogs.

To better comprehend the importance of faulted volume, and their macroscopic properties during the seismic cycle, in this study we look at the full energy balance of a fault volume over several seismic cycles. As the potential energy is building up during an interseismic period we investigate the role played by the off-fault damage in frictionally dissipating this, all the while the main fault is still relatively quiet i. e. not dissipating too much energy. We also determine the overall behavior of the fault volume during an entire seismic cycle.

Understanding this energy budget is crucial to understand the available strain energy for the main rupture to propagate from very slow to ultrafast rupture velocities.

Interpreting megathrust seismic cycle surface signals from seismotectonic laboratory experiments

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Abstract

Understanding the frictional behavior of subduction megathrusts is crucial for assessing their seismic hazards. The frictional behavior may feed back into the upper plate as deformation signals in short and long timescales. However, the extent to which spatiotemporal frictional heterogeneity at depth influences the deformation pattern in the upper plate and the correlation between the elastic signals and permanent records of the upper plate remains a field that needs further examination. To contribute to this understanding, we mimic frictionally homogeneous and heterogeneous megathrusts in our laboratory experiments. The experiments generate hundreds of stick-slip cycles (i.e., seismic cycles) in an elastoplastic subduction setting, and we record the surface deformation at different temporal resolutions.

At short timescales, we investigate the coseismic and early postseismic responses of the upper plate to earthquake-induced stress drop. Our results suggest a sequential elastic rebound following the coseismic shear-stress drop, with the upper plate exhibiting a fast rebound and the elastic belt (representing the slab) experiencing a delayed and smaller rebound. This rapid relaxation of the upper plate accelerates the relocking of the megathrust, triggering the failure of nearby asperities and enhancing slip reversal within the rupture area. Notably, significant trench-normal landward displacement occurs in the upper plate, contributing to stress build-up on the upper-plate backthrust (Kosari et al., 2022a).

At long timescales, we investigate the accumulation of permanent deformation in forearcs over multiple seismic cycles. To study the linkage between trench-normal elastic (short-term) and permanent (long-term) deformation signals in the upper plate, we configure compressional and extensionally critical wedge experiments and explore the mechanical and kinematic interaction between the upper plate and the interface. Our findings suggest that the response of the wedge to megathrust earthquake cycles results in the division of the wedge into three distinct segments across the strike of the forearc: Trench-normal shortening near the trench and extension on top of the seismogenic zone, as well as no deformation (extensional wedge geometry) to mild shortening (compressional wedge geometry) in the coastal zone. Along the strike of the forearc, the spatiotemporal frictional heterogeneity of megathrusts is reflected by a distinct pattern of along-strike coastal shortening (causing uplift and peninsulas?) between asperities and extension landward of asperities. Permanent deformation rates are generally a few percent of the interseismic rates. Along-strike strain patterns in the short-term (elastic) are generally more segmented than in the long-term (permanent) (Kosari et al., 2022b and 2023).

We suggest that the surface strain patterns can function as a proxy to interpret enduring spatial variations in the seismogenic behavior of subduction megathrusts. Evaluating the interplay between the upper plate and frictional heterogeneity and the trench-normal and -parallel deformation segmentation of the upper plate advance our knowledge of the seismic activity and hazard assessment in subduction megathrusts.

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Geodetic strain rate maps vs. analog models: What geodesy might, or might not, tell us about tectonics and lithosphere dynamics; and if it does, over which time scales?

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Abstract

Crustal deformation is a cross-scale process ranging in time from earthquake rupture (seconds) to tectonic evolution (millions of years). In some areas, short-term (geodetic) and long-term (tectonic) deformation rates correspond well while in others they differ by orders of magnitude. The latter inconsistency is typically related to the elastic rebound of the crust (e.g. seismic cycle) augmenting tectonic (permanent) deformation in short-term observations made by tectonic geodesy (GNSS, InSAR). Another, so far less appreciated feature of geodetic strain rate observations is the tri-axial nature of crustal deformation: The GNSS-based global strain rate map (Kreemer et al., 2014) highlights transversal strains (normal to the maximum horizontal strains) in some regions of the world. While these can reasonably be attributed to the elastic Poisson effect at short timescales, what is their legacy on long timescales? Are we biased towards plane strain in tectonic models because they are often restricted to cross-sections where out-of-plane deformation is neglected? What role does triaxial deformation play at regional tectonic scale and what do tectonic geodetic observations (not) tell us about long term tectonic processes?

To trigger this discussion, we here compare the global strain rate map (Kreemer et al. 2014) as a short-term observation with long-term observations from triaxial analogue modeling experiments, in which a rubber base covered with layers of sand and silicone is stretched. Our experiments mimic long-term crustal thinning and the development of extensional fault networks resulting from distributed basal (mantle) extension. In such an experimental setup, longitudinal extension is accompanied by lateral shortening (hence triaxial deformation). The two are related by the principal horizontal strain ratio (PHSR) which we define as the long-term equivalent of the Poisson ratio. In a series of brittle-viscous models, strain rates span three orders of magnitude (9×10^{-9}- 4.5×10^{-6} yr^{-1}) covering relevant natural ranges when upscaled. Strain rate determines two aspects of the developing fault networks through brittle-ductile coupling: First, the regional PHSR as reflected by the orientation of structures and fault slip to the principal strain direction; and second the strain localization represented by fault frequency and amount of fault slip. Accordingly, models at higher strain rates ($>10^{-7}$ yr^{-1}) form narrowly spaced, conjugate sets of bookshelf type faults with small, oblique displacement (half-graben, asymmetric). Models with lower strain rates ($<10^{-7}$ yr^{-1}) on the other hand develop widely spaced, parallel, symmetric horst-and-graben basins where few major normal faults accommodate extension. PHSR in the models decreases accordingly from >0.3 (prolate strain) to <0.1 (plane strain).

The focusing of strain localization onto a few dominant structures with decreasing strain rate can be attributed to a decrease in brittle-ductile coupling and consequently a larger degree of freedom in the system to self-organize. As the strain rate decreases, the regional PHSR decreases, too, testifying to an increased decoupling between the rubber base (simulated lithospheric mantle) and the brittle layer (upper crust). Interestingly, in the steady range of simulated PHSR (0-0.3) sudden switches in the

structural style of fault networks occur pointing to an emergent bifurcation behavior: Switching occurs from conjugate sets of strike-slip faults (at PHSR > 0.31) to sets of parallel oblique normal faults (at PHSR = 0.15-0.25) to a horst-and-graben system normal to the extension direction (at PHSR <0.1).

We compare our observations to the Basin and Range Province as a prototype for wide rifting at low strain rates ($2.11 \pm 0.14 \times 10^{-8}$ yr^{-1}) (Ward, 1998), the Apennines with variable strain rates (3.4×10^{-8} -2.6×10^{-9} yr^{-1}) (Faure Walker *et al.*, 2012) as well as the Himalaya where there is spatial variation in fault pattern from conjugate strike-slip faults in the center to horst and graben systems in the south of Tibet. We find that in those selected areas the regional PHSR derived from the geodetic strain maps show similar trends with a relation to the structural inventory as in the models (i.e. increasing with fault obliquity and complexity) but is of much higher magnitude. We attribute the difference in PHSR magnitude, which seems about a factor of 3, to the elastic effects dominating the short-term observation. This interpretation is the equivalent to the observation of different strain rates on short and long timescales, where the difference can be up to a factor of 10, e.g. in subduction zones, where seismic cycles dominate the concurrent surface deformation. To what extent the regional PHSR reflects seismic cycles of individual faults in fault networks and how it contributes to the complexity of collective earthquake behavior and to the accumulation of permanent deformation in the long term remains to be explored.

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Interplay of fault heterogeneity and geometrical complexity in analogue seismogenic strike-slip fault systems.

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Abstract
The occurrence of seismic and aseismic slip on faults, such as earthquakes, slow slip or secular creep, seems closely related to specific characteristics of the fault with potential candidates being geometry and frictional heterogeneity. Especially the distribution of frictionally stable (creeping) and unstable (stick-slip) patches, also called asperities and barriers, respectively, along the fault affects the recurrence and maximum magnitude of earthquakes on individual faults. Interaction of asperities between structurally separated but elastically connected (stress coupled) faults may complicate the individual seismic cycles and result in complex collective behaviour.
To understand such complex collective fault network behaviour, a simplified analog model was developed in which the distribution of stable patches and unstable asperities and the number of faults can be changed (Fig. 1). Using a parameter study, the effect on recurrence and magnitude of stick-slip events on unstable segments of different lengths, as well as the interaction in a system of up to four stable or unstable faults were tested. Numerical models of the experiments with the same parameters are used for benchmarking of the setup.

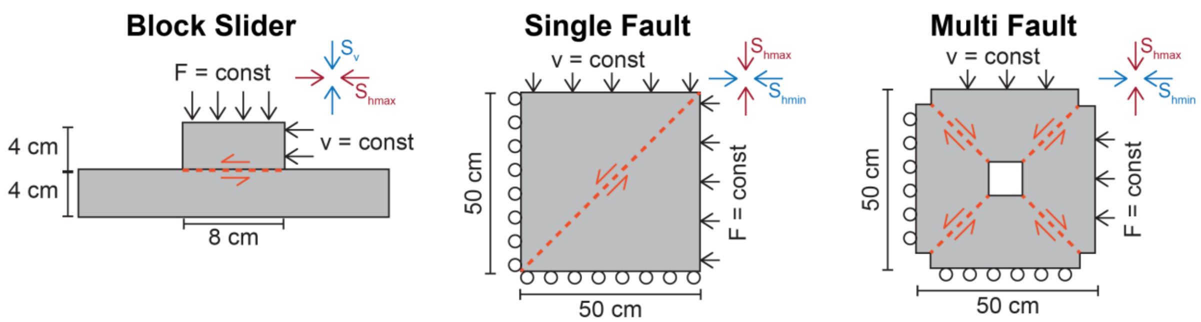

Figure 15 : Setups used for this study.

The setup uses several sets of neoprene foam blocks with a Young's Modulus of 150 kPa and a Poisson's ratio of 0.11. The block contacts (analogue faults) are coated with a layer of alkyd-based spray paint causing the interface to stick-slip when loaded externally. Using a block slider setup, we found that stick-slip is occurring under the targeted experimental conditions. The properties corresponding very well with natural rocks and gouges (friction μ=0.4, healing rate b=0.01). Stabely sliding segments were implemented using conventional grease as a lubricant between paint coated blocks. For the strike-slip fault models, foam blocks were deformed in a horizontal, biaxial shear apparatus. Here, the compression axis was driven at constant speed and the extension axis kept at constant force. The elastic deformation of the analogue crustal blocks in interaction with the rate-and-state analogue fault properties result in loading and unloading phases mimicking strike-slip fault seismic cycles. Characteristic fast slip events, that we call "neoquakes", could be recorded for single fault experiments with a PIV system. In the case of the multi fault setup, only the activity of individual segments could be recorded using an accelerometer due to the small deformation amounts and high slip velocity.
For single faults. we find that there is a nonlinear correlation of patch length with recurrence time and magnitude of the events. Event magnitude and recurrence times scale with (additional far-field) normal

load applied to the fault, with the scaling parameter depending on segment size. For single unstable segments, the recurrence and magnitude is very uniform and follows a characteristic earthquake behaviour. As complexity is increased, by implementing heterogenous distribution of stable and unstable slip and increasing the number of faults, the recurrence patterns change and supercyles of event clusters and event sequences occur. With this setup we can calibrate simple numerical experiments and validate more complex models. Furthermore, we hope to gain insights into the emergence of power-law-like distributions of earthquakes and the occurrence of characteristic earthquake and earthquake sequences.

Collective behavior of asperities before large stick-slip events

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Abstract
The multi-scale roughness of a fault interface is responsible for multiple asperities that establish a complex and discrete set of real contacts. Since asperities control the initiation and evolution of the fault slip, it is important to explore the intrinsic relationships between the collective behavior of local asperities and the frictional stability of the global fault. Here we propose a novel analog experimental approach, which allows us to capture the temporal evolution of the slip of each asperity on a faulting interface. We find that many destabilizing events at the local asperity scale occurred in the slip-strengthening stage which is conventionally considered as the stable regime of a fault. We compute the interseismic coupling to evaluate the slipping behaviors of asperities during the slip-strengthening stage. We evidence that the interseismic coupling can be affected by the elastic interactions between asperities through the embedding soft matrix. Scaling laws of natural slow slip events are reproduced by our setup in particular the moment-duration scaling. We also evidence an unexpected persistency of a disordering of the asperities through the seismic cycles despite the relaxation effects of the large slip events.

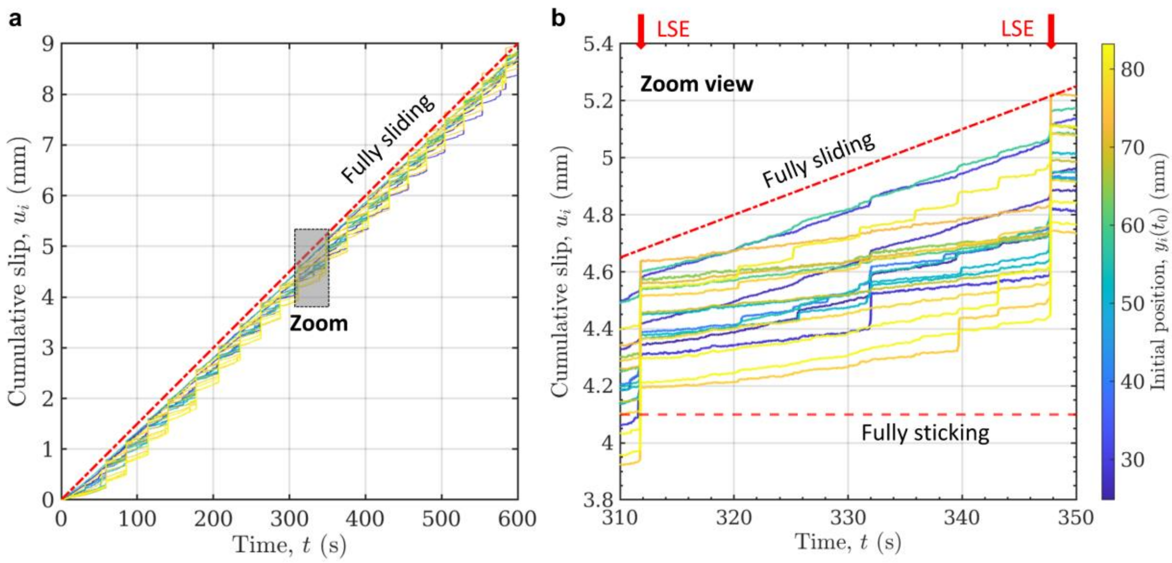

Figure 16. *a: Temporal evolution of the cumulative slip in the faulting direction for 20 asperities during an experiment under a normal load of 200 N and a loading rate of 15.0 µm/s. The cumulative slips of the 20 asperities are colored-coded by their initial y positions at time t_0. b: Zoom view of Figure 1a showing the detailed behaviors of asperities during one time interval between two large stick-slip events (LSE) and ranging from 310 s to 350 s. Fully sticking indicates a locked state while fully sliding gives the slope of the imposed displacement rate to the system.*

Combined Effect of Brittle Off-Fault Damage and Fault Roughness on Earthquake Rupture Dynamics.

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Abstract
Natural fault zone are complex objects. They not only consist of a fine-grained narrow fault core where the extensive shearing is observed, but it is also surrounded by pervasively fractured rocks, within an intricate 3-D geometry. If fault slip behavior is intrinsically linked to the properties of the fault core, the complex structure of fault zone systems impacts the rheological properties of the bulk, which influence the modes of deformation, and slip, as underlined by recent observations. Fault zone structure is therefore of key importance to understand the mechanics of faulting. Within the framework of a micromechanics based constitutive model that accounts for off-fault damage at high-strain rates, this numerical study aims to assess the interplay between earthquake ruptures along non-planar fault and the dynamically evolving off-fault medium. We consider 2D inplane models, with a 1D self-similar fault having a root mean square (rms) height fluctuations of order 10-3 to 10-2 times the profile length. We explore the dynamic effect of fault-roughness on off-fault damage structure and on earthquake rupture dynamics. We observe a high-frequency content in the radiated ground motion, consistent with strong motion records. It results from the combined effect of roughness-related accelerations and decelerations of fault rupture and slip rate oscillations due to the dynamic evolution of elastic moduli. These scenarios underline the importance of incorporating the complex structure of fault zone systems in dynamic models of earthquakes, with a particular emphasis on seismic hazard assessment.

Subsurface Geological Modeling of the Missa Keswal Area, Potwar Plateau, Upper Indus Basin, Pakistan: Insights into Tectonic Evolution and Crustal Shortening

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Abstract
The Missa Keswal area, situated within the active foreland fold and thrust belt of the Himalayan orogeny on the eastern side of the Potwar Plateau in Pakistan, represents a significant geological study. Our research utilizes 2D seismic data and well logs to construct a comprehensive subsurface structural model, focusing on investigating tectonic evolution and crustal shortening in the region. Through the utilization of synthetic seismograms and well ties, we have successfully identified three key horizon tops: Chorgali, Patala, and Kewra Sandstone. Furthermore, we have delineated one normal fault within the basement and seven significant reverse faults within the sedimentary cover sequence of the Missa Keswal area on the seismic section. These horizons have been meticulously mapped in terms of both time and depth contours, employing interval velocity conversion to transition from the time domain to the depth domain. Our findings unveil the presence of a pop-up anticline structure within the subsurface, restrained by reverse faults on both flanks. Our 2D modeling of the interpreted seismic section illustrates that the Missa Keswal area is located within a compressional tectonic regime, characterized by a NE-SW-oriented pop-up anticline structure, flanked by reverse faults. The compressional tectonics have played a significant role in the deformation processes within this area, which unfolded in two primary stages. Initially, normal faulting dominated the basement, followed by subsequent reverse faulting within the sedimentary cover sequence. These geological processes have resulted in substantial crustal shortening within the region. Notably, one major reverse fault is positioned on the SE limb, while the remaining reverse faults are distributed along the NW limb. Additionally, the presence of a normal fault within the basement signifies the Jurassic splitting and rifting of Pangea. Our integrated geological and seismic analyses collectively highlight the extensive deformation caused by the Himalayan orogeny, leading to crustal shortening and the development of a pop-up anticline structure confined by reverse faults along both the SE and NW limbs.

Keywords : Missa Keswal, Potwar Plateau, tectonic evolution, crustal shortening, pop-up anticline, Pangea.

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Dynamics and radiation of thrust earthquakes with coseismic off-fault damage

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Abstract
Major earthquake ruptures occur predominantly in thrust faults producing devastating events and tsunamis such as the 2011 Mw 9.0 Tohoku earthquake, the 2004 Mw 9.2 Sumatra earthquake and the 1999 Mw 7.7 Chi-Chi earthquake. Understanding the mechanics of earthquakes in thrust faults and the effect of the free surface is thus crucial to explain their large shallow slip, their asymmetric ground motion and their damage patterns surrounding the fault and the free surface. In this work, we carry out 2D dynamic rupture simulations on thrust faults to accurately characterize a possible unclamping effect, its responsible physical mechanism, and to produce dynamically activated off-fault fracture networks. To conduct the simulations, we use the software tool based on the Combined Finite-Discrete Element Method (FDEM), HOSSedu, developed by Los Alamos National Laboratory. Our dynamic rupture models in an elastic medium confirm that unclamping occurs in thrust faults and increases significantly as the rupture reaches the free surface and for the fault models with lower dip-angles. We show that this is a consequence of the torque mechanism induced in the hanging wall, and the release of this torque when the rupture reaches the free surface produces a "flapping" in the toe of the wedge where the most significant unclamping (possibly leading to fault opening) is taking place. Our results indicate that the free surface produces a considerable reduction of the compressive normal stress when the rupture is propagating up-dip that facilitates the extension and the amount of slip close to the trench as observed for large thrust earthquakes.This significant normal stress change is reflected in the orientation of the principal stresses before and after the rupture, where under certain conditions, the greatest principal stress changes from subhorizontal to almost vertical leading to a post-rupture tensional stress state in the hanging wall that has been confirmed by observations of recent in-situ, seismological and geodetic studies. Finally, we investigate whether this dramatic normal stress reduction stands when we allow for the activation of coseismic off-fault damage and explore its role in the rupture dynamics, the near-field deformation and radiation patterns.

Exploring the interplay of fault slip, poroelasticity, and permeability barriers in seismic swarms

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Abstract

The contribution of pore-fluid pressure dynamics and fault-zone fluid flow in the generation of earthquake swarms, foreshocks, and aftershocks is well recognized. However, the complex interaction of these factors, namely how pore-fluid pressure evolves due to slip and how fault slips in response to fluid pressurization, presents a significant challenge to our understanding of poroelasticity effect on earthquake physics. This complexity arises due to the difficulties in resolving the intricately coupled solid and fluid systems, whose dynamic nature and inherent unknowns often obstruct comprehensive modeling. In addition, the process and timing of swarms are still not well-understood due to limited information about the heterogeneous structures and stresses at seismogenic depths. Ample observations suggest that seismic swarms are likely to be triggered by fluids, as pore-fluid pressure affects the poroelastic response of the fault. Furthermore, the structure of permeability, particularly permeability barriers characterized by low permeability regions within the fault zone, can create localized pockets of high pore-fluid pressure. This process, in turn, triggers fault reactivation, representing a key factor in the occurrence of seismic swarms. In light of these challenges, our study employs a physics-based numerical model to predict fault behavior and study the dynamics of seismic swarms in a comprehensive manner. We present a newly-developed Hydro-Mechanical Earthquake Cycles (H-MECs) code, which enables the full coupling of solid rock deformation and fluid flow. Using a 2D anti-plane model, we simulate seismic cycles to study the evolution of frictional fault slip, pore-fluid pressure, and permeability. This continuum-based model is governed by rate-and-state friction and embedded in a poro-visco-elasto-plastic compressible medium, accounting for full inertia effects. An adaptive time stepping is applied to resolve events on varying scales, from long-term tectonic fault loading to rapid dynamic rupture. We integrate permeability barriers into the model as regions of low permeability, effectively simulating localized high pore-fluid pressure pockets. Furthermore, we consider permeability evolution, accounting for changes due to fault slip, healing, and sealing, which provide crucial feedback on the dynamics of pore-fluid pressure and fault slip. Despite a relatively straightforward model setup, our numerical experiments reveal complex fault behaviors. Our results show that high pore-fluid pressure pockets can result in stable fault creep, whereas seismic rupture originates from locked permeability barriers with relatively lower pore-fluid pressure. The size of these locked barriers and high-pressure pockets significantly influences the nucleation and propagation of aseismic creep, slow-slip transients, foreshocks, and seismic rupture through the permeability barriers. Furthermore, we find that the rupture of sealed permeability barriers leads to the injection and redistribution of fluid through the fault zone. This primarily on-fault fluid diffusion can rapidly propagate swarms and occasionally initiate a complete fault rupture. Consequently, variations in permeability evolution and pore-fluid pressure play a crucial role in modulating the seismic moment release and the migration rate of seismic swarms. Our results offer a compelling case for the critical role of pore-fluid pressure evolution and poroelastic effects in the dynamics of earthquake swarms. We demonstrate that these elements influence the stability of faults and the seismic or aseismic nature of fault slip. This study provides a significant step forward in improving our understanding of the processes driving seismic swarms.

DAY 2

Session 3

ORALS

Long-term surface processes and tectonics interactions: a biogeodynamics perspective

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Abstract

Biogeodynamics aims to bridge the gap between surface and deep Earth processes. Its challenge lies in the wide range of spatial and temporal scales connected to the interactions between mantle dynamics, lithosphere and crustal tectonics, surface processes and the evolution of life. At ETH-Zurich, we aim to understand how geological processes influence biodiversity. It is linked, among others, but not limited to understand the role of climatic and sea-level variations, and we particularly focus on the drivers of topographic variations in different tectonic and geodynamic settings.

In this study, we analyze the surface fingerprints of distinct crustal and mantle processes that are linked to the specific stages of the Wilson cycle, and we will particularly focus on the drivers of surface evolution, in terms of subsidence and uplift patterns. We aim to better understand the feedback mechanisms between tectonics, mantle melting and surface processes during the Wilson-cycle, including the evolution of continental rifts, crustal breakup, structural inversion, oceanic subduction and collision.

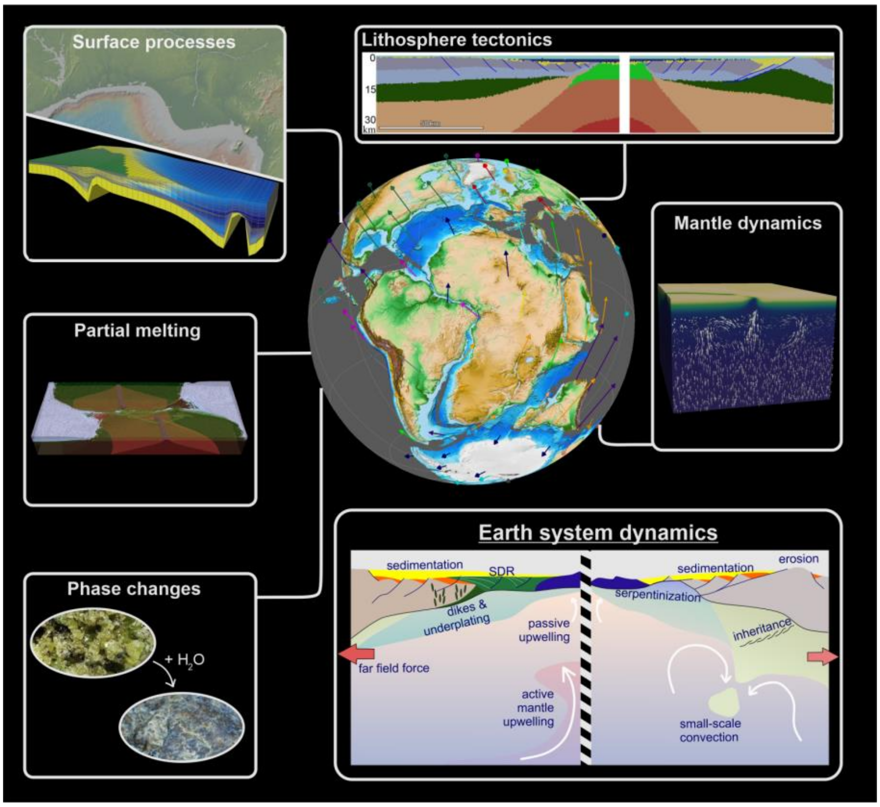

Figure 17 : Key elements of the coupled Earth system dynamics.

Our method is based on conducting and analyzing a series of 2D and 3D thermo-mechanical models by 2D/3D ELVIS (Gerya and Yuen 2007) and compare the model results with geological and geophysical observational data from orogen-sedimentary basin systems.

Our model results show the complex, non-linear interactions between geodynamics and surface processes during the different stages of the Wilson cycle. Tectonics primarily control the main sedimentary transport routes and alters the lithospheric stress field by sediment re-distribution. Sedimentation contributes to increased confining pressure leading to brittle strengthening of the crust, at same time driven by sediment blanketing it increases the crustal thermal gradients leading to ductile weakening effects. Depending on the rate of tectonic processes and the mantle thermal properties different surface processes rates alter the timing and flux of mantle melting, and by that primarily modify the style and further rates of tectonic processes (Balazs et al. 2023).

The topographic evolution of subduction zones is also governed by the links between surface and deep Earth processes. Enhanced sediment subduction lubricates the subduction interface and by water release weakens the overlying mantle. Forearc and back-arc sedimentary basins are sensitive proxies for variable plate and interface rheology. Lower surface processes rates enable a more efficient stress transfer between the plates facilitating back-arc extension. Whereas higher sediment subduction fluxes contribute to enhanced melting leading to arc rifting. The competition between the slab-pull force, upper plate strength and melt-induced weakening are all linked to variations of the subduction velocity and topography (Balazs et al. 2022).

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Modelling anisotropic viscosity

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Abstract

Many of Earth's layers – from the crust to the inner core – are mechanically anisotropic. Anisotropic (i.e. direction-dependent) behaviour of rocks can derive from intrinsic properties of rock forming minerals or from microscopic or macroscopic layering of rocks and/or melts with different composition (extrinsic anisotropy). The Earth Science community often discusses the phenomena of seismic anisotropy, which results from the direction dependent propagation of seismic waves. However, materials that are characterized by elastic (seismic) anisotropy often exhibit viscous anisotropy as well, which is less explored.

In geodynamics we are primarily interested in anisotropic viscosity in the crust and the mantle, where both intrinsic and extrinsic anisotropy are present. To model anisotropic viscous behaviour, we have to handle the viscosity as a 4^{th} order tensor while also thinking about the re-orientation of anisotropy (or evolution of texture) in time.

In the upper mantle the main source of anisotropy derives from the lattice preferred orientation (LPO) of olivine. Under deformation olivine grains rotate into the deformation direction (we often refer to this as texture evolution), resulting in a texture where some – or many – olivine grains are aligned with each other. Furthermore, because single olivine crystals are mechanically anisotropic – which means they deform more easily along some slip systems than others – then LPO that is developed in the upper mantle will yield anisotropic viscosity on a macroscopic scale.

The foundation of our modelling approach is the Modified Director Method, which includes texture evolution and micromechanical models, both deriving from rock mechanic laboratory experiments on olivine aggregates (Hansen et al., 2016a, 2016b). The micromechanical model allows us to calculate the stress needed to achieve a certain strain rate on an aggregate, while the texture evolution model calculates the rotation of grains under a given deformation. To integrate these models into a geodynamic code, or use it to model the evolution of texture and anisotropic viscosity under specific deformation paths, we have to characterize our texture with a rank 4 viscosity or fluidity tensor (Király et al., 2020). It has been shown that the anisotropy related to olivine textures can be characterized by the Hill coefficients (Hill, 1948; Signorelli et al., 2021). Here we show that by building a large database of different textures derived from geodynamic models, we can define a linear model between simple texture parameters and the Hill coefficients with a reasonable cost. This is advantageous for integrating anisotropic viscosity into 4D geodynamic models because it allows for a direct determination of the viscosity tensor from the evolving rock texture, saving a large amount of computational time.

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The time-dependent thermal trigger for intracontinental rifting and break-up of continents

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Abstract

The ocean closure often resulted in refertilization and enrichment of the orogeny-related, lithospheric mantle in radioactive elements, such as thorium and uranium. Based on conductive-convective thermal modelling, increased content of radioactive elements within the anomalous mantle block leads to a time-dependent rise of temperature, weakening the lithosphere with time and, therefore, providing favourable settings for rifting more than 50-100 million years after the closure of ocean. Furthermore, the results of the numerical modelling show that a global-scale mantle convection pattern is characterized by a clear tendency of the mantle upwellings to move with time in the direction of the anomalous heated upper-mantle block. These movements of the upwellings can theoretically cause extensional stresses that can potentially trigger the break-up of the already thermally-weakened, continental lithosphere. We propose that this time-dependent, thermal mechanism can clarify why extensional tectonics and continental break-up within the suture zones do not occur immediately after the orogenic event but with a certain time delay which is almost certainly controlled by the concentration of the radioactive, heat-producing elements in the anomalous mantle block and size of this heated mantle block.

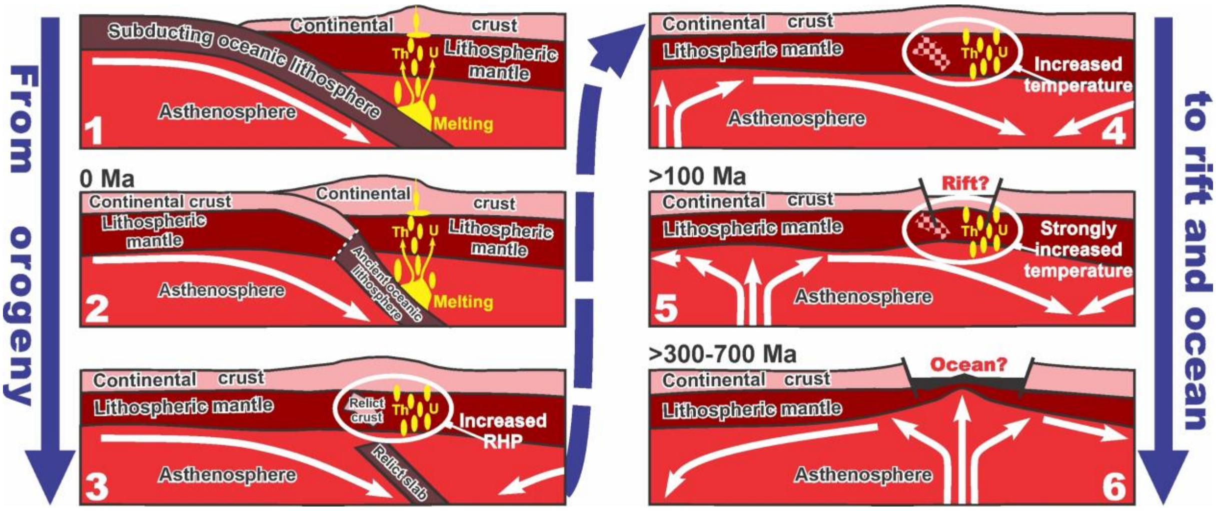

Figure 18: From ocean closure through orogeny and rifting to formation of a new ocean.

In this case, the presence of the orogeny-inherited, structural/compositional inhomogeneities within the former orogenic lithosphere plays a rather secondary role, controlling mostly the geometric configuration of the rift basin. This assumption is based on the fact that structural/compositional inhomogeneities within the suture zone are present immediately after the orogeny, but rifting occurs some tens of millions of years after. Thus, we propose a new, time-dependent process of weakening the continental lithosphere that can be responsible for the intracontinental rifting and the subsequent continental break-up controlled by the increased content of radioactive elements within the anomalous lithospheric mantle.

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SBFTEX: An Analytical Parameterization for Finite Strain-Induced Upper-Mantle Anisotropy

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Abstract
The use of seismic anisotropy to constrain the pattern of convective flow in Earth's mantle requires an understanding of how crystal preferred orientation (CPO) is generated by progressive deformation of mantle rocks. Here we present a new analytical parameterization (`SBFTEX') of CPO in upper mantle rocks as a function of the finite strain they have experienced. The starting point is a set of four analytical structured basis functions (SBFs), three for olivine and one for orthopyroxene. Each SBF is a solution of the evolution equation for the orientation distribution function (ODF) when only one slip system is active, and automatically becomes sharper as the strain increases. The ODF due to the conjoint action of several slip systems is then represented as a weighted sum of the SBFs. We use a least squares procedure to determine the weighting coefficients analytically as functions of the axial ratios of the finite strain ellipsoid and the ratios of the critical resolved shear stresses that measure the strengths of the different slip systems. The fully analytical character of SBFTEX renders it much cleaner and faster than existing models such as D-Rex and self-consistent (viscoplastic or second-order) models. To illustrate the practical application of SBFTEX, we will show calculations of CPO evolution in simple flow fields relevant to the mantle, and will compare the results with analogous predictions obtained using D-Rex.

Magmatic Fingerprints of Subduction Initiation and Mature Subduction of the Izu-Bonin-Mariana Subduction Zone

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Abstract

Subduction zones have been proposed as the main driving mechanism for plate tectonics and they are important for the evolution of life on Earth. Furthermore, they represent a key process for the geochemical cycle and shape the Earth surface. To maintain plate tectonics on Earth, it is crucial to initiate new and maintain ongoing subduction zones. However, physical and melting processes that occur when the oceanic lithosphere begins to founder and evolves to a mature self-sustained subduction zone is still debated. An ideal natural laboratory to study subduction initiation is the Izu-Bonin-Mariana (IBM) subduction zone. There, the rock record formed during subduction initiation is preserved and reveals a rapid compositional variability in slab-fluid tracers and in the mantle depletion-enrichment within 1 – 5 Ma during and after subduction initiation. Whether IBM initiated as a forced or spontaneous subduction zone (i.e. induced by or in absence of horizontal forcing, respectively) is still highly debated.

In this study, we conducted 2D high-resolution petrological-thermomechanical subduction models that include erosion, sedimentation and slab dehydration processes, as well as melting, and deformation assuming visco-plastic rheology using the i2VIS code (Gerya & Yuen, 2007). We aimed to model the initiation and the early stages of IBM triggered by transform collapse and testing ultra-low horizontal tectonic forcing. Our new numerical models show a viable possible transition from initiation to mature subduction zone. This juvenile evolution can be subdivided into distinct stages which include initiation by gravitational collapse of the slab, the development of a near-trench spreading, a gradual build-up of a return flow of asthenospheric mantle and the maturation of a volcanic arc. A gradual increase of depletion in the mantle wedge can be observed during the maturation of the subduction zone. Our numerical results of the subduction history of the IBM are further compared with seismological and geochemical data.

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Developing the global network of plate boundaries in 3D mantle convection models

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Abstract
The beginning of plate tectonics is when the single lid Earth was broken into a mosaic of plates, separated by high strain localized plate boundaries with horizontal displacement. The establishment of this global plate boundary network was primarily driven by local subduction zones. However, the transition from local subduction zones to a fully interconnected global network of plate boundaries remains poorly understood and is often overlooked. To elucidate the timescale and strain localization mechanisms over these tectonic regime transitions, we investigate the role of different physical parameters that may control the development of global plate boundary networks using 3D mantle convection models. We quantify the evolution of plate sizes, length of different plate boundaries and mobility of lithosphere. Our studies also demonstrate how the local subduction zones merge and interconnect to form the global plate boundary network. By comparing the numerical results with geological proxies of plate tectonics, we assess the key parameters that could contribute to the development of plate tectonics.

POSTERS

A new geodynamic model of the Azores archipelago: preliminary results

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Abstract

The Azores archipelago is an integral part of the Macaronesian geographic region (which also includes the volcanic archipelagos of Madeira, Selvagens, Canaries and Cape Verde). This region is located in the centre of Atlantic Ocean, with the individual islands being spread around a triple junction which is possibly affected by a plume-ridge interaction (Storch et al., 2020; Beier et al., 2022). Some questions regarding this region are still missing a complete answer, in particular why the entire archipelago has experienced complex vertical motion histories and why/how the Terceira Rift (i.e., the NW-SE oriented connection between the mid-ocean ridge and the Gloria Fault Zone) was formed.

To explore this complex geodynamic setting and to shed some light on these issues, we have created two sets of 3D viscoelastoplastic models for the region using the state-of-the-art modelling code LaMEM (Kaus et al., 2016). Initial models were based on previously established evolutionary models for the region, such as the leaky transform model (Madeira and Ribeiro, 1990) and geochron reconstruction models (e.g., Luis and Miranda, 2008). Here, the objective was to evaluate how the geological data and the suggested evolution for the region fits geodynamic constrains, as well as exploring the formation of the Terceira Rift (Figure 1). At a later stage, using data from bathymetric (e.g., Tozer et al., 2019) and geodetic campaigns, we developed a second set of models with the aim to study the present-day stress-strain distribution in archipelago and assess its influence on the observed vertical motions.

The preliminary results from the first set of models suggest that the formation of the Terceira Rift required a pre-existing weakening along the base of the lithosphere permitting an NW-SE opening. This was observed by including an initial plume event beneath the target region at different sites, thermally weakening the base of the lithosphere. Models without a strong weakening in this region tended to form E-W connections between the Gloria Fault Zone and the southern part of the mid-ocean ridge in the region. Regarding the second set of models and the present-day distribution of stress-strain, our preliminary results seem to hint that the presence of the Terceira Rift is fundamental to explain the vertical motion observed in the archipelago. All models ran without this feature displayed little to no vertical motion in or around the islands.

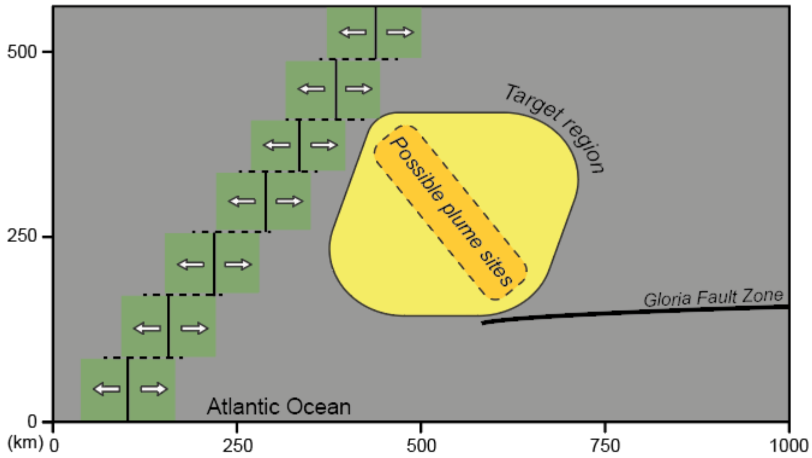

Figure 19 – Initial state for the leaky transform conceptual model. The green regions indicate the location of spreading centres. The plume sites indicate the range of locations where the plume head was placed during testing.

Acknowledgements

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Influence of overriding plate thickness on forearc topography:

Insights from analogue and numerical models

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Abstract

The forearc is the region of the overriding plate that physically interacts with the subducting plate and is therefore expected to record critical information about subduction dynamics. A way to access such information is through its topography, which presents a wide variability across the natural prototypes. Some forearcs show a peculiar topography characterised by a forearc high next to the trench and a forearc basin preceding the magmatic arc (e.g. Alaska, Java, Central Chile). This topographic signature is commonly observed in subduction zones that have generated the most energetic earthquakes ever recorded (e.g., Alaska 1964 Mw 9.2, Java 2004 Mw 9.1--9.3, Chile 1960 Mw 9.5). Thus, investigating the mechanisms that shape the surface of these forearcs may reveal key factors behind the origin of such destructive events.

Previous studies have proposed that the gradient of the vertical component of the suction force along the plate interface is the mechanism responsible for such topography (e.g., Hassani et al. 1997, Chen et al. 2017). However, these studies have only analysed the roll-back subduction mode, in which the suction force presents a downward vertical component. Recent work of Xue et al. 2022 showed that even roll-over subduction, in which the suction force presents an upward vertical component, can also produce this topographic signature. This result suggests that suction force may not be the only mechanism driving the development of this topography. A common observation between these studies is that the lowest point of the forearc basin corresponds to the surface projection of the deepest point of the plate interface, regardless of the subduction mode. Such observation indicates that the mechanism driving this type of topography must act on the plate interface.

To our knowledge, no previous studies have systematically investigated the role of the properties of the subducting and overriding plates in shaping the topography of the forearc. These properties include the thickness and viscosity of both plates, slab angle, and bending radius. In this preliminary work, we developed a series of dynamic and isoviscous models using both analogue and numerical technics to investigate the role of overriding plate thickness on the length scale of the forearc topography. For the analogue models, we applied a stereoscopic particle image velocimetry technique to monitor the topography of the forearc (following, e.g., Xue et al. 2022), while for the numerical models, we used the Underworld 2 numerical code (Moresi et al. 2003, 2007).

This study will investigate the previous observation that the location of the deepest point of the plate interface determines the position of the forearc basin. We expect to obtain a positive correlation between the overriding plate thickness and the distance of the forearc basin from the trench since the deepest point of the plate interface will shift accordingly with the thickness of the overriding plate. Moreover, we also expect to obtain a negative correlation between the overriding plate thickness and the relative depth of the basin, as the overriding plate strengthens as it gets thicker.

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Detachment vs. horst formation modulated by brittle softening in ultraslow-spreading oceanic lithosphere

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Detachment faults with significant displacement are commonly observed in slow-spreading mid-ocean ridges (MORs). These faults are typically associated with ridge sections that receive a moderate supply of magma. Interestingly, they are also present in specific areas of ultraslow-spreading MORs, which are predominantly amagmatic and characterized by unusually cold and thick (>15 km) brittle lithosphere. To understand the factors that enable and influence the growth of detachments under these unique conditions, we conducted a study combining geological observations and numerical simulations.

In our study, we use 2-D thermo-mechanical models to simulate amagmatic seafloor spreading, taking into account self-consistent thermal evolution. The brittle lithosphere is modeled as a Mohr-Coulomb elasto-plastic material, with its frictional behavior decreasing as accumulated plastic strain increases. Ductile deformation is parameterized using experimentally-derived olivine flow laws.

We first investigate how the difference in strength between the fault zone and the surrounding lithosphere affects tectonic evolution. Geological observations indicate that fault zones have lower effective friction coefficients due to serpentinization and fluid circulation. Additionally, evidence for grain size reduction in ultramafic rocks suggest additional ductile weakening. Our simulations reveal three distinct regimes resulting from variations in the strength contrast between faults and the lithosphere: (1) stable detachment migrating towards its hanging wall, (2) sequential growth of horsts bounded by two active antithetic faults, and (3) "flip-flopping" detachments that intersect each other, most resembling natural occurrences. A greater contrast in friction and/or cohesion favors the stable detachment mode, in agreement with previous studies.

Next, we focus on the specific influence of a strong, viscous lower lithosphere on brittle deformation in the upper lithosphere. We compare simulations using dry olivine flow laws for temperatures above ~700ºC with models in which the brittle lithosphere abruptly transitions into a low-viscosity asthenosphere. Our findings indicate that a stronger lower lithosphere tends to promote more distributed faulting and shifts the transition to the stable detachment regime towards greater strength contrasts.

We also examine the impact of widespread fluid circulation in the shallow axial lithosphere, which manifests as active hydrothermal sites. We incorporate its mechanical and thermal effects, which include a reduction in effective normal stress through hydrostatic fluid pressure and efficient cooling of young lithosphere. Although the latter strongly influences the depth at which the brittle-ductile transition occurs, we find that the former has little effect on tectonic behavior, similar to a slight weakening of the unfaulted lithosphere.

Finally, while extensive mass wasting is documented at mid-ocean ridge detachments, its precise influence on tectonics remains poorly known. To explore this, we implement diffusive erosion of the model's free surface, which facilitates a transition from the stable to flip-flopping detachment regime. This transition may be attributed to the modulation of topographic stresses.

Overall, the growth of detachments in cold, amagmatic sections of MORs necessitates some degree of rheological weakening, both in the brittle and ductile domains, due to the delocalizing effect of a strong ductile lithosphere. We find that even moderate frictional weakening (e.g., a friction coefficient decreasing from 0.6 to 0.4 with accumulated plastic strain), potentially resulting from serpentinization of the fault zone and aided by seafloor mass redistribution can suffice to explain observed styles of flip-flopping tectonics.

Is the Gibraltar subduction zone invading the Atlantic?

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Abstract
Subduction initiation is a fundamental element of the Wilson cycle. It marks the turning point in which a growing ocean starts to close, recycling its lithosphere back into the Earth's mantle. However, it is known that initiating new subduction zones in Atlantic-type oceans is physically challenging. This is because the only source of force capable of forming new subduction zones is the slab pull of another nearby subduction zone, which is generally unavailable in pristine oceans. Nevertheless, the Atlantic already has two fully developed subduction zones, the Lesser Antilles and the Scotia arcs. These subduction zones have formed in association with the nearby East Pacific subduction zone system. The Gibraltar Arc is a third location in which a subduction zone may just be migrating into the Atlantic. In this work, we have run a new three-dimensional geodynamic model using the code LaMEM to simulate the evolution of the Western Mediterranean arc-back-arc subduction system. Our goal was to understand what the fate of the Gibraltar subduction zone may be. The results show that Gibraltar Arc may be enduring a period of quiescence, after which may propagate further into the Atlantic Ocean.

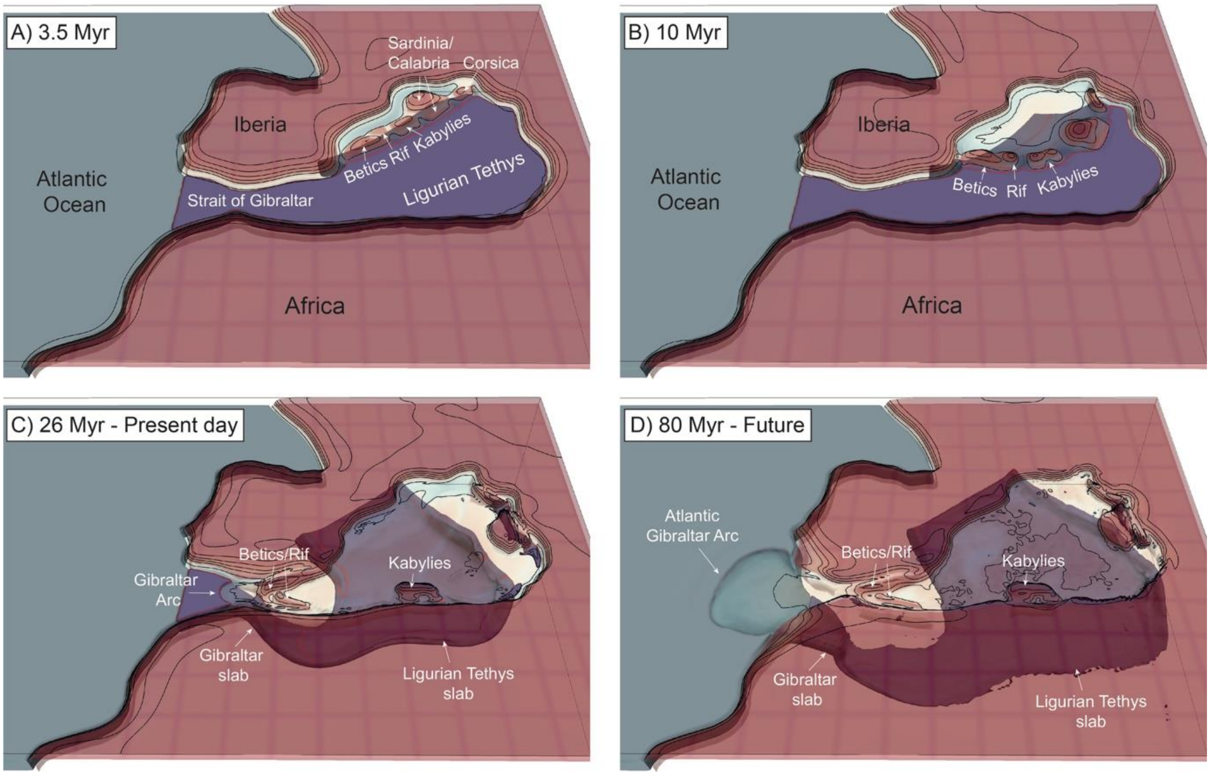

Figure 20 : Results of the numerical model showing the evolution of the Western Mediterranean reproducing the formation of the Gibraltar Arc.

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Gneiss domes & sedimentary basins formation in West Africa

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Abstract
In West Africa, Paleoproterozoic terranes are known for their abundant mineral deposits, yet the geodynamics and tectonic origins related to the stabilisation of these regions remain unclear. The regional surface geology consists of migmatitic gneiss domes and granites within mafic and sedimentary greenstone units, both overlain by detrital sedimentary basins. Over the years, various conceptual geodynamic models have been proposed to explain the complex surface geology and geophysics observed in these terranes, but they have not been tested within a robust physical framework.

In this study, we employ Underworld Geodynamics (Beucher et al., 2018) to investigate the 2D co-evolution of greenstone terrains, migmatite domes, and sedimentary basins in the context of the late-stage evolution of the Eburnean orogeny. The model comprises a 15-km-thick layer of air-like material, a 15-km-thick layer of dense visco-plastic mafic crust overlying a 40-km-thick radiogenic visco-plastic felsic crust capable of partial melting, and a mantle layer. The open-source Underworld code (Moresi et al., 2003, 2007) solves the Stokes equation for very low Reynolds numbers on a fixed Cartesian grid, with Lagrangian particles carrying material properties advected through the grid where pressure, velocity, and temperature are determined. We tested various 2D model configurations with different kinematic boundary conditions and extracted key synthetic data, such as metamorphic gradients, P-T-t paths, and migmatite dome foliation patterns. Those can be directly compared to published metamorphic P-T paths and mapped structural features in West African Paleoproterozoic terranes.

Based on our 2D experiments, we suggest that the Eburnean deformation pattern in West Africa is better explained by gravity-driven tectonics (Figure 1), similar to what has been proposed for Archean terrains (e.g., Thébaud and Rey, 2013). However, more accurate analysis of the 3D strain patterns in these complex terrains in which strike slip deformation is important will require 3D models.

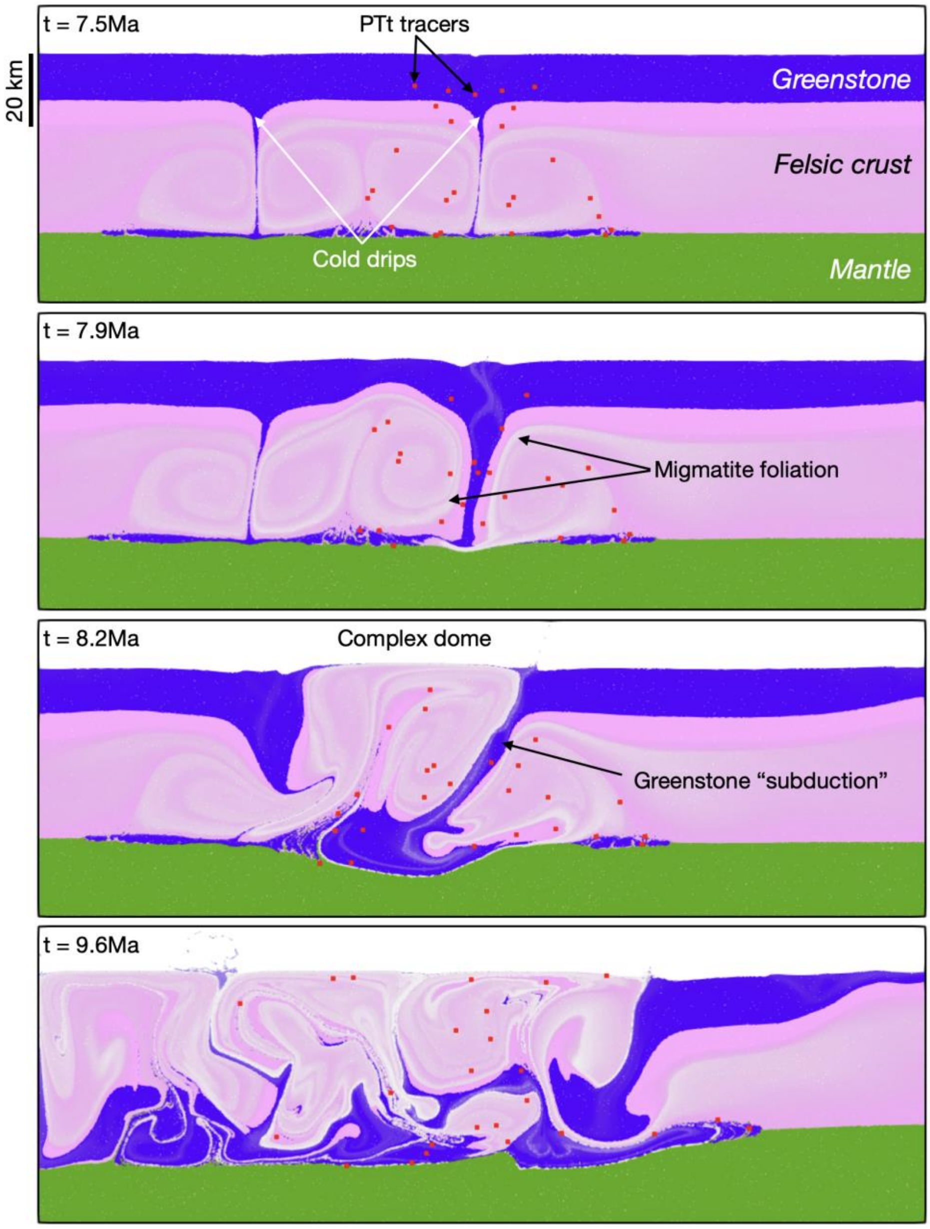

Figure 21 : snapshots of the rapid evolution of the greenstone-migmatite dome dynamics controlled by gravity-driven overturn. The greenstone unit is denser than the felsic crust. In this model no tectonic force is applied to the sides of the domain.

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50 shades of cold : how the thermal structures of subducted slabs reflect their past dynamics

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Cold subducting slabs imaged by seismic tomography exhibit various morphologies in the deep mantle, revealing a variety of slab deformation histories in the transition zone and the lower mantle. On the other hand, the thermal structures of slabs is considered as a key parameter for deep-focus earthquakes in subduction zones (e.g. the 1994 Bolivia Mw 8.3 earthquake at 647 km depth), since proposed mechanisms such as dehydration reactions or shear instabilities are controlled by temperature.

Using numerical models of subduction dynamics through time, we propose in this study to (i) characterize the deep thermal structures of subducted slabs and (ii) investigate how an instantaneous thermal structure is inherited from the cumulative past history of slab sinking and deformation.

We will build upon previous diagnostics, e.g. the “shallow” thermal parameter (age x velocity – Kirby et al., 1996) and the kinematic ratio quantifying slab folding (comparison of surface vs. sinking velocities – Cerpa et al., 2022).

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Eclogitization: Insights from Numerical Modelling

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Abstract

Recent research has highlighted the critical role that eclogitization plays in controlling subduction rates, slab morphologies, and upper plate stresses through its impact on interface viscosity and density (see Figure 1; e.g., Behr *et al.*, 2022). While eclogitization leads to an increase in interface viscosity, it also promotes a density increase, which enhances slab pull (van Hunen *et al.*, 2001). This increase in density is particularly important in understanding the subductability of oceanic plateaus (e.g.: Arrial & Billen, 2013). Recent studies highlight that the sediment-to-mafic-rock ratio affects the viscosity of the deep subduction interface, and that this can have a significant effect on plate speeds (Behr *et al.*, 2022). However, the influence of the eclogite viscosity increase on subduction dynamics is not well understood. In particular, whether the promoting density increase or inhibiting viscosity increase of eclogite is more prevalent in subduction system dynamics, and the interplay between eclogite and sediment lubrication effects (e.g., Brizzi et al., 2021).

In this study, we link the viscosity and density effects of eclogite in numerical models to understand the conditions for enhanced versus stalled subduction in modern-day subduction configurations (see Figure 1). We utilize the ASPECT code (Bangerth *et al.*, 2022) to construct 2D numerical subduction models. The approach used in this study is similar to that of Behr *et al.* (2022), where a crustal layer with adjustable properties is included in the model to enable dynamic subduction in a thermochemical convection system. The system involves a mobile subducting and overriding plate where the models evolve dynamically in that there are no external forces or velocities applied. The model domain consists of a 11600 × 2900 km box with a refined grid spacing of 1 km at the subduction interface and 2 km elsewhere in the lithosphere

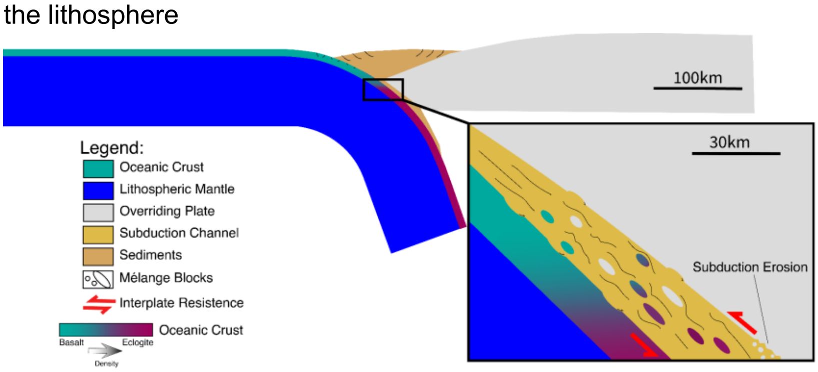

Figure 1: Summary diagram displaying the fundamental processes and effects to be explored in the project.

As seen in previous studies, we find that the increase in density from eclogitization promotes subduction, meanwhile the increased viscosity hinders it. Both of these result in a shift in the timing of peak velocity conditions. Our preliminary results suggest that the promoting effect of the density increase overshadows the viscosity increase, and that subduction does not stall. Overall, we find that the inclusion of eclogitization slightly increases subduction velocity, when both the viscosity and density increases are considered.

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Tracking surfaces in global scale geodynamic models using a volume of fluid method

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The study of coupled Earth systems, and in particular the coupled interactions between the lithosphere, atmosphere, and biosphere, have received greater attention in recent years (Gerya et al. 2020). Interactions between these systems occur primarily at the surface, and are driven on the large scale by topographic and bathymetric evolution controlled by deep mantle processes. However, due to the large difference in length scales between the mantle and the surface, it is difficult to capture topographic evolution to a high degree of accuracy in existing global mantle convection models including a free surface boundary condition.

Global mantle convection models incorporating a free surface often employ a marker-in-cell technique with a layer of "sticky air" (i.e. material with the density of the air and sufficiently low viscosity, which is still much higher than that of real air) to characterise the surface. However, accurate topographic evolution using this method requires a high density of markers near the surface. This need for additional computational resources motivates alternative methods of tracking the interface between the air and rock layers, as is done frequently in existing multiphase fluid flow codes. A volume of fluid method with piecewise-linear interface reconstruction provides a suitable method for tracking a surface in a performant way with the sub-grid level topographic resolution that is necessary for coupling geodynamic models to models of other Earth systems.

We demonstrate benchmarks of an implementation of a volume of fluid method within the existing advanced mantle convection code StagYY (Tackley, 2008) using the unsplit volume of fluid library gVOF (López & Hernández, 2022). The method is applicable to both 2D and 3D geometries, and on both Cartesian and non-Cartesian grids. Models of global scale topography and evolution produced using StagYY may later be used as a tool for further studies on the coupling of mantle dynamics with modelling of the landscape, and the evolution of the atmosphere and biosphere.

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Asthenospheric flow-driven back-arc basin extension and oroclinal bending: preliminary analogue modelling results

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Abstract

It is well demonstrated in many natural cases and tectonic models that subduction roll-back creates an asthenospheric flow below the upper plate in the roll-back direction (Schellart, 2004; Funiciello et al., 2006; Faccenna et al., 2014; Sternai et al, 2016; Király et al., 2021). In such a system, the degree of lithosphere-asthenosphere coupling is still debated and the contribution of asthenospheric flow to upper plate deformation is largely unknown (e.g., O'Neill et al., 2010; Doglioni et al., 2011; Warners-Ruckstuhl et al., 2012). In this study we test if asthenospheric flow can drive deformation in the upper plate to create oroclinal bending or back-arc extension and basin formation. Furthermore, we investigate how inherited structures in the lithospheric mantle can facilitate strain localization and the transfer of deformation from the asthenosphere to the overlying lithosphere. Our results are compared with the Pannonian-Carpathians system of South-Eastern Europe, where the large Pannonian back-arc basin formed during the Miocene retreat of the Carpathians slab (Matenco and Radivojević, 2012). This retreat is also considered as the main driver for oroclinal bending in the Carpathians-Balkanides mountain belt surrounding the Pannonian Basin (Krstekanić et al., 2022).

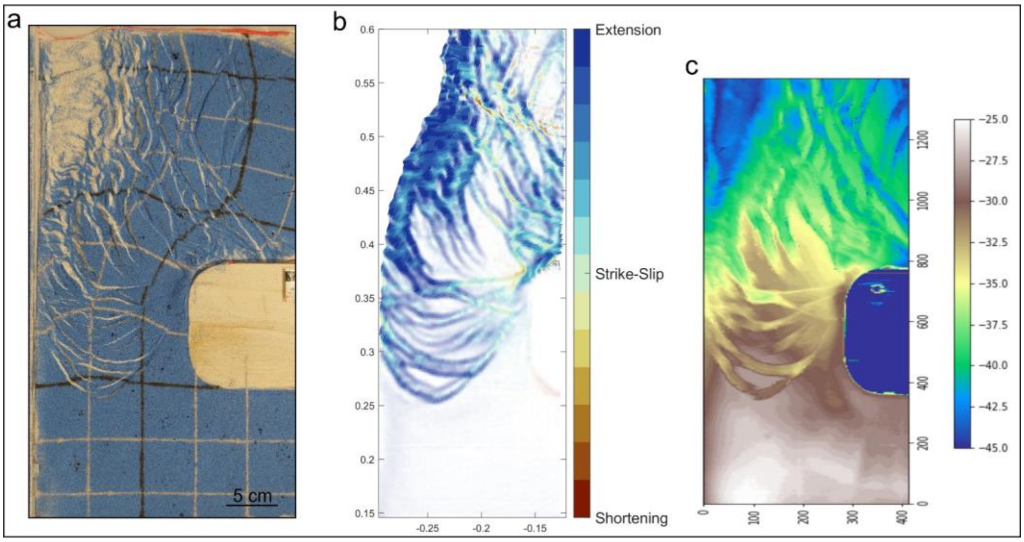

Figure 22 : Final stage of a preliminary model. a) Top-view photograph. b) Top-view cumulative strain map at the end of the experiment. c) CT scanner-derived top surface topography at the end of the experiment.

Preliminary results of our experiments (Fig. 1) show that the back-arc extension is initiated farther away from the origin of the asthenospheric flow (i.e., slab-roll back). The subsequent deformation propagates in two directions, towards the flow origin, and farther away from it, both directions being controlled by the shape of an indenter located laterally to the subduction zone. Most of the back-arc extension and the lithospheric thinning are accommodated in the area farther to the "slab" due to the strain shadow effect of the indenter. The indenter also contributes significantly to the strain partitioning in its closer proximity where a complex pattern of bi-directional extension, transtensional, strike-slip and transpressional deformation forms. These first models show several similarities with the Pannonian-Carpathians system, where most of the Pannonian lithospheric thinning is located at a significant distance from the subducting Carpathians slab, bypassing the Transylvanian-Apuseni area. Furthermore, several triangular shape sub-basins within and at the margin of the Pannonian Basin are radially located around the Moesian NW corner, similar to our modelling results. The complex pattern of the bi-directional extension and strike-slip observed in the models were recorded by the Carpathians-Balkanides orocline in the vicinity of the Moesian indenter.

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Topography and the Advance of Collisional Boundaries: Insights from 2D whole mantle numerical models of Subduction and Collision

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Abstract

Understanding the dynamic processes associated with continental collisions is crucial for unraveling Earth's tectonic evolution. One key aspect of these collisions is the topography along collisional boundaries, which provides valuable information about the deformation and interactions of tectonic plates. This study investigates the relationship between the advance of collisional boundaries and the resulting topographic features using buoyancy-driven self-consistent 2-D whole-mantle scale numerical models of subduction and collision implemented with the Underworld2 code[1].

To accurately simulate the processes of oceanic subduction and subsequent collision, our numerical models incorporate a sticky air layer atop the collision zone with free surface stabilization[2]. Furthermore, we explore the influence of the non-linear rheology of the upper mantle by varying its degree. Through the analysis of these geodynamic models, we examine how the non-linearity of the upper mantle affects the progression of topography during continental collision and post-collisional processes, including slab detachment and underplating of the colliding continent. Our findings highlight the intricate interplay between the length of the preceding oceanic slab and the non-linear nature of the upper mantle in shaping the observed topographic features. By elucidating these relationships, our research contributes to a comprehensive understanding of long-term tectonic evolution and provides insights into the underlying mechanisms driving both continental collisions and the resulting topography.

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The study of vanished ocean through numerical modelling

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Abstract

While the continents remain at the Earth’s surface, the oceans are incessantly renewed through subduction and continental breakup. Nowadays, these ancient oceanic domains have nearly vanished through subduction into the Earth's mantle. To study them, researchers can only rely on the scattered pieces of ophiolites found on the field, evidence of paleo-subduction zone, and tomographic imaging of the deep interior. However, this fragmented record restricts our comprehension of past oceans and hinders the development of plate paleoreconstruction models.

In this study, we propose a new mechanical approach base on 2D numerical modelling of subduction zone to investigate the history of vanished ocean. We simulate the slab pull force generated by oceanic lithosphere subduction and test the combination of mechanical parameters that leads to continental breakup within the continental domain of the lower plate. The results are collated with available geodynamic data to constrain the creation and disappearance of now vanished oceanic domains.

We show that the slab pull force increase related to the density jumps associated to the mantle phase transition at 410 km depth is sufficient to generate the breakup of the lower plate. For the breakup to occur within the continental domain of the lower plate, the lower plate has to be fixed compare to the asthenospheric mantle and the continental margin has to be weaker than the oceanic portion of the lower plate. Based on the simulation results we propose that the Paleotethys ridge subduction occurred before the Neotethys rifting and that the Proto South China Sea open during the Mesozoic.

Thermal inheritance in continental rifting.

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While a lot of literature exist modelling the effect of former tectonic structure faults, stacking of different lithologies with a dip or former lacolithes, little has been done in modelling the effect of heterogeneous thermal properties in the lithosphere and particularly in the crust and these contributions are old enough that some of their main results need to be reminded and extended using current modelling tools.

I will first recall how much periodic variations in heat production rate in the crust may affect the temperature at the Moho and the thickness of the lithosphere using analytical solution, I will then use thermo-mechanical simulation to demonstrate how important are these effects in 2 and 3D at tectonic timescale especially while reactivating former post orogenic collapse structures such as metamorphic core complexes and migmatite domes. I will illustrate how the simulation might apply to the West European rift, the Menderes massif or the South China Sea.

I will finally show using 2D numerical simulations how much the repartition of heat production in the crust influences the long-term survival of mobile belts and can explain partly why the European lithosphere keeps large heat flow despites its thermos-tectonic age.

Formation of brittle-ductile block-in-matrix structures along plate boundary shear zones

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Abstract

Deep slow earthquakes, which include slow slip and tremor events, are thought to be transition zones where brittle and ductile domains coexist. This hypothesis is supported by several numerical simulations that have successfully reproduced observed slow earthquake phenomena using models where brittle patches exist within ductile regions (e.g., Behr et al., 2021; Nakata et al., 2011). From a geological perspective, there have been reports of brittle lenses embedded within ductile matrices in areas associated with slow seismic activity (Kotowsk & Behr, 2019). Despite these findings, the formation of a block-in-matrix structure composed of both brittle and ductile materials remains a complex and underexplored area of study. Recent research has begun to shed light on this topic by investigating the rheology of the basalts that make up the subducting oceanic crust (Tulley et al., 2020). The results suggest that basalt has greater strength than clay-rich sediments in the shallow, brittle zone, but intriguingly, basalt can become weaker than sediments in the deeper, ductile zone (Okuda et al., 2022). To better understand these processes, this study aims to use geodynamic modeling to elucidate how the interaction of these materials affects the formation of a block-in-matrix structure of brittle lenses in a ductile matrix.

For this study, we employed the I2ELVIS code, a code known for its capability of executing thermo-mechanical modeling (Gerya & Yuen, 2007) (Figure 1). The strength profiles of the sediment and basalt comprising the oceanic crust were inputted into the simulation to set up our geodynamic modeling framework. Subsequently, the modeling process facilitated the emulation of deformation patterns, successfully reproducing the typical structural evolution of a subduction zone. In particular, the results reflect the formation of an accretionary wedge in the shallow part of the subduction zone and reproduce a subducting slab in the deeper part.

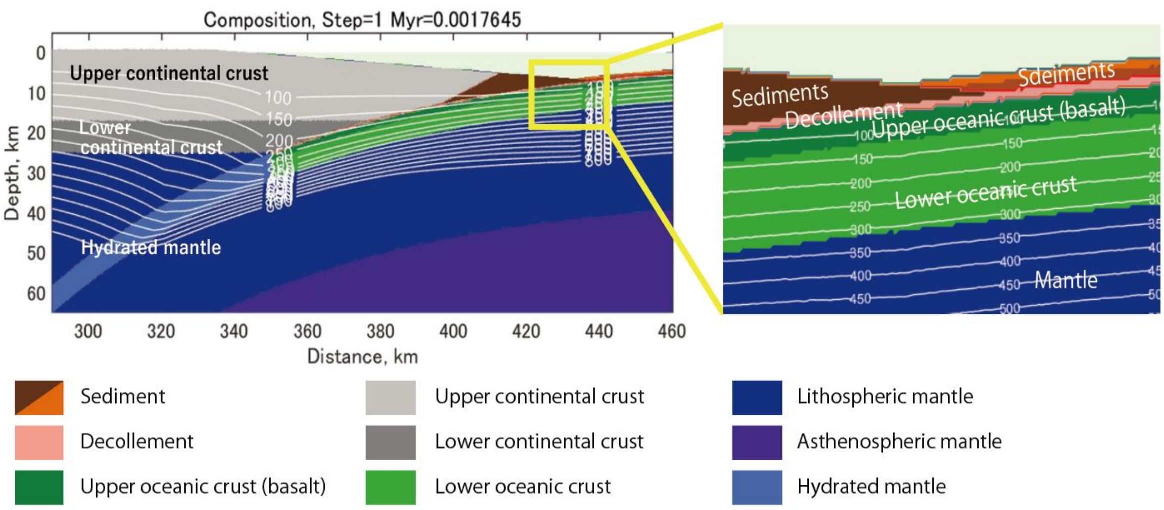

Figure 1 : Initial settings of the model

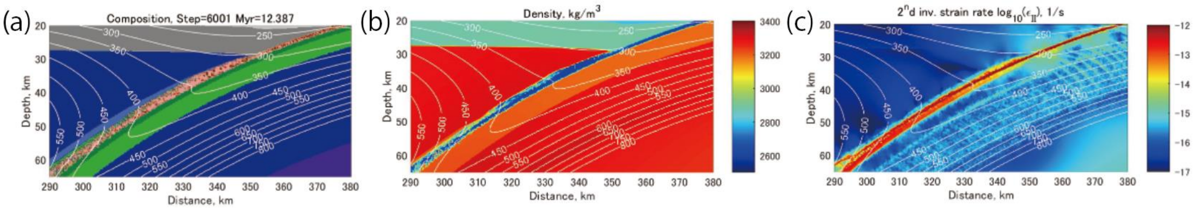

Figure 2: Simulation results. (a) Composition of materials. (b) Density distribution. (c) Second invariance of strain rate.

Our simulations revealed that the deformation patterns along the plate boundaries exhibit notable variations with depth (Figure 2). In particular, localized brittle shear zones were observed to form in the sediment layer of the shallow plate boundary. Upon investigating deeper sections, the shear zones were found to form a unique layered structure, composed of the brittle sediment and ductile basalt. Moving further into the depths, we observed that the brittle sediment blocks were incorporated into the ductile basaltic matrix. This discovery suggests the complex and dynamic nature of the geological interactions that occur along the plate boundary and provides further insight into seismic phenomena along plate boundaries.

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Slab detachment dynamics: insights from 0D to 3D numerical experiments

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Abstract
Slab detachment is a process that has been invoked to explain rapid uplift, deep seismicity, and magmatic activity in several active orogens (e.g., Alps, Himalaya). However, it is not yet clear to which extent slab detachment is the primary cause of these phenomena. Thus, deciphering the physical processes controlling the slab break-off is important to understand its impact on the post-collisional evolution of orogens.

Here, we employ numerical models to investigate the nonlinear coupling between mantle flow and slab detachment. Due to the three-dimensional nature of slab detachment and the variety of involved processes, it is daunting to pinpoint the first order controls on the time scale of this process. We, therefore, started to investigate this issue by developing a simplified 0D necking model that describes the temporal evolution of the thickness of a detaching slab. We accounted for the effects of the nonlinear coupling between upper mantle and detaching slab and derive a set of nondimensional numbers that control the slab detachment process.

Based on these findings, we then used 2D and 3D numerical models to further determine higher dimensional geometrical effects on slab detachment. Results show that the predictions from the 0D experiments predict the 2D and 3D experiments sufficiently well simple scenarios. For more complex slab geometries, higher dimensional results deviate from the 0D predictions. Nevertheless, the combination of 0D and 2D/3D numerical models allows to determine first order controls on slab detachment and thus also on specific geological observations such as seismicity and surface response.

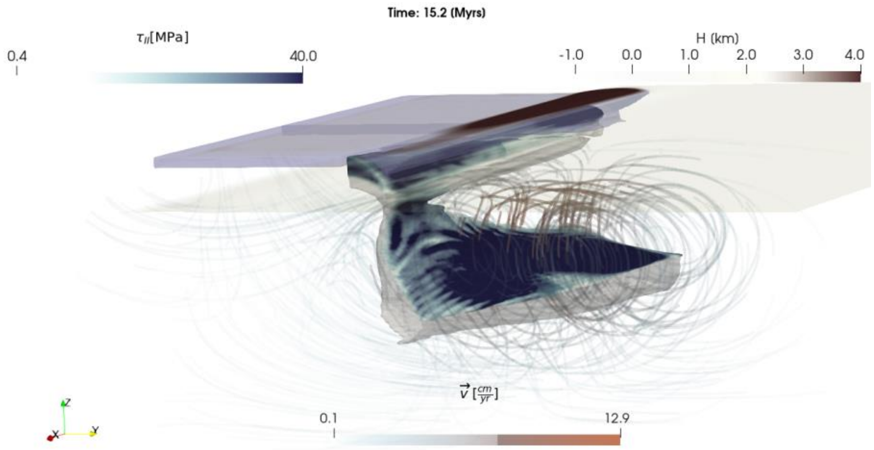

Figure 23 : 3D numerical experiments showing the tearing dynamics. The streams line represent the velocity field and they are colored as a function of the magnitude of the velocity. The slab is colored as a function of the second invariant of the deviatoric stress tensor, while the surface is colored as a function of the topography (H).

Stress rotation in the Tonga subduction region

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Abstract

While the origin of deep earthquakes occurring at the base of the mantle transition zone remains enigmatic, they provide unique information about the stress distribution in the slabs. Thanks to the resistance of the endothermic phase transition at the depth of 660 km which is usually associated also with an increase of viscosity, down-dip compression is expected in the slabs in this depth range. Focal mechanisms for ordinary deep (620-680 km) earthquakes in the Tonga subduction zone exhibit down-dip compressional stresses in agreement with this expectation. However, a set of unusually deep (≥680 km) Tonga earthquakes exhibit focal mechanisms with vertical tension and horizontal compression (Fukao et al., 2014). Such a change of stress orientation occurring on a short spatial scale might be associated with phase transition-related petrological buoyancy, slab bending in the transition zone and shallow lower mantle, and/or interactions with more viscous lower mantle.
We present a numerical modelling study of the evolution of the Tonga slab with a focus on the stress pattern in the transition zone. The Pacific plate subducting in the Tonga-Kermadec zone is one of the oldest and thus coldest plates in the world; one may thus expect that the effects of phase transitions could be expressed here more strongly than in other deep subducting slabs. We thus perform a parametric study testing the effects of rheological description and phase transitions on the stress evolution in the transition zone for a model with an exceptionally cold subducting plate. Our results suggest that the direct buoyancy effects associated with the endothermic phase transition at 660-km depth are overprinted by bending-related forces and by resistance of the more viscous lower mantle transmitted by a strong slab up-dip. Among the tested model parameters, the stress pattern best fitting seismogenic stresses is found for the coldest tested subducting plate (initially 150 Ma old at the trench), a yield stress of 0.5 GPa, and a viscosity interface between the upper and lower mantle decoupled from the 660-km phase transition and shifted to 1000-km depth. An abrupt change of stress orientations in this model is observed when the slab, temporarily deflected by the endothermic phase transition, penetrates to the shallow lower mantle and the fold of the flat-lying part is tightening.

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2D numerical simulations of micro-continents collision in ocean-continent subduction systems

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Abstract

Heterogeneities of the oceanic crust are very diffuse and considered to represent remnants of extinct arcs, abandoned spreading ridges, detached, and submerged continental fragments, anomalous volcanic piles, and uplifted oceanic crust (Stein and Ben-Avraham, 2007; Vogt and Gerya, 2014). Here, we simulated the collision of micro-continents with different different sizes in an oceanic-continent subduction setting characterized by different convergence velocities, to verify their effects on the thermo-mechanical evolution of the subduction systems.

Our results show that the subduction of a micro-continent has an impact both on the thermal state and on the dynamics of the subduction complex. In particular, the larger the micro-continent, the higher the temperature increase in the slab, while from the mechanical point of view, larger micro-continents cause higher forces at the trench during the collision. Consequently, for larger micro-continent can be observed a jump of the subduction to the back of the micro-continent with the development of a new subduction zone (Fig. 1). In addition, the convergence velocity affects the occurrence of a slab or trench retreat and, therefore the slab dip. Lastly, a strain partition can be observed in the subducted micro-continent, from portions highly deformed to portions where the accumulated strain is almost zero.

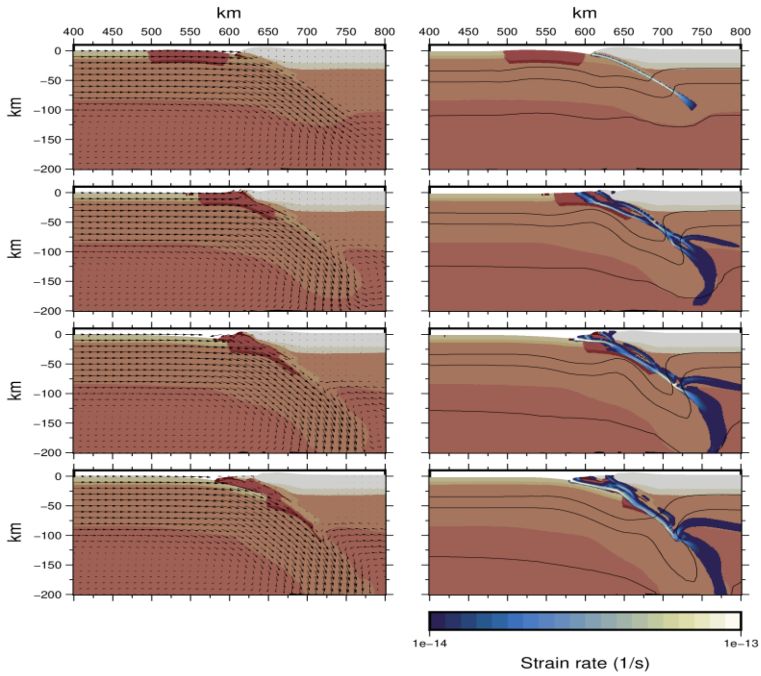

Figure 24 : Evolution of the model with a 100 km width microcontinent (dark brown).

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2D Geodynamic numerical modelling of continental subduction and exhumation

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Abstract
The main (geo)dynamic processes governing continental subduction are still not fully understood. In general subduction requires two main conditions: a) subduction rates in the order of ~5 cm/yr (Shellart, 2023), which maintain the subducting slab cold and dense enough to deliver sufficient slab-pull force; and b) a weak subduction channel (Gerya and Meilick, 2011) to prevent coupling between the overriding and subduction plates, which generally leads to slab break-off ending subduction (e.g., Duarte et al., 2015). Neither of these conditions are seemingly favoured during continental subduction, since the absence of a serpentinized oceanic slab hinders fluid circulation and chemical weakening of the subduction channel, and subducting continental lithosphere (due to its continental crust) is positively buoyant.
As such, we carried out a set of 2D numerical geodynamic models to investigate the first order geodynamic controls on continental subduction, assuming a generic tectonic scenario implying the arrival of a passive continental margin to an intra-oceanic subduction zone and its subsequent subduction beneath an oceanic overriding plate (Fig. 1).We thus used the Underworld code (Moresi et al., 2007) in our numerical modelling, to specifically understand how does dominant trench retreat (roll-back) vs. trench advance (roll forward) subduction might influence the possibility and efficiency of continental subduction and associated synthetic obduction. To do so, in our models we either considered an overriding plate with a fixed vs. free trailing edge, respectively. No pre-imposed, external, velocity boundary conditions were ever prescribed in our models in any case, with all observed model velocities and forces emerging exclusively from the dynamic balance between existing buoyancy forces (slab pull) and (counteracting) crustal and mantle viscous resistance.
Our numerical modelling results show that continental subduction and implied synthetic obduction is possible to achieve in both, roll-back and roll forward, subduction scenarios. However, important differences occur in the two simulated regimes, regarding the timing (i.e., the rate) of the continental subduction-exhumation cycle, the amplitude of such a cycle (namely the maximum depth of continental burying and the minimum depth of exhumation), the generic geometric-kinematic configuration implied in subduction-exhumation processes and synthetic ophiolite obduction, and the amount of allochthonous transport of ophiolitic nappes and exhumed continental segments on top of the continental plate (Fig.2).

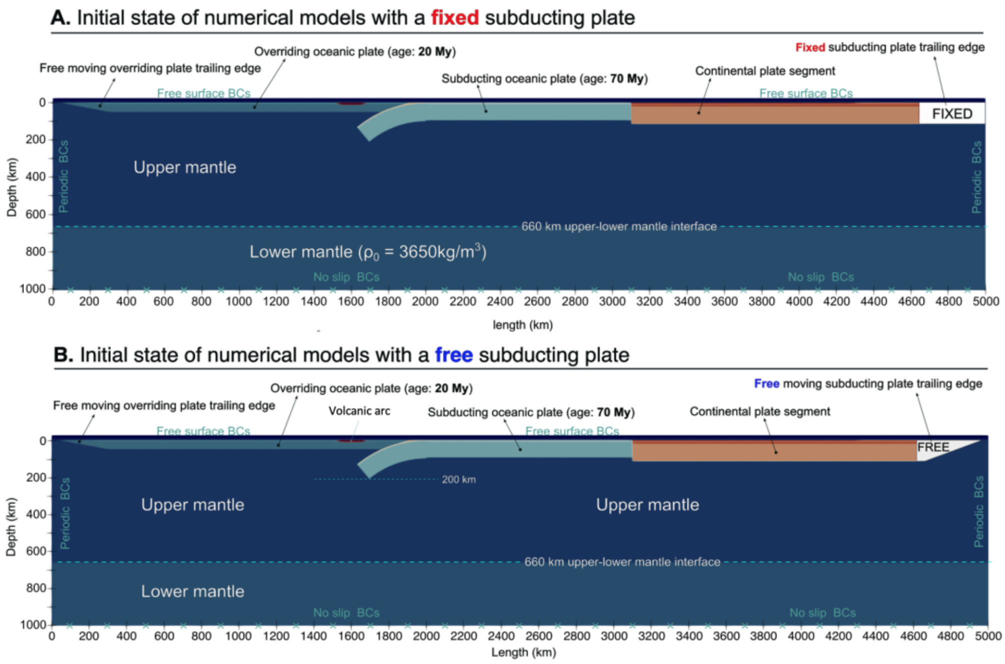

Figure 25 : Initial modelling geometry and boundary conditions: (A) Fixed overriding plate trailing edge; (B) Free overriding plate trailing edge.

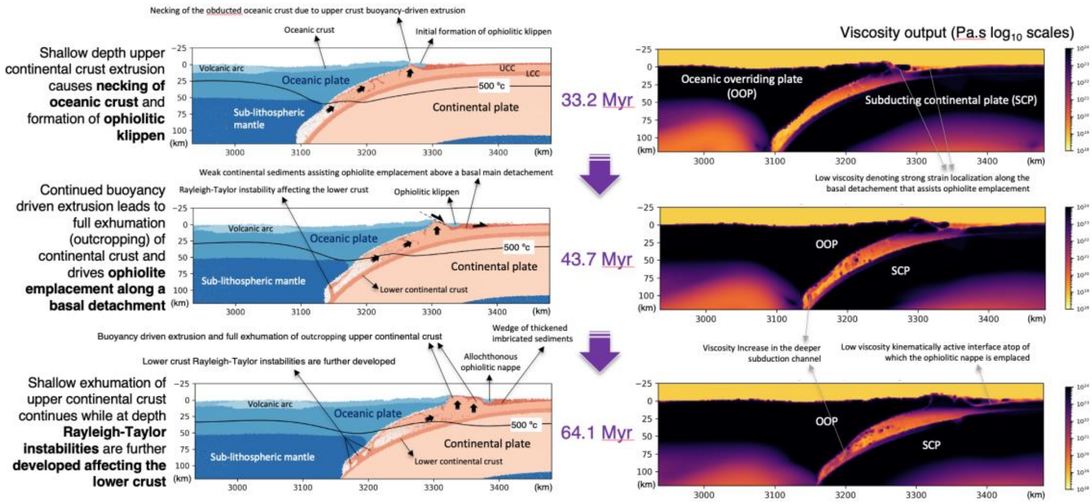

Figure 2 : Example of the obtained numerical results for the subduction roll-back scenario (fixed overriding plate)

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Control of subduction zone size on subduction dynamics and overriding plate deformation

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Abstract

At subduction zones the overriding plate is often deformed. In many cases, it is extended, resulting in the formation of a basin (e.g. East Scotia Sea, North Fiji Basin, Aegean Sea), while in some other cases it is shortened, resulting in a massive mountain range (e.g. Andes). It remains unclear what might cause some overriding plates to shorten, others to extend, and yet others to remain relatively undeformed. In this contribution, numerical geodynamic simulations of subduction are presented, using the code Underworld (Moresi et al., 2003; Stegman et al., 2006; Schellart et al., 2007; Mansour et al., 2020), that evolve over time in three-dimensional space. These models have been specifically designed to investigate the role of time and subduction zone size (with, i.e. trench-parallel extent) on subduction zone evolution, overriding plate deformation and overriding plate stresses. The numerical models demonstrate that shortening, compressive stresses, and mountain building only occur at very large subduction zones (large width) that have been active for a long time (i.e. old subduction zones). The models further show that overriding plate extension occurs more frequently, taking place both for small and intermediate size subduction zones throughout their evolution, and for large subduction zones in the early (upper mantle) stage of their evolution as well as near lateral slab edges of large subduction zones during the middle (upper part of lower mantle) stage of their evolution. The model results are compared with global datasets of active subduction zones, providing an explanation for the present-day deformation style at these subduction zones and showing that the model results are consistent with a number of subduction zone characteristics such as their geometry (e.g. trench curvature, slab dip angle) and kinematics. In particular, the comparison between models and global datasets provides an explanation for the observation that on Earth, at present, overriding plate extension occurs more frequently than shortening.

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Shear-driven formation of olivine veins by dehydration of ductile serpentinite: a numerical study with implications for porosity production and transient weakening

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Abstract
Serpentinite subduction and associated dehydration vein formation are important for subduction zone dynamics and water cycling. Field observations suggest that en échelon olivine veins in serpentinite mylonites formed by dehydration during simultaneous shearing of serpentinite. Here, we test a hypothesis of shear-driven formation of dehydration veins with a two-dimensional hydro-mechanical-chemical numerical model. We consider the reaction antigorite + brucite = forsterite + water. Shearing is viscous and the shear viscosity decreases with increasing porosity. Total and fluid pressures are initially homogeneous and in the serpentinite stability field. Initial perturbations in porosity, and hence viscosity, cause fluid pressure perturbations during simple shearing. Dehydration nucleates where fluid pressure decreases locally below the thermodynamic pressure defining the reaction boundary. During shearing, dehydration veins grow in direction parallel to the maximum principal stress and serpentinite transforms into olivine inside the veins. Simulations show that the relation between compaction length and porosity as well as the ambient pressure have a strong impact on vein formation, while the orientation of the initial porosity perturbation and a pressure-insensitive yield stress have a minor impact. Porosity production associated with dehydration is controlled by three mechanisms: solid volumetric deformation, solid density variation and reactive mass transfer. Vein formation is self-limiting and slows down due to fluid flow decreasing fluid pressure gradients. We discuss applications to natural olivine veins as well as implications for slow slip and tremor, transient weakening, anisotropy generation and the formation of shear-driven high-porosity bands in the absence of a dehydration reaction.

Investigating the plate motion of the Adriatic microplate by 3D thermomechanical modelling

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Mantle dynamics in the Alpine-Mediterranean area provide a complex geodynamic picture and is still subject of ongoing debate. The Adriatic microplate represents the central part of the Mediterranean and is affected by various subduction zones, like the Hellenic slab, the Calabrian slab or the Appenninic slab. These different processes pose challenges in making qualitative assumptions about the unique impact factors influencing the plate motion.

In this study, we conduct 3D thermomechanical forward simulations of the Alpine-Mediterranean area using LaMEM (Kaus et al., 2016). Our simulations incorporate a viscoelastoplastic rheology and an internal free surface, enabling us to investigate both internal dynamics and surface response. The initial setup for the simulations is based on the kinematic reconstructions of Le Breton et al. (2021) at 35 Ma. Our objective is to determine the main driving forces behind the plate motion of the Adriatic microplate by examining the effects of different model parameters, such as the thermal structure, slab geometry, mantle viscosity, and brittle parameters of the crust.

Although these forward simulations do not precisely reconstruct the current tectonic setting, they provide valuable insights into the parameters that influence the subduction dynamics. Based on our findings, we have identified two distinct stages of plate motion affecting Adria over the past 35 million years. The initial phase is dominated by the northwards moving African plate, which pushes Adria to the north. However, as the Hellenic slab advances from the east and the Calabrian and Appenninic slabs propagate from the west, the Adriatic microplate becomes decoupled from the African plate which induces an anticlockwise rotation of Adria.

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Rheological controls on strain localisation and topography in continental corner collision settings

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Abstract

In the framework of the Wilson cycle, continental collision has been studied primarily as a two-dimensional process. This approach applies relatively well to across-strike strain localisation, but overestimates topography and lacks along-strike variations. Therefore, it cannot be applied to the edges of continental collision zones, i.e., continental corners. Two such corners occur at the Eastern and Western edges of the Himalayas. The dynamics of continental corner collision are complex, and poorly understood. Previous studies do not include surface processes, use simplified rheological approximations, and have not attempted to model the lithospheric structure of a continental corner. The present work investigates the influence of three-dimensional rheological heterogeneities on the topographic evolution and propagation of deformation within a simplified continental corner collision setting. To do so, we make use of the finite-difference, marker-in-cell geodynamic code I3ELVIS (Gerya & Yuen, 2007) with viscoplastic rheologies. Diffusion-advection-based surface processes are included through full coupling to the finite difference surface process model (FDSPM, Munch et al., 2022).

The lithosphere-scale collision models are run in a 1000 x 1000 x 200 km domain with a permeable lower boundary and a 2 km grid spacing in each direction. Our parameter study includes the configuration of strong and weak zones, Moho temperature contrasts between indenter and overriding plate, and strain weakening, among others. We compare a selection of models using quantitative diagnostics and cross-sections in convergence-parallel and oblique directions.

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An efficiency index and localization potential to quantify (ductile) deformation in the lithosphere

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Plate tectonics' components are rigid plates moving coherently, and plate boundaries where deformation concentrates. Cold lithospheric mantle and the hotter asthenosphere underneath are made of the same rocky material, mostly olivine, whose rheology depends on physical conditions (temperature, strain, strain rate), and material properties (e.g. grain size). In this study, we investigate deformation localization in the ductile domain by analysing the results of numerical simulations displaying intraplate deformation localization up to the formation of a new weak boundary.
The first set-up is a 2D cartesian subduction model featuring temperature- and strain-rate-dependent (non-Newtonian) viscosity. The second set-up is a 2D spherical annulus model with temperature-, strain-rate-, and grain-size-dependent (non-Newtonian) viscosity.
Tracking the temporal evolution of the different components controlling viscosity reveals the chronology of feedbacks at play, for instance between thermal upwelling, strain-rate increase, and/or grain-size reduction. We propose various quantifications of a « localization efficiency index » to evaluate deformation localization through time. We also discuss the derivation of an a priori « localization potential » assessing the rheological requirements to trigger deformation localization in the lithosphere after a realistic thermal or mechanical disruption.

Numerical models simulating mantle exhumation in (inverted) rifts

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Abstract
The tectonic exhumation of mantle material is known to occur during both rifting and subsequent (large-scale) basin inversion. However, the exact processes facilitating the exhumation of mantle material towards the surface, Mantle material is relatively dense compared to crustal material, and therefore negatively buoyant remain poorly understood. In order to shed light on these processes, we completed a series of thermomechanical simulations using the geodynamics code ASPECT coupled with the surface processes code FastScape to test the influence of a number of geodynamic parameters on the exhumation of mantle material in inverted rift systems (Fig. 1).
Our results show that rift duration has a major impact on mantle exhumation during rifting and during subsequent inversion. When our models undergo only a short period of rifting, the crustal layers remain connected so that the dense mantle material below cannot be significantly exhumed. During subsequent inversion, a symmetric pop-up structure tends to develop through the reactivation of the rift boundary faults. As a result, any exhumed dense mantle material is forced down again as low-density crustal layers accrete on top of it. Only after extensive rifting does sufficient thinning of the crust occur for mantle material to be significantly exhumed. Instead of being forced down again, part of the exhumed mantle material remains near the surface or is further exhumed during subsequent inversion of the basin. Asymmetric inversion of the rift basin tends to promote more extensive mantle exhumation, as it allows mantle material to be thrusted upwards, on top of the downgoing plate.
The development of such asymmetric orogens is typical of modelled systems with only short-lived tectonic quiescence between rifting and inversion, in which no significant cooling of the exhumed mantle domain is allowed to take place. The result is that reactivation is localized along one margin during inversion. By contrast, longer tectonic quiescence prior to rifting cools and strengthens the lithosphere, such that delayed inversion generates more symmetric orogens. Even so, these symmetric orogens can preserve large blocks of mantle material close to the surface.
Another factor influencing mantle exhumation in our models is erosional efficiency in the system. Efficient erosion removes crustal material so that the mantle can be more readily exhumed during both rifting and inversion, even in symmetric orogenic systems. Efficient erosion also promotes the establishment of asymmetric orogenic systems, thus contributing to mantle exhumation directly as well as indirectly. Relatively slow convergence rates have a similar effect as efficient erosion, since faster plate motion introduces larger amounts of crustal material into the system. This material can then not be removed in a timely manner via erosion at normal rates. Hence, mantle exhumation is positively correlated to erosion efficiency, and is negatively correlated to plate velocities.

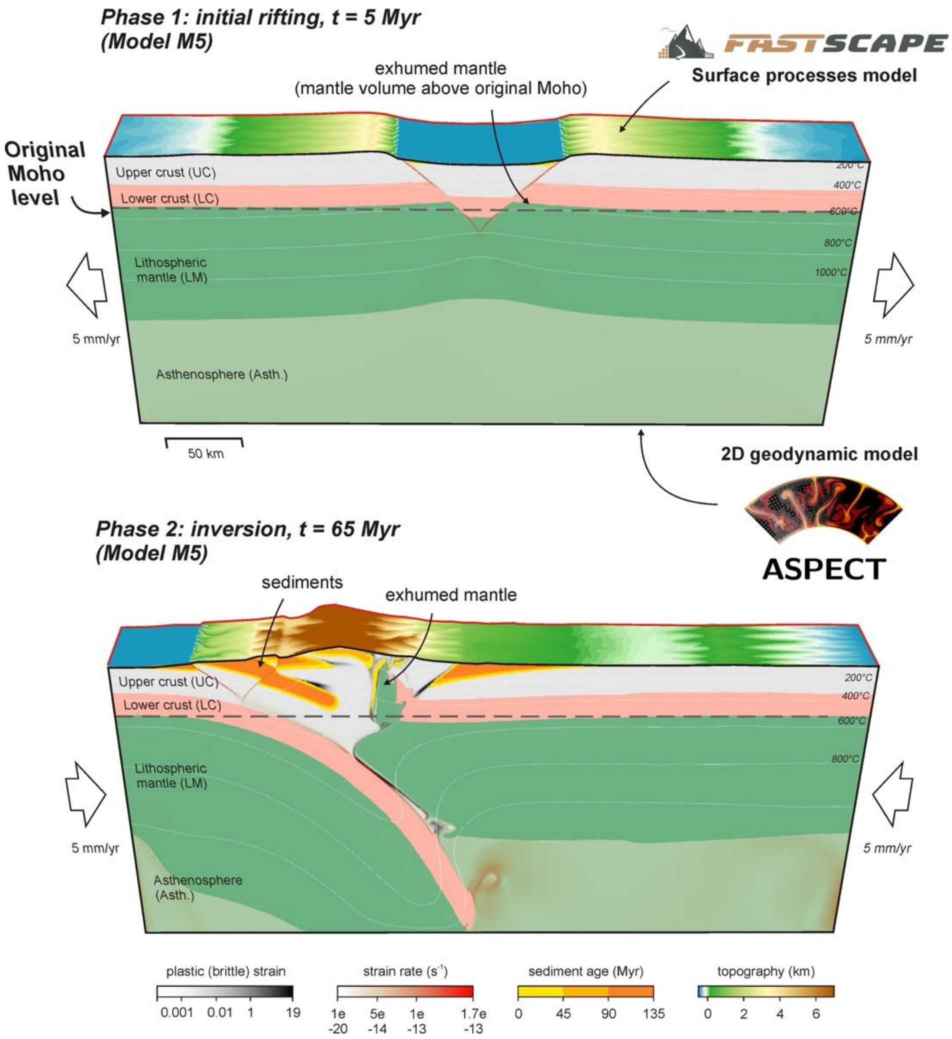

Figure 26 : 3D rendering of one of our rift-inversion models (M5) showing mantle exhumation below the rift basin during initial rifting, (top) and subsequent (asymmetric) inversion involving mantle material being thrusted upwards, on top of the downgoining place (bottom). .

Session 4

ORALS

How do extreme events impact landscape morphology? Benefits of analogue and numerical modelling.

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Abstract

Tectonics and surface processes control the shape of the Earth's surface. Due to climate change, the increase in intensity and frequency of extreme events require a better understanding of the long-term effect of these sudden and intense forcings. Here, we develop a combined analogue and numerical modelling approach. These two methods are complementary. The micrometric grain size of analogue material powders and the associated high-resolution Digital Elevation Model (DEM) counteracts the low resolution of the numerical model. At the same time, the numerical model allows the quantification of poorly constrained parameters of the analogue material. We apply our approach to a part of the Siwaliks range[1,2], located near the Nepal border in the northeast of India. It is well-known that this region is prone to natural disasters such as earthquakes, landslides, and flash floods. However, the impact of these events on the morphological evolution of the Himalayas still needs to be studied.

We perform analogue modelling experiments at the Analogue Modelling Laboratory of Geosciences Montpellier (LMA : https://modelanalogique.gm.univ-montp2.fr/). Following previous studies[3,4,5], we use an experimental device based on a pre-topography consistent with our study area. A misting cycle reproduces the climatic variations, and we simulate thrust faulting by uplifting the upper part of the model. We use a new multi-component granular material, which provides sediment transport and erosion efficiency consistent with processes acting on natural landscapes. The numerical approach is based on Landlab[6,7] (https://landlab.readthedocs.io/en/master/), a Python library simulating hillslope and fluvial processes. We test the effect of sudden and intense tectonic and climatic variations on the long-term landscape evolution with both methods. We perform more than a dozen analogue experiments and several thousand numerical simulations. Last, we process the obtained DEM with the Matlab library TopoToolBox[8] (https://topotoolbox.wordpress.com/references/).

After 50 ka, the signature of extreme tectonic events is tenuous. The drainage network remains mostly unchanged. The main differences are located near the fault scarp, where the fault slip history (creep or stick-slip) generates slope difference: the larger the earthquake, the steeper the slope. The obtained elevation differences are only a few meters for 1 km of shortening. Our results suggest that this signal is associated with fault scarp formation and diffusive degradation. The differences increase over time as the critical slope is exceeded.

Our results also suggest a morphological signature associated with extreme climatic events. Rainfalls favor flash floods affecting landscape evolution. The river incision increases with intense rainfall, leading to valley entrenchment and lasting changes to the drainage network.

This combined approach is promising and can be applied to different natural cases and climatic/tectonic environments. Different outlooks are envisaged. In analog modeling, a change in the composition of the material to increase the incision of rivers. In numerical modeling, an improvement in the tectonic deformation is simulated currently with a tri-shear kinematic model.

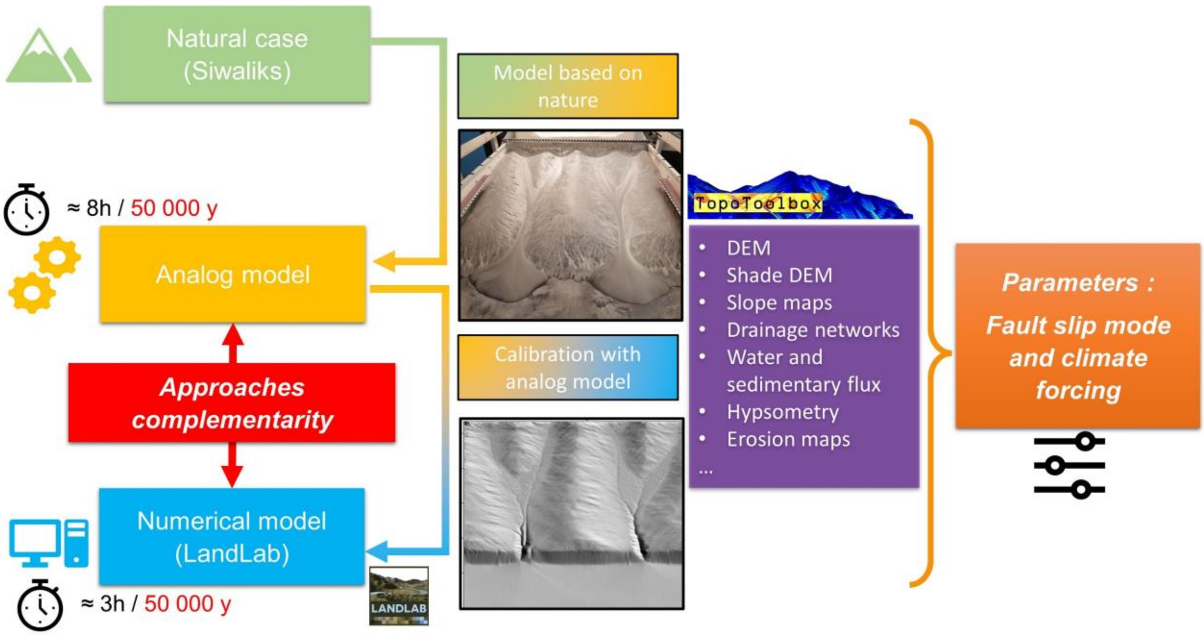

Figure 27 : Work flow of the combined analogue and numerical modelling approach

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GraphFlood: Fast stationary solution for 2D hydrodynamism in Landscapes Evolution Models

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Abstract

In Landscape Evolution Models, methods to simulate hydrology can be broadly categorized into two end-members. First the methods where drainage area proxies hydrology: water is assumed to accumulate downslope and water dischage can be estimated by weighting the area with precipitation rates. The other end member is the direct calculation of the shallow water equation, which explicitly approximates flow depth and discharge. The latter bears a lot more information about the channel geometry and floodplains dynamics, but is by nature limited to short time scales and is computationally expensive to calculate – making its use for long-term LEMs particularly challenging. In this contribution, we present GraphFlood, a fast iterative method computing flow depth and water discharge om digital elevation models (DEM). This new method leverages the Directed Acyclic Graph (DAG) nature of surface topography to iteratively solve for the 2D shallow water equation without the inertia terms. At each iteration, we first use DAGs-related algorithms to efficiently calculate flow accumulation on the hydraulic surface and approximate the discharge input at every location. Then, we use a flow resistance equation, in a manner similar to the Floodos model (Davy et al., 2017), to calculate the outletting discharge. Finally, the divergence of the discharges increments the water height and the process is repeated until reaching a stationary state. This method can be slightly modified to solve flood wave propagation by approximating the input discharge function of the immediate upstream neighbours. Water depths obtained with the stationary solution were validated against an analytical solutions and with the Floodos model for natural DEMs. Compared to previous hydrodynamic models, the main benefits of GraphFlood are (i) its simplicity of implementation - which mainly requires common flow routing and local minima resolver algorithms ; and (ii) its efficiency - as our tests suggested a 10 times speed-up compared to Floodos model (Davy et al., 2017) which was already significantly faster than other hydrodynamic models. While case-dependent, the computational time scales sub-linearly with the number of cells, which makes GraphFlood a suitable solution even for large DEMs (10s millions of cells). We demonstrate the suitability of the method for integrating realistic hydrology in a wide range of topographic analyses (e.g. channel width assessment, floodplain delineation, Flint-Morisawa metrics - Bernard et al., 2022) and in Landscape Evolution Models – even for longer timescales.

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From solid Earth and climate dynamics to physiography; from physiography to life dynamics

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Abstract
The promise of coupling all the Earth's spheres into a single model is fast becoming reality. Climate and geodynamic models have reached a certain maturity, making their predictions suitable for confidently considering the reconstruction of past, present and future physiographies. Landscape evolution models not only calculate elevations, but also a multitude of variables crucial to deciphering the Earth system, such as erosion and sedimentation rates, drainage networks, sediment and freshwater fluxes, and landscape complexity. goSPL (Salles et al., 2020) is among the most advanced LEMs available, and can be conveniently adapted to problems on a regional or global scale.
The physiography, in this sense, sets the stage for the evolution of life. Using contrasted examples in time and space scales (Fig. 1), I will show how LEMs can be used to unravel the history of life. At the Quaternary time scale, we will see how the transience of the landscape set the dynamics of hominin displacement in SE Asia. At the other end of the spectrum, we will evaluate how the dynamics of the global physiography have shaped the long-term patterns of marine and terrestrial life, at a global scale across the entire Phanerozoic eon. Finally, by aiming for higher spatial and temporal resolutions, we will quickly assess how emerging biogeographic and macroecological modeling techniques fit in timely and judiciously with advances in LEM.

Contrasting surface evolution during structural inversion of rifted basins: 3D coupled geodynamical and surface processes models

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Abstract
The structural inversion of rifted basins is generally associated with surface uplift and erosion of the exhuming syn-rift sedimentary strata, while the uplift rates and patterns are primarily governed by variable convergence rates and inherited crustal or lithospheric structures. However, contrasting observational data from young continental rift basins infer that the surface response to basin inversion often leads to basin-wide subsidence and widespread syn-tectonic sedimentation, like in the Pannonian Basin or Tyrrhenian Sea.

In this study, we conducted a series of high resolution 3D numerical models using the I3ELVIS-FDSPM numerical code (Gerya, 2013; Munch et al., 2022) to investigate the controlling processes of the contrasting uplift and subsidence patterns during basin inversion. This code handles visco-plastic rheologies, staggered finite differences and marker-in-cell techniques to solve the mass, momentum and energy conservation equations for incompressible media. Our simulations included the preceding continental rifting phase to account for structural and thermal inheritance, while two-way coupling between the thermo-mechanical and surface processes models allowed for the joint analysis of crustal tectonics, mantle processes, erosion and sedimentation, and topographic evolution.

Our results show that the surface evolution is not solely linked to the underlying crustal stress or strain patterns, instead it reflects the balance between several competing tectonic, mantle-driven geodynamic and climate-controlled sedimentary processes. The dynamic interplay between the tectonic-induced crustal deformation, post-rift thermal cooling of the inherited lithosphere and the intensity of surface processes influences strain localization, determines the tectonic style of inversion and exerts control on differential vertical movements. Relatively high convergence rates (i.e. 2 cm/yr) can result in the growth of fold and thrust belts with exhuming orogenic cores and subsiding foreland basins, whereas in case of low convergence rates (i.e. 2 mm/yr), thermal subsidence of the inherited lithosphere may hinder the effects of localized contractional deformation, leading to basin-wide subsidence.

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Reconstructing landscapes: an adjoint model of the Stream Power advection-diffusion equation

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Abstract

The majority of Landscape Evolution Models (LEMs) commonly used in geomorphology are forward models, wherein the model parameters are validated retrospectively by comparing the results to observations. These models typically possess a multitude of parameters, such as erodibility coefficient, precipitation rate, diffusion coefficient, initial topography, and uplift rate. However, determining the sensitivity of model outcomes to each parameter is challenging. In the past, inverse models using neighborhood algorithms have been employed to constrain some parameters of the Stream Power Law (Croissant and Braun, 2014). Another powerful tool for estimating model sensitivity and inverting model parameters is the adjoint method. Despite its potential, adjoint models have rarely been applied in geomorphology, with few exceptions in related fields like hydrodynamics (Clare et al., 2022) or turbidity currents modeling (Parkinson et al., 2017). Landscape evolution models often combine the Stream Power Law for fluvial erosion with a diffusion law for hillslope processes, hence resembling a diffusion-advection equation (Braun and Willett, 2013; Simpson and Schlunegger, 2003). However, due to the discretization of the topographic grid and water routing algorithms, the drainage direction is not always parallel to the topographic gradient, as it should be. Consequently, the treatment of the topographic "slope" varies between the advective and diffusive terms. Certain routing algorithms, such as the D_∞ method (Tarboton, 1997), perform better than others by distributing the water flux among nodes with links oriented closer to the gradient direction. In this study, we employ the firedrake and firedrake-adjoint finite element tools, coupled with the D_∞ water routing algorithm, to represent landscape evolution as a true diffusion-advection equation. First, we apply this approach to various synthetic forward models and treat them as "observations" to assess the feasibility of minimizing unknown parameters like the diffusion coefficient, erodibility coefficient, source (uplift) term, and initial topographic conditions.

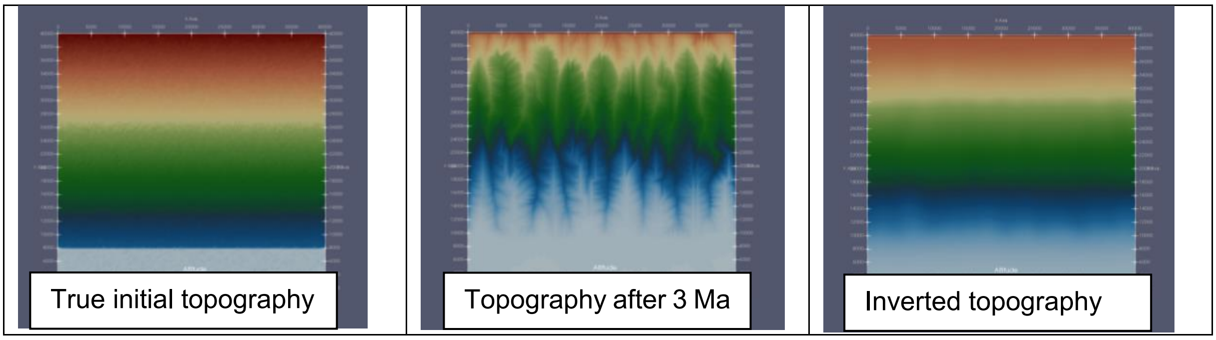

Figure 28 : Left: "true" initial conditions for a scarp degradation model; middle: topography after 3 Ma of landscape evolution; right: inverted initial conditions using the adjoint method. Not quite perfect (because of diffusion), but a large part of the eroded relief can be reconstructed.

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Tectonics or Surface Processes: The Beaumont number of mountain belts on Earth

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Abstract

To first order collisional mountain belts grow by crustal thickening and gain elevated topography through isostatic compensation. Elevated topography is the main locus of precipitation, and the ensuing flow of water redistributes mass through erosion and deposition, counteracts orogenic growth, shapes the appearance of the landscape, and most importantly provides a feedback-loop between climate, surface processes, and tectonics. However, the factors controlling height, width, and longevity in collisional orogens remain debated. Here, we use a tight coupling between a landscape evolution model (FastScape) and a thermo-mechanically coupled mantle-scale tectonic model (Fantom) to investigate mountain belt growth. Based on several end-member models and the new non-dimensional Beaumont number, *Bm*, we provide a quantitative measure of the interaction between surface processes and tectonics, and define three end-member orogen types: Type 1, non-steady state, strength controlled (Bm > 0.5); Type 2, flux steady state, strength controlled (Bm ≈ 0.4−0.5); and Type 3, flux steady state, erosion controlled (Bm < 0.4). *Bm* is defined as the ratio between the critical non-dimensional number determining tectonics and the critical non-dimensional number determining surface process efficiency, and can be assessed simply by knowing a mountain belt's convergence rate, height, width, first order shortening distribution, and widening rate, without complex measurements or assumptions. The Beaumont number of an orogen provides information about its crustal strength and average fluvial erodibility and gives insight into the factors controlling orogen type. Applying *Bm* to the Southern Alps of New Zealand (SANZ), Taiwan, Himalaya-Tibet, Tian Shan, Zagros, European Alps, Pyrenees, and Northern and Central Andes, we find that only the Southern Alps of New Zealand are erosion limited and at flux steady state (*Bm* < *0.4*, Type 3), Taiwan is likely strength limited and at flux steady state (*Bm* ≈ 0.4-0.5, Type 2), while all other orogens are strength limited and do not reach steady state (*Bm* > 0.5, Type 1). We analyse correlations among the main parameters of *Bm* and find that the ratio of shortening rate over fluvial erodibility determines *Bm*, that fluvial erodibility correlates with shortening rate and precipitation, and that crustal strength has no significant influence on orogen type. Our analysis suggests that most present-day collisional orogens are strength-limited and at non-steady state, have a natural tendency towards moderate *Bm* values in the range [1-3], and a tectonic style dominated by tectonics and modified by climatic conditions. The results presented here provide a simple unifying framework quantifying how surface processes and tectonics control the evolution of topography of mountain belts on Earth.

POSTERS

Fingering enhanced by particle-size polydispersity in granular flows

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Abstract
The origin and dynamics of subparallel longitudinal ridges observed at the surface of debris or rock avalanches and landslides remain poorly studied. These ridges resemble those observed in experiments where coarse-rich margins of granular fingers coalesce. In this context, we did experiments on dry granular matter flowing down an inclined plane in order to better understand the causes of fingering. We used different mixtures of glass beads with Gaussian particle-size distributions of 100 – 800 µm (more-polydisperse) to 400 – 500 µm (less-polydisperse). During an experiment, the material was suddenly released from a double gate reservoir on the inclined plane, which was previously roughened with glued 400-500 µm-diameter glass beads. For a given particle-size range, we carried out experiments by varying the gate opening and the slope angle of the inclined plane. Once the flow propagated down slope, the coarse particles are segregated towards the surface and accumulated at the flow front, therefore inducing instabilities and development of granular fingers.
We measured the flow front kinematics as well as the morphometric parameters of the deposits (distance of onset of fingering, and fingers length, width, thickness and distance between axes). We observed granular fingering in all experiments. However, with more-polydisperse mixtures onset of fingering occurred at shorter distance and the flows propagated slower compared to less-polydisperse mixtures (Fig. 1). This shows that particle size segregation controls both onset of fingering and the flow front velocity. Preliminary observations also revealed a slight positive correlation of finger width and distance between finger axes with increasing polydispersity. These experiments suggest that particle-size polydispersity is essential for controlling the characteristics of granular fingering in debris and rock avalanches.

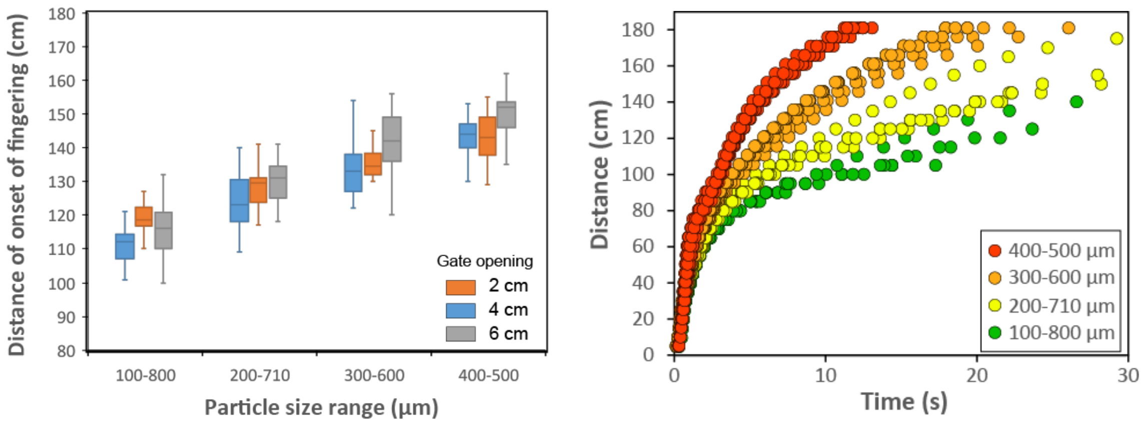

Figure 29 : Kinematic data of the front of flows of different particle-size mixtures.

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From flood to turbiditic events: reduced complexity modelling of the Var source-to-sink system

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Abstract

Turbidity currents are a form of gravity-driven flow that occurs in marine environments. These currents contain a low volumetric percentage of sediment but are very important in transporting particles from the coastal environments to the deep marine. These particles can be of organic matter, leading to blooms in life at the margins of the oceans. The particles can also be microplastics, where turbidity currents transport microplastics to their eventual deposition within mixed contourite drift deposits. Turbidity currents could therefore be a conveyor belt of pollutants to the marine environment. In the Var sediment routing system, southern France, there is a history of turbidity currents formed by submarine landslides and flooding of the Var River. In the year 2006 there was continuous monitoring of the marine section, where four turbidity current events were recorded. To explore the connectivity between the terrestrial source to marine sink we linked two reduced complexity models of sediment transport and landscape change. The landscape evolution model Caesar-Lisflood (Coulthard et al. 2013) was used to model discharge and sediment yield. The flow of turbidity currents and their deposition were modelled with CATS (Teles et al. 2016). From calibration of the two models against observations of discharge and suspended sediment in the Var River system we find that in 2006 two rainfall events would have led to hyperpycnal flow and the creation of turbidity currents. These two events match well with two of the four recorded events. Focusing on the largest event we find that the source pulse of sediment from the terrestrial environment is short lived, less than half a day, but contains a significant quantity of fine particles. From the sink end, around 10^5 m^3 of suspended sediment is needed to match the flow event duration and sedimentary deposits. From the source end, the best fit model releases around 10^5 m^3 of suspended sediment, and this is within the same range as estimates from sediment traps within the Var canyon system. Given the simplifying assumptions behind both models, we find that the source-to-sink comparison is surprisingly good. This study demonstrates the potential of applying reduced complexity models to estimating the transport of particulate pollution from the terrestrial to marine environment, and the inversion of turbidite deposition to understand the full dynamic range sediment routing system response to catastrophic flooding.

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Evaluating the uplift history of the Troodos ophiolite in Cyprus with numerical modelling and field analysis of mass transfer deposits.

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Abstract

Although the oceanic crust of the Cyprus ophiolite once formed below sea-level (e.g. Moores & Robinson, 1984; Mukasa & Ludden, 1987), its mantle rocks are now exposed at 2 km altitude. These rocks have thus experienced a vertical motion between 8 km and 18 km (Evans et al., 2021). Processes that occur during obduction that can accommodate vertical motion are 1) thickening and uplift of the overriding plate at the subduction front/forearc (Fernández-Blanco et al., 2020), 2) isostatic equilibration after obduction ceases, 3) serpentinisation of the mantle at the subduction interface or below the overriding plate (Morag et al., 2016; Ring & Pantazides, 2019) and 4) meteoric serpentinisation of exposed mantle material (Evans & Teagle, 2021).

In this project we combine numerical modelling with field work to quantify the amount of uplift related to each process and the associated uplift rates. We use the 2D numerical code FLAMAR to simulate the first phases of the subduction/obduction process with varying crustal structures (i.e. continental versus oceanic crust (Khair & Tsokas, 1999)) and rheologies for the subduction contact. We complement this with a field analysis of the various mass transfer deposits found on the north flank of the Troodos mountains to quantify the recent uplift rates. Our model results show that the final uplift after 10 Myr varies with the type of subducting lithosphere: an uplift of between 6.5 km and 7.5 km is predicted for subducting oceanic-continental lithosphere, while subduction of oceanic lithosphere results in 3.5 to 8.0 km uplift. When varying the amount of serpentinite, we observe that thicker serpentinite bodies generally result in more uplift compared to thinner serpentinite bodies, whereas less dense serpentinite bodies also generally lead to more uplift compared to denser serpentinite bodies.

Since the total amount of uplift predicted by Evans et al. (2021) cannot completely be explained by our numerical models, not enough uplift is generated with early obduction processes, we complemented our analysis with field work. Our field analysis of mass transfer deposits (MTD) shows an increasingly mafic content of clasts with increasing distance from the Troodos and decreasing age of the MTDs. Uplift rates since 74.0 Ma vary between 0.1 to 8.7 km/Myr with a significant increase in uplift rate (>4km/Myr) between 2.5 Ma and 2.0 Ma followed by a decrease in uplift rates of (<0.5 km/Myr) until 0.01 Ma.

From these results, we propose that most of the uplift of the Troodos Mountains on Cyprus occurs during the early phases of obduction, but the highest uplift rates occur since 2.5 Ma.

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Micro-properties of a new analog material (MAT-V) dedicated to geomorphic Experiments

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Abstract
The experimental study of interactions between Crustal deformation and Surface Processes is an ambitious challenge, implying the development of analog materials capable of jointly simulating geomorphological and geological deformation processes. About ten years ago, we developed a first analog material (MAT-IV) meeting the required criteria to study Tectonic-Erosion-Sedimentation couplings in active mountain forelands (1, 2). This material has since been used for 5 thesis carried out at Géosciences Montpellier (e.g. 3, 4, 5), revealing its potentials and limitations. Recently, several international teams, from Italy and China, have begun using analog materials based on the MAT-IV composition (6, 7 and other references from these groups). These works confirmed our previous results, provided new data on the properties of MAT-IV, and interesting applications for the study of natural cases. Over the past two years, we have improved and adapted the physical and mechanical properties of the MAT-IV analog material to extend its field of application. Our objective was to study the impact of extreme events (earthquakes, climate change, gravity instabilities, etc.) on the geomorphology of continents, but also on their margins, where sea-land geomorphological couplings still need to be better understood. This first step was successfully achieved by significantly reducing the particle size of the granular materials composing the MAT-IV and adding a new compound; Ponce powder. Its micro-vesicular structure enables a greater quantity of water to be sequestered in the material without altering its low permeability. The morphometric analyses, carried out on a dozen experiments, showed that the new material, called MAT-V, enables particularly realistic morphologies to be reproduced. What remained to be done was a detailed analysis of MAT-V properties, in particular, the characterization at the microscopic scale of its physical and mechanical properties. To do so, we complete the macroscopic measurements (particle size spectra, permeability, porosity, bulk mechanical properties, etc.) by developing a dedicated micro-penetrometer, in collaboration with the Laboratoire de Mécanique et Génie Civil of Montpellier (LMGC). We used this device to better characterize the rheology and texturometry of the critical zone, i.e. the thin layer on the surface of the model, where the material loses its cohesion and passes from a solid state to a fluidized one, triggering particle erosion and transport. First results will be presented.

Figure 1 : Detailed view of an analog model surface during a geomorphological experiment including reverse faulting.

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Controls on Island Morphologic Evolution

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Abstract

Islands are interesting geomorphic features because they possess a well defined base level. Non-volcanic islands, in particular, are the product of rifting of a small continental fragment such that they start their geomorphic evolution as a more or less elevated flat plateau. After tens of millions of years of evolution, some islands, such as Madagascar, still present a pi-shaped form composed of large watersheds on top of a central plateau surrounded by smaller ones that connect the plateau to the coastline. Other islands, such as Sri Lanka have a more conical or lambda-shape composed of a radial distribution of basins directly connecting the island summit to the coastline. Here we investigate the conditions that lead to the transformation of an initially plateau-shape island to either a pi- or lambda-shape by using a Landscape Evolution Model solving the Stream Power Law and talking into account flexural isostasy.

We find that to maintain a pi-shape, an island must fulfil two criteria: firstly, its size (extent) must be constrained by the underlying effective elastic thickness (EET), such that isostatic rebound is greatest along the island margins than its center, and, secondly, it must be subjected to limited erosion as all islands ultimately erode away to reach a lambda-shape. We introduce a morphometric index that allows to discriminate between the two types of morphologies and show how it evolves through time as a function of both EET and erodibility.

Constraining the time evolution of the morphology of an island is important to study the evolution of its bio-diversity, which is known to be strongly affected by the distribution of and connectivity between watersheds. Our finding implies that the micro-endemism that characterises Madagascar is linked to the strength of the underlying lithosphere.

Analogue modeling of the kinematic evolution of fold-and-thrust belts under various syntectonic sedimentation rates, shallow décollement properties and basement inherited structure configurations

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Abstract

Structural deformation of fold-and-thrust belts is influenced by the properties of *décollements* (number, rheology, thickness, etc.), the presence of inherited structures in the basement as well as the amount of syntectonic sedimentation, among others. Although the effect of each of these parameters has been well constrained with a series of numerical and experimental works in the literature, few sandbox models consider all these parameters together, and particularly investigate the effect of their lateral variation.

To gain insight on this issue, we carried out several 3-D sandbox models and investigated the effect of increasing syntectonic sedimentation rate on the kinematic evolution of fold-and-thrust systems. Models contain a basal brittle detachment layer and a shallow detachment layer that changed from a brittle to a viscous domain along the model strike. The effect of basement high and syntectonic sedimentation are also considered meanwhile. Model results are compared with field data from the Wushi-Kuqa fold-and-thrust belt (FTB) in Southern Tianshan, Tarim basin, Central Asia.

Natural example

The Wushi-Kuqa is one of the south-vergent FTBs that developed in the southern Tian Shan orogen, within the Tarim basin (Fig. 1). The Wushi (W) and Kuqa (E) FTBs are separated by the Kalayuergun right-lateral strike-slip fault. According to geological maps and drilling data, the shallow *décollement* involved in the deformation of both FTBs changes laterally in rheological properties. The Neogene Jidike mudstones in the Wushi FTB (W) are considered as frictional, whereas the Paleogene evaporites in the Kuqa FTB (E) are viscous. This leads to different deformation styles along the strike, single fault and fold to the W, and salt nappe and folds to the E.

In both FTB, two basement high structures, the Wensu (to the W) and Xiqiu (to the E) basement high, have been interpreted from seismic profiles and affected the *décollement* continuity and thickness (Fig. 1.c). Thus, the Jidike mudstones in the Wushi FTB decreases in thickness toward the south (Line-1, Fig. 1.c). In the Kuqa FTB, the Xiqiu basement high is closer to the mountain front to the west than to the east. Its arcuate shape is likely responsible for the similar shape of the Qiulitage belt (Line-2 and 3, Fig. 1.c).

Re-examining marine terraces: the topographic signature of rock uplift and wave erosion in numerical landscapes.

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Abstract
The coastal landscapes of active margins are shaped by rock uplift progressively moving formerly submerged land out of the sea — in part directly linked to the pattern of seismic locking of the megathrust — and by the cumulative work of wave erosion during the glacial-interglacial sea level seesaw. A fraction of the earthquake cycle can usually be measured with geodetic methods. A geomorphological approach is needed to provide a 10–100 kyr geological context to the measured deformation. Marine terraces are typically used to constrain deformation rates at these timescales. Commonly, the complex landscape at active coasts has been reduced to a binary dataset terrace/no terrace assuming that successive marine terraces correspond to successive sea level high stands, a hypothesis that was never rigorously tested.
In this contribution, we test four different numerical models for marine terrace creation in a unified framework. The models simulate wave erosion by 1) platform beveling and cliff retreat (Anderson et al., 1999), 2) focused erosion in the surf zone (Walkden and Hall, 2005), 3) dissipation of wave energy and deposition of eroded material (Noda et al., 2018), as well as 4) a constant rate of cliff retreat at sea level.
Each model successfully produces a classical terraced geometry but they are all different despite identical wave and rock uplift conditions. Importantly, in all models, the total duration of sea-level occupation matters for the final elevation of terraces and can separate them from the elevation of sealevel high stands. The output of the models is best inspected with a hypsometric curve that can be compared to a “sea-level occupation map” (Malatesta et al., 2022). Our approach is an important first step towards a calibration of physically reasonable numerical models and their eventual use for quantitative predictions.

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Figure 1 : Distribution of marine terraces on a numerical coastline using the model proposed by Anderson et al. (1999). The elevation of terraces is dissociated from marine high stands.

Erosion laws in analogue models

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Abstract
The presence of a strong interaction between tectonic deformation and surface processes is widely recognized. Still, the nature of this interaction is difficult to unravel and quantify. In the last decades, analogue landscape evolution models have been widely implemented and employed in different tectonic settings, to complement field campaign studies. Since the aim of these analogue models is to help the interpretation of data coming from natural prototypes, it is important to test how well empirical erosional laws built upon natural landscapes, explain analogue model behavior. We perform a series of experiments for a straight interpretation of the relationship between applied boundary conditions and analogue landscape evolution. The selected analogue material is composed of 40 wt.% of silica powder, 40 wt.% of glass microbeads, and 20 wt.% of PVC powder. The analogue material fills a rectangular box (30×35×5 cm3) placed over a reclined table. Over the box, a series of sprinklers generate a dense mist (i.e., rainfall) that triggers surface processes. The boundary conditions applied to the models are the imposed slope of the reclined table and the rainfall rate. We test three rainfall rates (9, 22, and 70 mm h-1) and three imposed slopes (10, 15, and 20°), analyzing how the combination of these boundary conditions results in different landscape metrics (e.g., basins length, basins width, drainage area, channel slope, erosional efficiency) and erosion rates. Results show that in models affected by high rainfall rates (70 mm h-1), the implemented analogue material is characterized almost no channelization, and erosion acts uniformly and diffusively over the models' surface. Lower rainfall rates (9, 22 mm h-1) allow more discrete channelization instead. On the other hand, as expected, the imposed slope controls the amount of incision, so that the volumes of material removed by erosion increase moving from 10° to 20°. However, even if the maximum incision is generally controlled by the slope, the coupling with rainfall rate tunes the effectiveness of erosion. In this work we compare the imposed boundary conditions with the corresponding erosion rates, using geomorphic markers and landscape metrics to define if and how natural erosional laws apply to analogue landscape evolution models. Finally, we interpret results coming from analogue landscapes of convergent settings in the frame of these new findings.

DAY 3

Session 5

ORALS

Physics-based and probabilistic modelling of reservoirs' induced seismicity; where we stand and where to go

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Abstract

Induced seismicity, that is, seismicity associated with subsurface operations, has been reported over the last 50 years in different sites world-wide. The knowledge gained from those empirical case studies have helped to pinpoint the main co-factors leading to fault instability, being related to the tectonic stress state of the reservoir, its local geology, induced pore pressure and thermo-chemical changes, local stress redistribution from event-event interactions and feedback from (a)seimic slip on faults. Despite the progress made, forecasting of the induced seismic risk during each stage of a reservoir project remains a challenge. Studies relying on classical earthquake catalogue parameters, which are fed into advanced traffic light system (ATLs) have been partly successful in linking the seismic risk to operational parameters. However, these datasets are generally „biased" toward more energetic sequences (i.e. few high magnitude events) and are limited by the highly variable quality of operational data available for each particular site. A growing number of field studies (e.g. the Mw5.5 Pohang earthquake, the Mw3.9 Strasbourg earthquake) have been challenging the general validity of usually adopted log-linear frequency-magnitude correlation statistics, thereby calling for a critical revision of our current understanding of the dynamics leading to induced earthquakes.

In this contribution, I will discuss how integrating information derived from physics-based quantitative models into existing stochastic frameworks can help to overcome the shortcomings of purely statistical approaches to induced seismicity.

I will dedicate a first part of this contribution to showcase via diverse field and laboratory examples how physics-based models can provide effective to improve our understanding of structure-property relationships under transient loading and across-scale, and to discriminate intrinsic spatio-temporal footprints of the driving dynamics leading to and/or triggering induced earthquakes including expected magnitudes, their spatial and temporal distribution with respect to site-specific conditions and operational parameters. I will then open a second chapter where I will discuss how front ending these software solutions to existing state-of-the-art HPC platforms can enable near real-time model calibration and to additionally explore the sensitivity in terms of either reservoir performance and/or induced seismicity to a wide spectrum of reservoir parameters therefore outperforming classical forecasting models based on field data alone. I will then conclude with an open discussion on how these hybrid approaches can benefit from novel methods from the field of Artificial Intelligence and machine learning and where existing knowledge gaps remain.

Modeling the Shape and Velocity of Magmatic Intrusions, a New Numerical Approach

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Abstract

Dikes are fractures filled with magma that propagate through the brittle crust. Understanding the physics of the diking process is essential for mitigating the volcanic hazards associated with the formation of new eruptive fissures on the surface. Existing physics-based models often focus on either the fracturing of the host rock (Dahm, 2000a; Davis et al., 2020; Heimisson et al., 2015; Maccaferri et al., 2010, 2011) or the viscous flow of magma (Mériaux & Jaupart, 1998; Pinel & Jaupart, 2000; Traversa et al., 2010) as the dominant energy dissipation mechanisms during dike propagation. In this study, we present a numerical model that effectively captures the interaction between fracturing at the crack tip and the transport of viscous fluid. Built with the boundary element technique, we discretize the dike using a finite number of dislocation elements (Figure 1a). Our model enables the computation of crack shape and velocity as the fluid-filled crack grows, taking into account the viscosity of the fluid. The model considers the viscous pressure drop induced by fluid flow along the crack walls, which in turn modifies the crack shape. By incorporating the energy conservation equation, we can determine the crack growth velocity, assuming that brittle fracturing and viscous flow are the primary energy dissipation processes. Using a parameter range that represents typical magmatic intrusions, we obtain crack shapes displaying typical characteristics, including a tear-drop head and an open tail that depend on rock rigidity, magma viscosity, and buoyancy. We validate our model by comparing the results with relevant analytical solutions available in literature. Furthermore, we apply the model to interpret experimental results involving the propagation of viscous fluid-filled cracks in gelatin tanks, serving as analogs for magmatic intrusions within the crust. Our findings demonstrate that viscous forces significantly contribute to the energy dissipated during the propagation of magmatic dikes. Additionally, we apply our numerical model to the 1998 intrusion at Piton de la Fournaise on La Réunion Island (Figure 1b). By adjusting the numerical velocity to match the observed migration of volcano-tectonic events (Battaglia et al., 2005), we provide ranges for dike lengths and openings. Interestingly, we observe that the range of fracture toughness obtained from our numerical simulations aligns closely with field estimates rather than laboratory values, in agreement with Rivalta et al. (2015). Overall, our study contributes valuable insights into the physics of dike propagation and the role of viscous forces in energy dissipation. The combination of fracturing and viscous flow in our numerical model provides a more comprehensive understanding of magmatic dike behavior, advancing our ability to assess and mitigate volcanic hazards.

Laboratory modelling of magma-fault interactions

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Abstract
The dynamics of magma transport and how the host rock affects intrusion geometries are important aspects for understanding volcanic plumbing systems in the upper crust. It is commonly acknowledged, that magma emplacement can be influenced by or interact with pre-existing weaknesses like fractures or faults. Even though this assumption is well established in the geoscience community, very few direct observations of magma emplaced within faults have been published (e.g., Spacapan et al., 2016), few models of magma emplacement accounting for faults exist (Le Corvec et al., 2013), and the conditions under which magma-fault interactions occur are not yet well understood (Paterson and Schmidt, 1999). This contribution describes innovative laboratory experiments to investigate how pre-existing strike-slip faults control the emplacement of magma. Our models simulated brittle crusts of variable cohesions and angles of friction using dry mixtures of fine-grained silica flour and micro-glass beads (Abdelmalak et al., 2016). We also investigated the effect of magma viscosity by performing experimental series with low-viscosity (molten vegetable oil) and high-viscosity (glucose syrup) liquids. The models consisted of (1) model deformation by strike-slip faulting, followed by (2) liquid injection at the base of the models at constant flow rate. Photogrammetry was used to monitor surface deformation and assess how magma intrusions were using or reactivating the pre-existing faults (Galland et al., 2016).
In high-cohesion models, segments of the intrusions form dykes that clearly follow fault segments. In these experiments, the dyke emplacement did not generate new structures. In contrast, in low-cohesion models, intrusions were subcircular laccoliths that grew by prominent doming of the model crust. The doming was accommodated by newly formed structures that were almost not affected by pre-existing strike-slip faults. Models of intermediate cohesions exhibit hybrid behaviours where the intrusions both generated new fractures and partly followed pre-existing fault segments. Models with both the low- and high-viscosity model magmas exhibited similar trends, but the hybrid experiments occur for experiments with higher cohesions when the magma was of high-viscosity.
These models demonstrate that the structural control of pre-existing faults on magma emplacement is not systematic. Magma-fault interactions are most prominent in brittle rocks of high-cohesion, but becomes negligible in rocks of low-cohesion. Our models suggest that magma-fault interactions are less prominent for high-viscosity magmas, however magma viscosity seems to play a less important role than rock cohesion.

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Using Julia to simulate geodynamic and magmatic processes

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Abstract
Active magmatic systems can be studied with various geophysical methods, which gives an idea about the present-day structure of the system (and perhaps how that relates to recent eruptions). Petrological/geochemical data on erupted rocks tell us something about past eruptions. How these are linked to the currently active system is often unclear. Moreover, the structure of the presently active system is often unclear, because in many cases geophysical data sets are non-unique and interpreted in isolation rather than jointly. Whereas seismic Vs or Vp/Vs body-wave tomography may give an idea where partial melt is located, but it is often unclear whether the resulting interpretation is consistent with other data such as uplift rates or gravity anomalies.

If we, as a community, want to understand the *dynamics* of magmatic systems, we will have to move from a qualitative interpretation of the various datasets to a quantitative understanding, which takes the physics of the system into account and allows interpreting both geophysical and geological data in a consistent manner. In climate science, a similar venture started over 5 decades ago with the generation of the first quantitative climate models, which has been indispensable in our understanding of the ongoing and future climate change. A similar effort for magmatic systems does not yet exist, even when individual processes can already be described with numerical models.

The aim of this presentation is to give an overview of recent progress towards a physics-based understanding of magmatic systems, as well as show how the Julia scientific programming language can greatly simplify our life in doing so. We have worked on various aspects of this, most of which are already available as open-source software packages:

- We developed a new thermodynamic Gibbs energy minimization code, MAGEMin and its Julia interface MAGEMin_C, which can compute the mineralogy, melt content, and chemistry as well as Vp,Vs velocities, as a function of temperature, pressure and bulk rock chemistry. The requirement is that well-calibrated thermodynamic melting models exists, which is the case for (hydrous) arc magmas, pelite melting, but not yet for the Eifel.
- We developed a Julia package, GeophysicalModelGenerator.jl, which allows to quickly collect different geophysical/geological datasets for any location in the Earth and plot/interpret them in a consistent manner. Ideally, such data is available in digital format, but since this is not always the case, one can also plot screenshots from published papers in their 3D context. The same tool can be used to create 3D numerical model setups for geodynamic codes, or to compute gravity anomalies.
- We have developed an (adjoint-based) geodynamic inverse modelling approach and incorporated that in our 3D parallel geodynamics code, LaMEM. This has been employed to better understand the (3D) structure of the magmatic systems in Yellowstone and the Puna area.
- To make it easier for users to perform 2D/3D geodynamic simulations, we provide the Julia package LaMEM.jl which comes with precompiled versions of LaMEM which run in parallel on all modern operating systems. With this, you can start simulations from Julia and read LaMEM timesteps back into Julia for further processing. The only thing users need to do is write “add LaMEM” in the Julia package manager.
- We have created a package that builds graphical user interfaces on top of LaMEM simulations. With InteractiveGeodynamics.jl you can

- Many of the difficulties in writing new geodynamic codes comes from the complex constitutive relationships, which are usually point-wise calculations that are the same for finite element and finite difference calculations. To make it easier to write new codes, we created a package, GeoParams.jl that does this as well as automatic non-dimensionalisation of input material parameters. This package can be used to create deformation maps or plot 1D strength envelops for the lithosphere, useful in teaching. Yet, he exact same routines can also be implemented as part of a 2D or 3D forward code that may even run on GPUs. As these material parameters only have to be implemented once, it significantly simplifies developing new codes, and reduces the risk that errors are introduced when reimplementing the same material properties in different codes.
- We are working on various pseudotransient solvers to solve 2D or 3D geodynamic problems on (massively parallel) GPU systems, which is available under JustRelax.jl.
- We have developed a Julia package, MagmaThermoKinematics.jl, to simulate the thermal evolution of magmatic systems resulting from intruding sills and dikes in the crust. Zircon ages and age distributions can be computed from such models and compared with geochemical constraints of a region. Since the programming language Julia allows for composable software packages, we can combine it in a straightforward manner with the above-mentioned packages to incorporate, for example, phase diagrams specifically tuned to a region, take geological or geophysical constraints into account in the model setup, or compute synthetic Vs, Vp velocity models from the forward simulations. We have benchmarked this with 2 other packages (Schmitt et al., 2023).
- Ongoing work focusses on taking more physics into account in such simulations, for example by allowing the spontaneous formation of both mode-1 (dikes) and mode-2 (faults) failure in the simulations, or to quantify the effect of thermal stresses and volume changes on the magmatic system (Kiss et al. 2023).

Whereas we are obviously still quite a bit removed from having a fully integrated (predictive?) magmatic system model, the above steps nevertheless show that there has been quite some progress in this direction. Likewise, it has become significantly easier to create model setups and develop new geodynamic codes. Give it a try!

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Two-phase flow modelling of melt migration during continental extension: from rifting to spreading

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Two-phase flow, a system where Stokes flow and Darcy flow are coupled, is of great importance in the Earth's interior, such as in subduction zones, mid-ocean ridges, and hotspots. While the governing equations of the coupled two-phase system have been proposed long time ago, it remains challenging to solve the two-phase equations accurately in the zero-porosity limit, for example when melt is fully frozen below solidus temperature. In this limit, the Darcy equation is redundant such that the coupled system becomes under-determined. Here we propose a new formulation of the two-phase system and present a robust finite-element implementation, which can successfully solve for the system where zero and non-zero porosity domains are both present. By integrating the new formulation into our existing 2-D finite-element code FANTOM, we present a fully coupled hydro-thermo-mechanical model that combines tectonic extension, decompression melting, and two-phase melt migration. Results show that the cold lithosphere with zero porosity forms a non-permeable barrier. Melt migrates upward until it reaches the base of the lithosphere, where it is deflected towards ridge axis. We demonstrate that this permeability barrier effect is best resolved in our new-generation two-phase flow model. We explore as well feedback of mantle melting on continental rifting and mid oceanic ridge spreading dynamics through coupling with viscous and brittle rheologies.

Dynamics of dike propagation and magma chamber formation

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Abstract

Magma ascending through the Earth's crust via dike propagation undergoes complex physical and chemical transformations induced by decompression and cooling. We present a mathematical model of dike propagation for silicic magmas considering the presence of multiple volatile species (H_2O and CO_2), bubble growth, heat advection and loss, crystallization and latent heat release. The model predicts short ascent times (hours to days), with a large increase in viscosity at shallow depth, leading to stagnation and solidification of the dike. Higher initial water content, temperature, and larger mass of the magma in the dike promote faster propagation and shallower arrest. Volatile loss from ascending magma remains small, providing a potential mechanism for transfer of volatiles to intrusions associated with porphyry ore deposits.

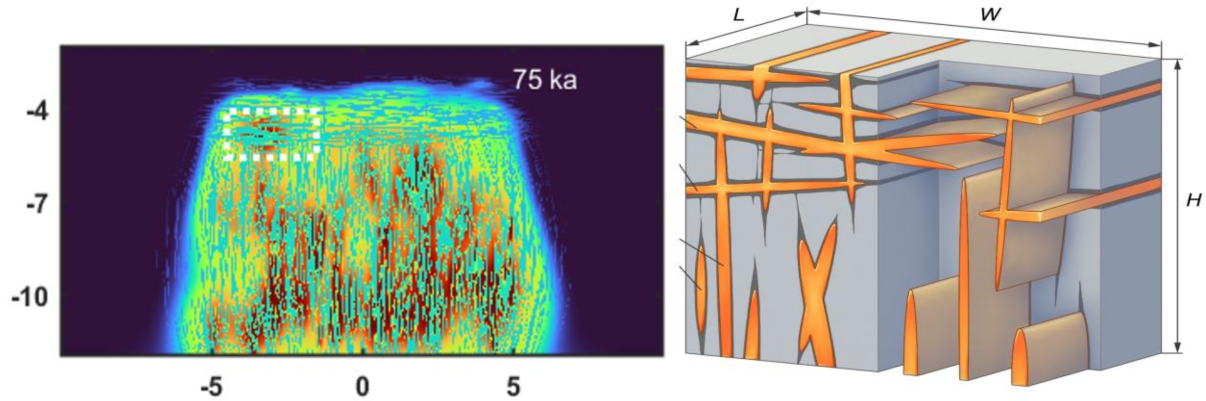

Figure 30. Conceptual model and melt fraction distribution.

We present a 2D thermo-elastic model of a magma body formation in a granitic crust by injection of rhyolitic or basaltic dikes and sills. Elastic analytical solutions enable the computation of rock displacement in response to magma intrusion and evacuation during volcanic eruptions. Phase diagrams for magma and rocks govern melting/crystallization behavior. Calculated temperature histories are used to predict zircon crystallization/dissolution and their ages. Incremental dike injection generates magma batches of melt that form clusters appearing with diverse shapes, horizontal and vertical interconnectivity (Fig. 1). The volume of eruptive melt strongly depends on magma influx rates, the width of the injection region, and eruptions. High injection intensities produce magma reservoirs capable of large eruptions, while repetitive eruptions lead to shrinkage of magma bodies. High heat input causes host rock zircons to lose a significant portion of their old cores. Magmatic zircons in the periphery form quickly due to rapid cooling of intruded dikes while in the central part crystals can grow during several hundreds of ka.

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POSTERS

Towards Unraveling Caldera-forming Eruption Dynamics: Thermal Evolution and the Role of Plasticity

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Abstract
Understanding the processes involved in caldera-forming eruptions and the buildup of large-scale magmatic systems is of paramount importance for comprehending the complete eruption cycle. This study employs a multiphysical approach to investigate various aspects, such as magma accumulation, stress development, strain rate and magma chamber dynamics. Emphasizing the significance of plasticity in the host rock, we account for the deformability and nonlinear response exhibited by the materials in the system.

To facilitate our research, we utilize an open-source thermal evolution magma intrusion model, coupled with a pseudo-transient visco-elasto-plastic Stokes solver implemented in Julia. This coupling enables us to simulate the growth of the magmatic system while capturing the complex rheological behavior of the materials involved. Our study optimizes computational efficiency by leveraging the power of graphics processing units (GPUs) on modern high-performance computing (HPC) machines.

By utilizing this state-of-the-art framework, we assess the thermal and volumetric changes occurring within the magmatic system, considering the intricate interplay between the accumulation of hot magma and the surrounding host rock. The implemented visco-elasto-plastic rheology of the lithosphere enables us to assess the fracturing and thermal effects on the lithosphere, which lead to weak zones later used as eruption channel. These faults not only provide pathways but are also associated with the caldera collapse stage of the eruption cycle, that lead to geomorphological transformations of the surface.

Our study underscores the importance of considering appropriate visco-elasto-plastic rheology of the lithosphere during the modelling of magma chamber dynamics and caldera collapse.

Numerical modeling of melt-fluid/solid segregation and differentiation in partially melting orogenic crust

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Abstract

This PHD study aims to develop a numerical modeling approach coupling thermodynamics and thermomechanics to quantify the liquid-fluid/solid segregation and transport processes in partially melting continental crust by controlling its rheological evolution during melting. This study therefore involves metamorphic and magmatic processes, fluid generation and circulation that play a role in metallogenic processes and have an impact on the transfer of elements of economic/ social interest (Chi and Xue, 2011).

Our work builds on a previous study that modeled the segregation of deca-kilometric size rock domains with different rheologies during partial melting (e.g Louis-Napoleon, 2020). We use the open-source code OpenFOAM and one of its embedded solvers, multiMeltInterFoam developed by Louis-Napoleon et al. (2022). This solver will be adjusted to meet the conditions of our chosen set-up; here we focus on a mesoscale (from centimeters to meters) setting to emphasize the transport and differentiation processes between melting and non-melting phases, with or without bearing fluids and test the influence of varying the thermodynamic and thermo-mechanical conditions.

Processes related to melt and fluid transport such as percolation, migration, and mixing in the system will be described by analytical techniques and by thermodynamical modeling of metamorphic reactions, using Perple_X and MAGEMIN. This will allow to identify the thermodynamic conditions, percentage of melt and the set-up parameters that will be used to constrain the melt and fluid behavior in our thermo-mechanical models. The thermo-mechanical models in turn will help to identify how the transport processes can be controled by buoyancy and viscous flow in the chosen set-up.

For this project we use the data collected from our first case study on the south-eastern migmatite Velay dome (French Massif Central) that represents pluri-kilometric volumes of melted crustal rocks and displays a representative metamorphic gradient from the preliminary protholith to the partially melted rocks (a.k.a the migmatites).

The main goal of this study is to reach a better understanding of the mechanisms underlying the crustal heterogeneities genesis and how partial melting and liquid/solid segregation can contribute to the redistribution of elements and thus to the crustal differentiation.

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3D Modeling of pegmatites migration at the onset of partial melting

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Abstract

Rare Metal Pegmatites and Granites (RMPG) are the mains sources of Lithium in hard rock in Europe. Rare metals (as Lithium) are critical for technology of renewable energy and storage. Therefore, the understanding of RMPG formation is crucial for the independence of Europe in the energy transition.

Several genetic models already exist. Peraluminous granite have commonly a concentration of Lithium of 30ppm where RMPG magma can go to 1000ppm of Lithium. To explain these differences in concentration, one needs either to consider that these liquids are the residual liquid from the crystallization of parent granite [1] or at the contrary that they form at the onset of melting; the anatectic model[2]. In both case, one needs to be able to model the percolation of melt into low porosity/permeability ductile middle crust. Statistics on spatial reparation of RMPG indicates that long-term tectonic environment is an important parameter that control their emplacement suggesting that fault zones and shear bands and long term tectonic environment active over millions of years impact the shorter term melt ascent dynamics.

The aim of my PhD is to improve the knowledge we have about parameters that control the distance between migmatites and RMPG, how are form by the same anatectic event in 3 dimensions. As melting and tectonics take place at different time scale and corresponds to different physics, we will need to use a multi-scale and multi-physics modelling approach, which consist at coupling efficiently two types of codes.

pTatin3D [3] a finite element code written in C which heavily relies on Petsc Libraries will be used to produce high resolution simulation for a set-up of strike slip 3D domes based on [4] but adapted to the geometry of migmatitic dome of Beauvoir (France) and Fregeneda-Almendra (Portugal). A newly developed two phase flow finite difference code based on the same physics as [5] but using ParallelStencil and ImplicitGlobalGrid Julia packages to simulate the melt migration at smaller time scale.

The long term simulations will provide high-resolution shear strain rates and geothermal gradient to short-term simulations of the melt. One of the objective is to increase the resolution of tectonic model from 64*64*32 elements [4] to 512*512*256 elements, reaching a resolution of 195 m for a model size of 100 km long term tectonic model. As the geological RMPG bodies are 600m large, we aim for a resolution of 100m cube for the two phase flow simulations.

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Seismicity near Mayotte explained by interacting magma bodies: Insights from numerical modeling

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Abstract

Mayotte island has experienced a large volcanic eruption in 2018-2021 with the submarine Fani Maoré volcano, located 50 km offshore. The eruption was accompanied by intense seismicity, outlining a large, complex and previously undetected magma feeding system at mantle depths (45-20 km). The earthquake distribution is divided into a “proximal” and a “distal” cluster (10 km and 30 km away from the island, respectively ; Figure 1). Previous studies suggest that two reservoirs may lie at the proximal cluster’s top and bottom boundary.

Our aim is to assess whether two interacting reservoirs are a mechanically viable explanation for the proximal cluster’s conical shape. We develop finite-element models of pressurized magma reservoirs in a 2D axisymmetric domain. The reservoirs are modeled as compliant elastic ellipsoids embedded in an elastoplastic host rock.

Our parameter exploration range shows that, at these depths, extremely low friction is required to generate failure at realistic low reservoir pressures. This implies in turn that mechanical weakening must occur at such mantle depth, induced by fractures or pore fluid overpressure in the volcanic system.

We find that two superimposed reservoirs can generate a plastic domain in between, if they are spatially close enough. Several geometries (from spherical to sill-like) are plausible. A conical fracture domain is more likely to appear for reservoirs with opposite pressure loads (i.e. one inflating, one deflating). Given the geometrical match with the proximal seismicity cluster at Mayotte, we suggest that an inflating reservoir has settled at Moho depths, posing a potential threat for the island and which remains to be studied in more detail.

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Numerical modelling of the hydrothermal system of Piton de la Fournaise volcano

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Abstract
In volcanoes, magma bodies heat underground waters. These hot fluids flow in the porosity of the rock which becomes altered as a result: this forms a hydrothermal system. Hydrothermal activity depends on the magmatic heat flux and on the rock permeability which describes its ability to let a fluid flow through it. Although permeability is the dominant parameter in the control of hydrothermal circulation, it is also the least constrained because of the wide range of rock permeabilities and the difficulty to evaluate them at the scale of a volcano. Therefore, numerical models along with geophysical observations should be used to reduce the uncertainty on permeability and represent site-specific hydrothermal systems. Here we present the first numerical model of Piton de la Fournaise's hydrothermal system using the commercial software COMSOL© . We first designed a 2D model, solving fluid flow in an unsaturated edifice, to simulate a dome-shaped water table fitting with geophysical measurements, and propose a new permeability structure consistent with geological data. We then coupled fluid flow with heat transfer equations to constrain heat fluxes and permeability more finely in hydrothermally active areas. Using a 2D model, we found that permeability should be $\sim 10^{-14}$ m^2 beneath the summit crater. Results of our 3D model suggest that hydrothermal activity could extend to the rift zones if they receive a few $W.m^{-2}$ and their vertical permeability ($\sim 10^{-15}$ m^2) is about one order of magnitude higher than their horizontal one. We demonstrate that site-specific numerical modelling is a powerful tool to understand quantitatively the hydrothermal system of a volcano.

Laboratory modelling of magma propagation in a layered Mohr-Coulomb brittle crust

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Abstract
Dykes, sills and laccoliths are the main igneous bodies accommodating for magma transport and emplacement in the Earth's brittle crust. These intrusions are commonly emplaced in layered portions of the crust, for examples in sedimentary basins or volcanic deposits. Most models of dyke, sill and laccolith emplacement in the layered crust assume magma propagation by tensile hydraulic fracturing, host rock deformation by elastic bending, and propagation direction controlled by local stresses at the intrusion's tip. Geological field observations, however, show that the Mohr-Coulomb properties of the brittle crust can play a major role on dyke and sill propagation.
This contribution describes for the first-time laboratory experiments of magma emplacement in a layered Mohr-Coulomb crust. The laboratory setup is a quasi-2D cell, filled with cohesive, fine-grained, dry granular material. Layering is simulated by 3-mm thick layers of low-cohesion, low friction dry micro glass beads. The model magma is glucose syrup injected at constant flow rate (0.2 mL.min^{-1}) via a syringe pump. The propagation of the intrusions and the deformation of the model were monitored by a sideview camera (Figure 1, right).

Pressure versus shear strain map

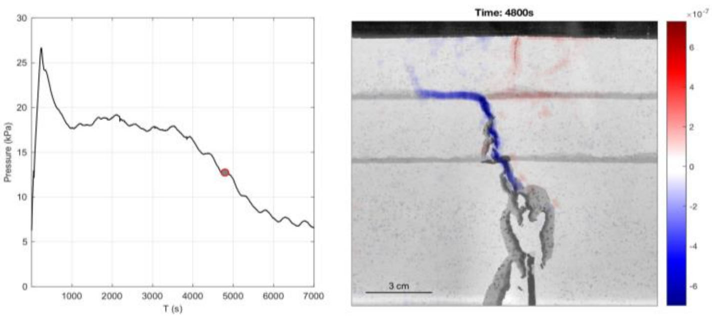

Figure 31. Left: plot of liquid pressure as a function of time during syrup injection in experiment with two weak layers. Red and gray dot indicates the time corresponding to photograph to the right. Right. Photograph of experiment with two weak layers at time indicated in pressure plot. Shear strain map plotted on top of the photograph locates bands of inelastic deformation.

In homogeneous experiment, a dyke propagates continuously until ~3 cm depth, where it lifts up its overburden and generates conjugate reverse damage zones that channel the subsequent dyke propagation. In layered experiments, a dyke first propagates upward until reaching the bottom of a weak layer. While injection proceeds, the dyke propagation halts, the dyke thickens, the dyke tip gets rounded, and the whole overburden is lifted up. Eventually the dyke tip pierces through the weak layer by nucleating damage bands above, which guide the subsequent propagation of the syrup. Locally, significant inelastic damage is accommodated by interbed detachment along a weak layer, which can enhance the formation of a sill (Figure 1).
Our models highlight that (1) weak Mohr-Coulomb layers greatly affect magma propagation, (2) weak layers impede upward dyke propagation, (3) magma-induced inelastic damage is precursor for subsequent magma propagation, and (4) weak layers can localise damage due to interbed detachment and control the formation of sills. All in all, our Mohr-Coulomb models show that revealing inelastic damage is key for understanding magma propagation in the layered brittle crust, and in the brittle crust in general.

Fluid and fault motion interactions

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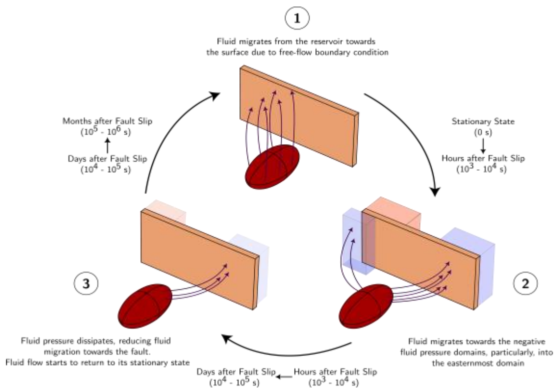
The Southern volcanic zone of Chile's subduction zone is structured along a main North-South trending active fault structure, the Liquine Ofqui fault system, and displays hundred of volcanic complexes. There, several intersecting fault systems are linked with volcanic complexes and geothermal alteration areas, but sometimes in a puzzling three dimensional geometry. Some of these geothermal areas present economic interest, but the risk of mechanical destabliisation due to exploitation refrains further investigation. Among the remaining open questions, i) whether a growing magmatic pulse from the base of the crust is able to destabilize a fault zone, and ii) how a fault zone upon motion, may control fluid flow from depth towards the surface (Ruz Ginouves et al., 2021). The strongly strike-slip component of these faults induces dilatational jogs, calling for a fault valve mechanism controling the migration of fluids to the surface (Sibson, 1990), which still lacks a self consistent numerical implementation. Here we move a step forward towards modeling the transient behavior of an initially steady state flow in response to a strike -slip fault motion, inspired from the natural system set in Planchon Peteora gethermal system (Pearce et al., 2020).

Figure 32 : Evolutionary stages of a steady fluid flow from an elliptical source. Upon strike-slip motion of the fault zone (rectangular area), fluids get sucked into dilational areas (areas) of relatively lower pressure. After a few weeks this pressure gradient resumes and fluid flow progressively returns to steady state. Lets get to the Ice Breaker at the top of this hell tower.



We developed an original poro-elasto-plastic Finite Element Method based on the FEniCs library, and in which the poro-elastic and the elasto-plastic constitutive equations are implicitly coupled. Two classical benchmarks were used to validate both the poroelastic and the elastoplastic implementations, and can be found here: https://github.com/FNSL1996/PEP_FeniCS.
The development of dilational and contractional domains in the fault's surroundings lead to deviatoric stresses and strains that range between ±1 MPa and $\pm 10^{-4}$, respectively. Negative and positive fluid pressure in these domains lead to a time-dependent focused fluid flow, which shows similarities with the suction-pump mechanism (Sibson, 1990).
- The spatial and temporal evolution of this fluid flow is shown to depend on fault permeability (greater oscillation range), shear modulus (lower flow), fluid viscosity and rock's yield strength (greater flow).
- We report a maximum fluid flux reaching 8 to 70 times the initial stationary flux.
- Pressure-driven fluid diffusion returns to stationary state between weeks to months after fault slip.
- We also show how the simple von Mises plasticity criterion already enhances fluid flow, locally.

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Tectonics controls on melt production and crustal architecture during magma-poor seafloor spreading

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Abstract
The wide variability in oceanic crust composition and architecture observed along ultra-slow spreading ridges has challenged the standard model of oceanic crust formation derived from magmatic ridges. Current understanding of the processes governing oceanic accretion suggests that these features depend on the balance between magmatism and tectonics, with variations in magma supply being the key control on faulting and crustal architecture. However, the correlation between faulting, serpentinization and oceanic crustal thickening recently observed at the amagmatic ridge at 64°30' East in the Southwest Indian Ridge challenges the role of magma supply. Here, we focus on this magma-poor ridge and use 2-D numerical models to investigate how feedbacks between tectonics, serpentinization, and magmatism shape oceanic crust. Our model also includes hydrothermal cooling, the load of the ocean as a force on bathymetry and the oceanic crust buoyancy. We reproduce the observed bathymetry, shown to be shaped by short (~1Myr) and long (~2Myr) lived detachment faults (DFs) formed in flip-flop mode. We find that the crust along the detachment faults thickens due to fault-related serpentinization and thins during phases between alternating detachments, with serpentinization becoming limited while magmatism dominates. This trend correlates with decreasing and increasing melt production, which over time shows 1-3 Myr cycles in melt productivity, an observed cyclicity, which we find results from tectonic influence on mantle flow. These results provide new understanding of the formation of heterogeneous oceanic crust in magma-poor tectonic environments.

Discrete Element Method modelling of fracturing and surface displacements during viscous magma intrusion

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Abstract

Inflation of viscous magma intrusions in the shallowest 1-2 kms of crust of rocky planetary bodies, including Earth, often induces dome-shaped ground deformation. It also produces fracturing and compaction within the host rocks that further weakens the strength of that crust. Most models that simulate magma-induced deformation assume a homogeneous and isotropic medium wherein stress patterns indicate the potential for failure, but without simulating actual fracturing. We use a two-dimensional Discrete Element Method (DEM) model that simulates the concentration of high strains and fracturing induced by magma emplacement (Morand et al., 2023). In the DEM, the medium is discretised by an assemblage of circular rigid particles bonded together by force contact laws. Particle bonds can break at any numerical timestep and thus fractures can propagate during magma intrusion in our model (Figure 1).

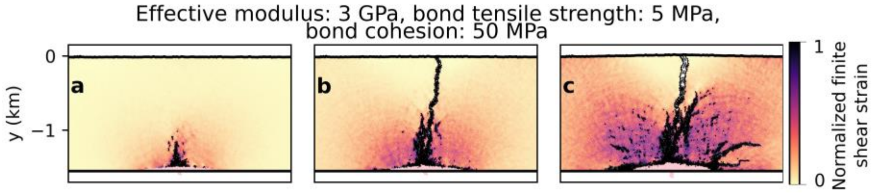

Figure 33 : Temporal evolution of the fracture pattern and finite shear strain as the injection is progressing.

We first numerically investigate for an initially intact host rock the effect of the host rock toughness (resistance to fracturing) and stiffness (resistance to deformation) and the effect of the intrusion depth, on stress, strain, spatial fracture distribution, and surface displacements. Our results show that the spatial fracture distribution varies between two end-members. Our results also show that abrupt increases in surface displacement magnitude that occur in response to fracturing, even at constant magma injection rates. Secondly, we investigate how the presence of preexisting fractures impacts the host rock deformation. Our model provides a novel approach to understand the effects of host rock mechanical strength and fracturing during viscous silicic magma intrusion and the associated development of hydrothermal systems and mineral deposits on Earth and other rocky planetary bodies.

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An overview of the velocity and attenuation distribution in the Krafla volcanic system

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Abstract

Natural resources, such as geothermal energy, are usually allocated in the uppermost part of the crust. The exploration and exploitation of these resources rely on a proper understanding of the rock's physical and rheological properties. For instance, the reduction in the rock's permeability with depth depends on the progressive porosity decrease, due to the lithostatic pressure increase and the transition from brittle to ductile deformation (BDT), related to the rising temperature. Therefore, the characterization of underground conditions is crucial for planning explorative studies in geothermal systems. One way to retrieve subsurface information is through the analysis of the propagation of seismic waves, which provides information on physical rocks' behavior and an alternative assessment of the BDT depth [1]. In particular, the decay of the amplitude of the seismic waves (i.e. seismic attenuation), usually described by a "quality factor", depends on the seismic frequency, temperature, water content, and grain size of the rocks. Depending on the seismic scale, it could be used as an indicator of subsurface heterogeneities.

In this study, we investigate the seismic velocity and attenuation sensitivity to the crustal heterogeneities in the volcanic system of Krafla, an area affected by young tectonics and hot thermal conditions. To this aim, we implement a Q seismic tomography, using as input a published seismic tomography model [2] and estimate the seismic quality factors of basalt rocks sampled in the Krafla area.

To retrieve the Q_P perturbations, we implement a method consisting of a combination of a spectral decay technique to derive the attenuation operator (t^*) and seismic tomographic inversion [3]. The distribution of seismic wave velocities is obtained from a 3D tomographic inversion, using 1453 earthquakes detected from a local seismic network (2009-2012) [2]. Q_P inversion is performed with the simul2014 algorithm [3], while a linearized technique solves a nonlinear problem that uses a damped least-squares inversion for model perturbations. We obtain a map of Q_P variations for the first 4 km, which we jointly interpret with the seismic wave velocities [2]. In this way, we can discriminate between temperature anomalies and compositional heterogeneities. We also test the possibility to detect the BDT depth on the base of the reduction of the Q_P, related to hot temperatures/melt conditions. In order to estimate the seismic quality factors at the laboratory scale, we first develop a numerical method to extract seismic attenuation information from ultrasonic signals in the frequency domain (Spectral Ratio Method). The technique is implemented and tested on suitable synthetic attenuated models [4]. The aim of this test is to assess the reliability and robustness of the method in diverse signal noise conditions and absorption levels.

Additionally, the test helps identify the frequency ranges satisfying the assumption of constant seismic quality factor and assess the influence of the windowing effect on providing an accurate seismic quality factor. Subsequently, the method is applied to real ultrasonic waves acquired in the basalts during the execution of a hydrostatic test. The results help constrain the Q_P variations previously obtained.

This study will contribute to understanding the dynamics of the tectonic features and help plan explorative investigations of high enthalpy geothermal systems, adding constraints to the correlation between viscous rocks' deformation and their seismic attenuation

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The hottest thermal spring in Europe (82°C, Chaudes-Aigues, French Massif Central) and its geothermal potential : a multidisciplinary approach

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Located in the southern Massif Central, the village of Chaudes-Aigues is a remarkable example of French thermalism. In addition to hosting the hottest spring in Europe (the Par spring) at a temperature of 82°C and a constant flow rate of 500 $L.min^{-1}$, 26 other springs with temperatures between 25 and 68°C have been identified. At first sight, this system could be linked to the surrounding volcanic edifices (the Cantal and Aubrac volcanoes), but to date there is no evidence of a magma chamber influencing fluid circulation. The emergence zone is located near a network of microgranite dykes in the gneissic basement. It is also at the intersection of three major Variscan fault systems forming a Y-shaped structure. According to previous studies, two hydrodynamic circuits coexist, one at a depth of around 5 km and the other at 2 km, but the general functioning of the system and the origin of the emerging waters remain unknown. Geothermometers indicate a reservoir temperature of 170 ± 20°C. This suggests that there is significant geothermal potential at depth. In this sense, the Chaudes-Aigues region is an ideal natural laboratory for exploring this type of geothermal reservoir. The numerical approach was organized in three successive stages. Heat equation, mass conservation and Darcy law were coupled using Comsol Multiphysics™ software (finite elements method). An initial 2D dynamic numerical approach indicates a convective system involving a geothermal reservoir of 90 km^3 between 2 and 5 km depth. Then, in order to understand the hydrodynamic functioning of the granitic reservoir and the interactions between the different fault cluster oriented N150 (southern branch of the Y), 3D models were performed. Taking into account the 3-dimensional topography allows the impluvium zone to be determined and the system residence times to be constrained. The two infiltration zones correspond mainly to the Aubrac massif and to the Cantal massif to the north. Initial results show a deep circulation of fluids from the Aubrac towards the Chaudes-Aigues fault cluster. Other convective loops exist in this deformation zone and would explain the existence of the Chaldette hot spring (34°C, 10 km to the south) in the Margeride granite. A lineament study and highly localised dynamic models will also supplement the observations made in the field. Traces of fluid palaeocirculation indicate that the intersections between faults oriented N30 and N140 are fundamental to the functioning of the current system. These results will be completed by geochemical analyses to understand the origin of the thermal waters and the hydrogeological processes at depth.

Spatio-temporal Dynamics of Hydrothermal Circulation over 10 million years of Ultraslow- Rifting and Spreading

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Abstract

Present spatio-temporal variations of hydrothermal fluxes in the modern and recent ocean provide an observational snapshot of the dynamic interaction between the tectonics of ocean basins and submarine hydrothermal systems. In order to support the understanding of feedbacks between tectonics and the life cycle of hydrothermal systems, we discuss the mechanical, fluid flow and heat flux patterns in a coupled ThermoHydroMechanical model at the ocean basin scale. The case study is an ultra-slow spreading basin, evolving from the initial rifting stages up to the ridge formation. Heat release by plastic deformation at fractures and faults, exothermic serpentinization reactions, sensible and latent crystallization heat from magmatic emplacement and radiogenic heat provide different energy-source signatures promoting hydrothermal activity. The large basin-scale domain allows us to navigate through the evolution of the modelled concurrent hydrothermal systems, emerging and decaying in consonance with the tectonics and the energy-sources. We discuss how the evolving permeability field in crust and sediments exerts a strong control on the hydrothermal circulation, and describe the dynamics of reorganization patterns in fluid flow in response to the mechanical strains and heat sources.

Evaluation of magma rising-induced surface displacement models using analog experiments.

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Abstract

Magma intrusions ascending through the upper crust induce a displacement of the Earth's surface, the amplitude of which increases as the magma approaches the surface. Most geodetic observations of ground displacements induced by magma transport are interpreted using static elastic models of open dislocations or pressurized surfaces without any *a priori* knowledge of the surface shape of the magma intrusion. In particular, the OKADA model is by far the most used to invert surface displacement resulting from dike emplacement at depth. In addition, current numerical models developed for the propagation of fluid-filled cracks, which are also elastic but may include dynamic effects of viscous fluid flow, generally do not generally resolve the 3D displacement field induced at the free surface. Our aim is to bridge these two distinct approaches by using fluid-filled crack propagation models to derive the evolution of the surface displacement over time, thus providing a useful tool for the assimilation of geodetic data based on dynamic models.

In a first step, we use Weertman crack theory, which provides the shape of a non-viscous fluid-filled crack to derive the surface displacement field from a finite element model. This solution is then compared to the classical dislocation model (OKADA formulation) and to 2D displacement field inferred from the simulation of the propagation of the fluid filled using a 2D boundary element model. Eventually, the results are validated using analogue experiments injecting a finite volume of air inside a transparent gelatin characterized by elastic behavior. In the experiments, the position and shape of the crack are monitored by cameras while the surface displacement field is recovered by photogrammetry (3D components) and by scanner measurements (only the vertical component). Figure 1 shows the comparison between the observed and modelled vertical displacement field for a characteristic experiment. It shows that the numerical simulation performs better, mainly due to the consideration of the crack shape. However, the elastic models cannot accurately estimate the vertical displacement observed in the near-field just above the crack. The next step will involve improving the numerical models based on this comparison with observations, so that they can be used for inversion or assimilation strategies. We will then carry out similar experiments, but injecting a viscous fluid that better simulates magma intrusions.

Mathematical modeling of the population of zircon crystals growth

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Abstract

Due to the active use of zircons for geochronology, as well as isotopic and chemical analyses, it is important to link quantitatively conditions of the dynamics of zircon population growth with changes in magma temperature. Laboratory experiments do not allow estimations of rates of growth and nucleation of zircons on natural magmatic systems timescales since these processes can take thousands or tens of thousands of years. In this regard, numerical modeling of the growth of the zircon population in a cooling magmatic melt becomes essential.

Here we present a mathematical model of the dynamics of a population of zircon crystals in a cooling magmatic intrusion and compare calculated the size distributions of zircon crystals (CSD) with measurements on several well documented eruptions. The problem is considered in 1D (Sorokin et al., 2022), 2D and 3D formulations. The model is based on the numerical solution of the diffusion equation taking into account the nucleation and growth of individual crystals, the dependence of the equilibrium concentration of zirconium and the diffusion coefficient on temperature. The CSDs are calculated for different cooling rates of the magmatic chambers and compared with measurements.

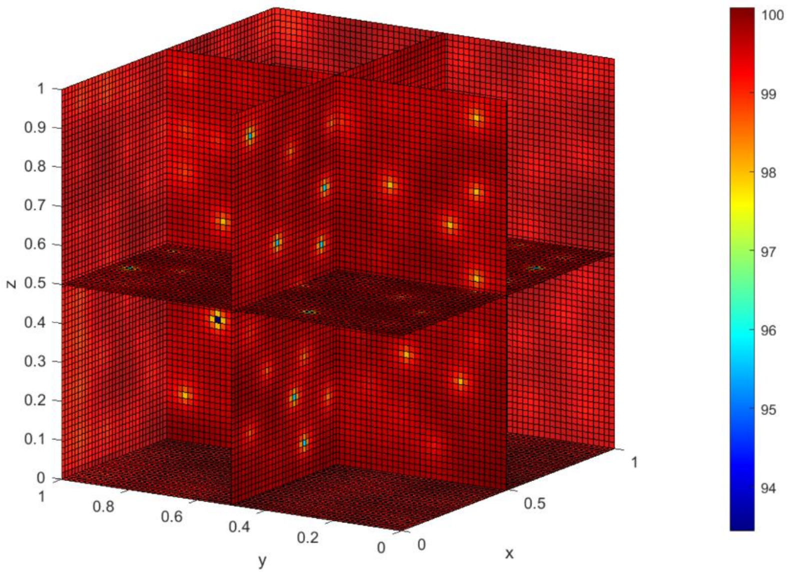

Figure 34 : The result of a program written on the basis of a constructed three-dimensional mathematical model.

The code for the numerical solution in a 3D formulation (Fig.1) is written for accelerated calculation using GPU in CUDA language. Calculated 3D CSDs are in good agreement with measurements on samples of volcanic eruption products (Bindeman, 2003). For the first time we made estimates of the dependence of the nucleation rate on undercooling for zircon crystals in a cooling magmatic chamber.

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Session 6

ORALS

Partitioned fault slip in transpressional zones: Insights from analogue model experiments

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Abstract

Strain partitioning in obliquely convergent zones is generally understood to imply that fault slip is taken up by both pure strike-slip faults and parallel oriented dip-slip thrust faults that are coevally active. Although it is well known that the continental crust generally contains major, pre-existing weak zones (e.g. older faults), little is known about their influence on strain partitioning.

Here, we use analogue models to investigate the influence of pre-existing weak zones and their orientation on strain partitioning in transpressional settings. Our set-up consisted of a viscous layer made of a PDMS-Corundum sand mixture to model the ductile lower crust, and of quartz sand to model the brittle upper crust. All models contained a central viscous seed overlying the basal viscous layer, and in addition, some models included a pre-existing fault in the upper brittle crust, whose dip and orientation was varied. The convergence angle varied between 0° and 20° with respect to the longitudinal borders of the model.

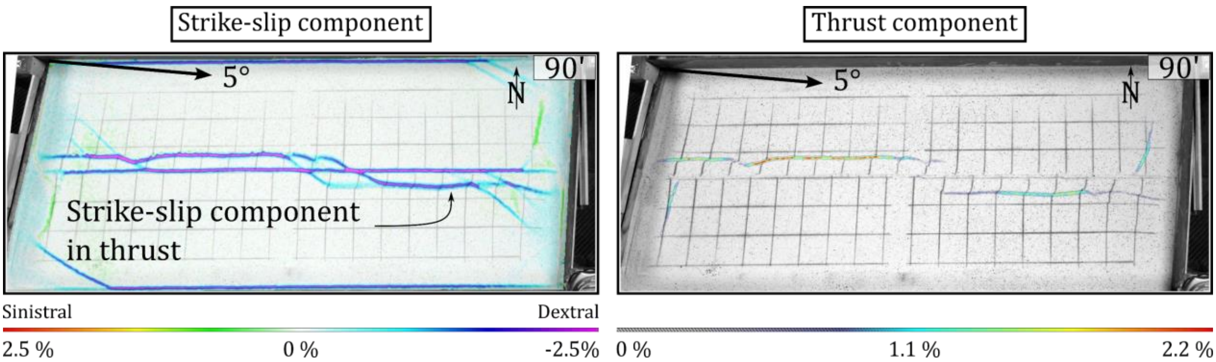

Figure 35 : Top views and superposed PIV analysis of Model 1109 after 90 minutes. The left panel shows the strike-slip component of deformation, whereas the right panel shows the thrust component of deformation. The initial set-up included a E-W striking central viscous seed at the base of the model and a vertical pre-existing fault in the brittle material above. In this experiment the convergence angle was 5° with respect to the longitudinal borders of the model. PIV analysis shows reactivation of the vertical pre-existing fault zone as a pure E-W trending strike-slip fault and parallel striking thrust faults on either side with an important strike-slip component.

The models showed various results going from no observation of strain partitioning to models in which both c. 30° dipping thrust faults and parallel striking vertical strike-slip faults form (Fig. 1). However, in contrast to what is assumed for the "idealized strain partitioning" case in nature, the displacement along the thrust faults in the models is not a pure dip-slip movement, but an oblique-slip movement, with the slip rake decreasing with decreasing convergence angle. This suggests that natural examples of transpressional deformation might show a similar behaviour, i.e. an oblique-slip component along the thrust fault. In nature, it is generally easier to determine the approximate dip of the fault than to determine the slip movement along the fault, especially in regions with poor outcrop conditions. It is thus possible, that the concept of perfect strain partitioning (parallel striking pure strike-slip and pure dip-slip thrust faults) is an idealized concept and might need to be revised.

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Structural inheritance during the inversion of a salt-bearing domino-style rift system: Insights from analogue modelling

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Abstract
Positive basin inversion is highly influenced by the presence of decoupling layers as well as by the inherited structures from the rifting stage. Salt thickness conditions the amount of coupling between the basement and the overburden during tectonic events that, together with its distribution and continuity determines the style of deformation (i.e., thick- vs. thin-skinned deformation) during inversion.

In this work, a systematic analogue modelling program explores the evolution of extensional basins developed above a pre-extension salt layer and the evolution of inherited salt structures during subsequent inversion. The modeling apparatus is designed with five metal fault blocks that rotate counterclockwise during extension and clockwise during inversion. A constant velocity of 4.6mm/h was applied to the blocks during extension and inversion by means of a worm-screw motor. While a total of 10cm of deformation was applied during the former, total inversion was applied during the latter. This setup allows us to simulate the development of an extensional domino basement-fault system but also how it is inverted. For such reason, an initial set of five extensional models with varying salt and overburden thicknesses were performed so to understand the impact these parameters have on the development of salt structures during thick-skinned extension. In order to study the inversion of such basins, some of the extensional model configurations were replicated so to comprehend the role exerted by the pre-existing extensional and salt structures during inversion.

This study proved that the extensional evolution and structure development during the rifting phase are highly influenced by the thicknesses of the salt layer and of the overburden succession. Due to the decoupling degree, salt structures are easily developed in models with a thick salt layer where decoupling is more effective. In contrast, models with a thinner salt layer result in the development of crestal collapse grabens at the footwall of extensional faults (Fig. 1).

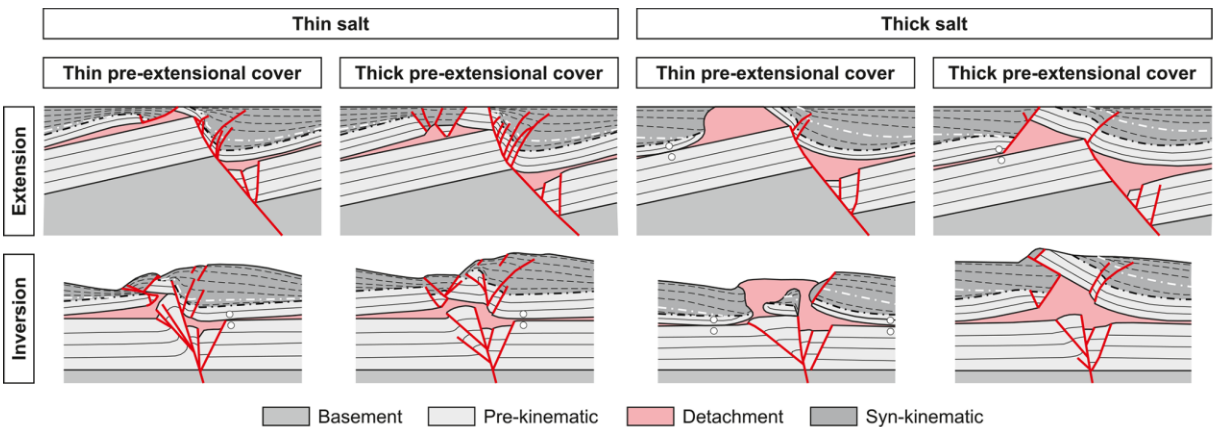

Figure 36: Theoretical models after extension and inversion of the domino style system (Ferrer et al., 2023).

The results also showed that the compressional structural style is influenced by inheritances from the rifting phase. The inherited extensional structures and the salt thickness condition the decoupling degree between the basement and overburden and therefore, the structures developed during inversion (Fig. 1). In models with a thick inherited salt layer, extensional geometries might be preserved while in models with a thinner inherited salt layer, total inversion of extensional structures occurs. Finally, the analogue modelling program performed allowed to comprehend how diapir rejuvenation, primary weld reactivation, and thrust emplacement occur in domino-style systems with a decoupling layer.

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Generalization of the Navier-slip boundary conditions to apply obliquity in regional geodynamic models

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Abstract

Regional geodynamic models require to impose boundary conditions that best represent the physical information exchanged between the modelled and a larger, non-modelled domain. Depending on the nature of the physical information exchange, the internal evolution of the regional system may differ. Nevertheless, the first and foremost observation is that the deformation in tectonic plates boundaries is three-dimensional, i.e., non-cylindrical, oblique.

To model 3D non-cylindrical deformation, regional geodynamic models mostly use initial conditions through oblique or offset weak zones together with cylindrical boundary conditions implying free slip. However, the problem with the free-slip boundary condition is that it enforces cylindrical behaviours in the vicinity of the boundary, limiting the obliquity of the whole system or forcing to consider very large domains to avoid a too strong influence of the boundary condition on the solution.

In this work, we use a formulation that we tailored to impose oblique boundary conditions by enforcing the velocity direction, but without constraining the magnitude of the velocity vectors. Using this method, we impose a 3D boundary-driven strike-slip velocity field.

To study strain localization of 3D strike-slip systems we impose different initial configurations using plastically weakened material. Models show the evolution of strain localization through time and space in 3D and the interactions between shear zones with different geometries.

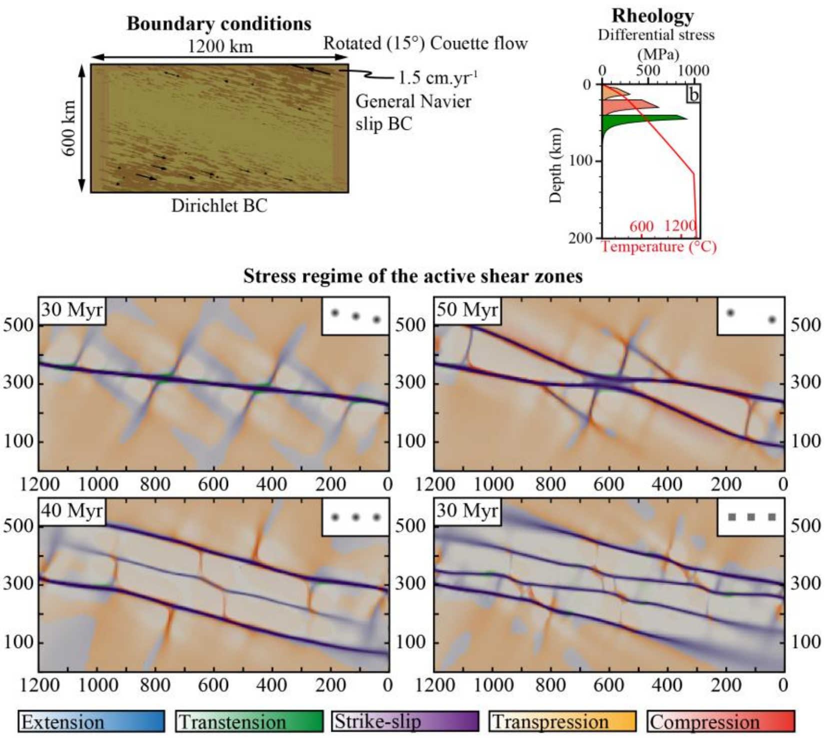

Figure 37: Map view of 3D strike-slip models using general Navier-slip boundary conditions. Colours show the stress regime of active shear zones.

Crustal Fault Zone as geothermal power systems. Contribution of numerical modeling and comparison with natural systems.

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Abstract

Crustal fault zones offer intriguing geological prospects for high-temperature geothermal energy sources in naturally fractured basement regions. Field and laboratory investigations have demonstrated the potential of these systems to facilitate fluid flow down to the brittle-ductile transition. Nevertheless, various essential questions about exploration remain unanswered, particularly concerning the role of structural dip, permeability, fault zone thickness, and the broader influence of tectonic regimes on fluid flow within naturally fractured basement domains. By employing 2D and 3D numerical modeling, with TH and THM coupling, three discernible trends can be identified and integrated to guide exploration in these areas: (i) vertical faults concentrate the highest temperature anomalies at shallow depths, (ii) thermal convection is more vigorous where the fault thickness is largest, and (iii) strike-slip systems favor the more spacial extend positive temperature anomalies. Geological and geophysical data indicate that the Pontgibaud fault zone, located in the French Massif Central, is a crustal fault zone that host an active hydrothermal system at a depth of a few kilometers. We conducted an integrated study to assess its potential for high-temperature geothermal resources. Field measurements were utilized to control the 3D geometry of geological structures. Observations from 2D (thin-section) and 3D (X-Ray microtomography) analyses reveal a well-defined spatial propagation of fractures and voids, exhibiting consistent fracture patterns across various scales ranging from 2.5 μm to 2 mm. Furthermore, measurements of porosity and permeability confirm that the highly fractured and altered samples are characterized by high permeability values, with one sample defined by a permeability as high as 10^{-12} m^2. Lastly, employing a large-scale 3D numerical model of the Pontgibaud crustal fault zone, incorporating THM coupling and comparisons with field data (temperature, heat flux, and electrical resistivity), allowed for the exploration of the spatial extent of the 150°C isotherm, which rises up to a depth of 2.3 km.

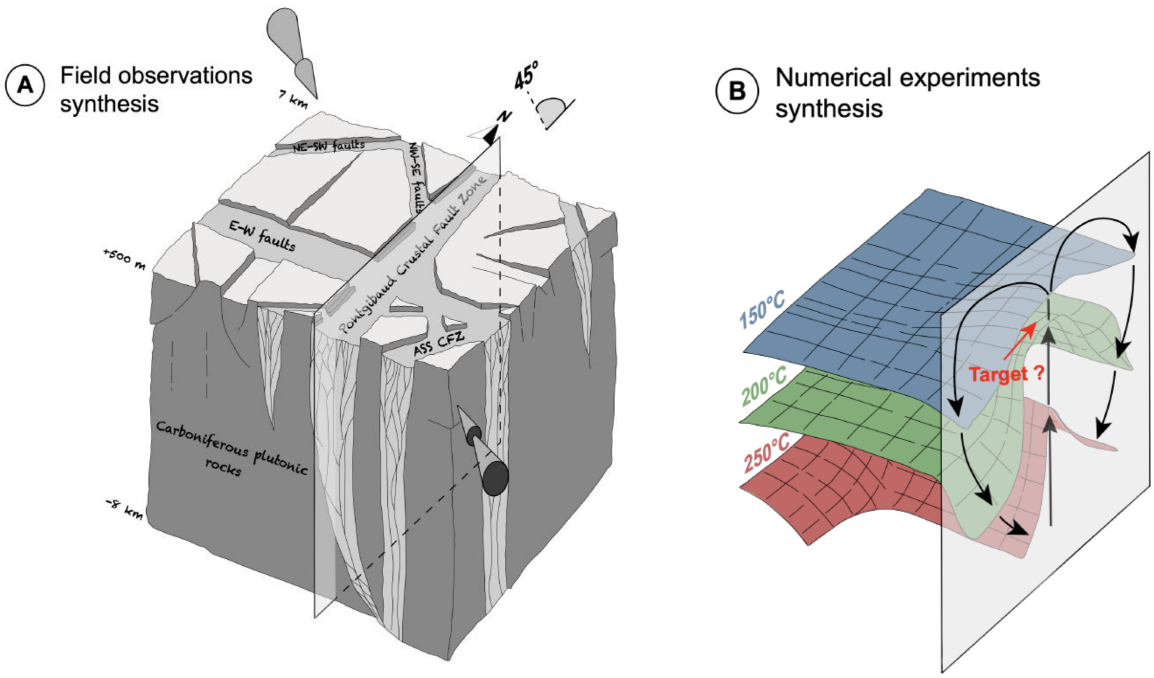

Figure 38 : "(a) A three-dimensional conceptual model of the Pontgibaud CFZ represents it as a potential geothermal reservoir. (b) A comparison between the results of large-scale modeling and field data reveals that fluid may follow a blob-like pattern and position the 150°C isotherm at a depth of 2.3 km."

Although built upon simplified assumptions, our model successfully replicates field data. By employing a multidisciplinary integrative approach, incorporating coupled 3D modeling, we have demonstrated an effective means of assessing the geothermal potential of crustal fault zones (CFZs) and predicting temperature distributions. This approach can serve as a predictive tool to facilitate the development of high-temperature geothermal operations within basement rocks hosting large-scale fault systems.

Deepening Process Understanding through Global Sensitivity Analyses and Physics-Based Machine Learning

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Abstract
Reliable predictions of the subsurface state distributions (e.g., temperature, pressure) are relevant for a wide range of subsurface applications, for example in the context of the energy transition. However, these predictions prove to be challenging since we have to consider many sources of uncertainties, arising from, for instance, uncertainties in the material properties, the geometry, or unknown physical processes. At the same time, data is often sparse, so it is essential to understand which of these possible sources of uncertainties dominate the application at hand. Even so, analyses that can address these questions tend to be computationally expensive since they require numerous evaluations of the governing equations.

To address this computational challenge, we employ the non-intrusive RB method, which combines advanced mathematical algorithms and novel machine learning concepts. The method produces models that considerably reduce the dimensionality of a process simulation, yielding an acceleration of several orders of magnitude while maintaining the physical principles. In contrast to other machine learning methods, the non-intrusive RB method produces explainable models, which is a crucial aspect for later analyses and predictions.

In this work, we demonstrate how the methodology can be beneficially used for the construction of reliable surrogate models of applications for deep geothermal energy and nuclear waste disposal without impacting the underlying physics. Furthermore, we show the benefits of global variance-based sensitivity analysis to quantify the influence of the various source of uncertainties.

Modeling of Subsurface Processes in the Energy Transition

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Abstract
Combining fossil and renewable energy sources is essential in the energy transition towards net-zero emissions. The energy mix scenario is based on clean H2 production, large-scale CCS, and underground H2 storage. Several pilots and small-scale industrial projects have increased confidence in underground CO2 and H2 storage reliability. However, gigaton-scale CO2 injection has yet to be implemented, and many challenges and unresolved questions remain. For example, large injection rates could bring significant geomechanical effects such as surface uplift, fault reactivation, and induced seismicity. Gas chimneys, fluid-escape pipes, and diffused gas clouds are common geohazards above or below most petroleum reservoirs and in some CO2 storage sites. However, the processes driving the formation of such structures need to be better understood, as are the time scales associated with their

growth or their role as long-term preferential fluid-migration pathways in sedimentary basins. CO_2 mixed from multiple sources raises a question of CO_2 quality and the effect of impurities such as H_2S on the reservoir flow and seal integrity. CO_2 storage in depleted reservoirs faces challenges related to possible CO_2 leakage through old plugged and abandoned wells. When CO_2 reaches the well, old cement compositions react with CO_2 and H_2S, compromising well integrity due to chemical degradation.
Addressing these challenges and achieving the desired gigatonne/year capacity in reservoirs necessitates the advancement of multi-physics, multi-scale subsurface fluid flow models. The coupling of several physical processes brings additional challenges to the modeling. For example, most existing models of chemical reactions coupled with fluid transport assume the dissolution-precipitation process or mineral growth in rocks. However, dissolution-precipitation models predict a very limited extent of reaction hampered by pore clogging and blocking reactive surfaces, which will stop reaction progress due to limited fluid supply to reactive surfaces. Mineral growth models, on the other hand, preserve solid volume but do not consider its feedback on porosity evolution. Furthermore, published models lack consensus regarding purely elastic behavior, even without reactions. Here, we discuss how such models can be built based on irreversible thermodynamics and effective media approaches [*Yarushina and Podladchikov*, 2015]. We focus on hydro-mechano-chemical coupling and discuss the role of rock rheology, physical nonlinearity, and reaction on subsurface processes. To better understand the time-dependent behavior of the rock, verify obtained constitutive equations, and determine model parameters, we perform creep and stress relaxation experiments on common types of reservoir rocks and caprocks [*Sabitova et al.*, 2021]. Verified model equations are incorporated into numerical codes using state-of-the-art matrix-free methods that have shown a significant advantage over matrix-based methods in terms of memory use and parallel efficiency. The code is further tested vs. analog experiments on fluid localization in a porous deformable media. Additionally, we present examples of how coupled models can be applied to study natural reservoir leakage and assess cement stability [*Yarushina et al.*, 2022]. By developing and verifying these coupled models, we can improve our understanding of the complex processes involved in underground CO_2 and H_2 storage and enhance the reliability and safety of large-scale implementation.

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POSTERS

Inversion of half-grabens with salt: Analogue modelling and comparison with the Mid Polish Swell

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Abstract

In inverted rift basins the presence of salt (pre- or syn-rift) and the structural heritage play a key role in the degree of coupling or decoupling between the cover and the subsalt rocks. Using the Mid Polish Swell (Polish Basin) as a natural prototype to design the model configuration, this work presents an experimental program consisting of eight scaled sandbox models simulating the inversion of a half-graben partially filled with salt.

Through systematic modifications of several parameters such as the thickness of the sedimentary overburden, the dip of the basement fault, the deformation rate, and the erosion and sedimentation rates, the final geometry of the salt-cored anticline developed during the inversion of the pre-existing half-graben has been studied. Based on the deformation of coloured silicone markers located at different structural positions within the transparent polymer unit simulating Zechstein evaporites in our natural prototype, it has also been possible to model the internal deformation and types of flow within the salt body. The kinematic evolution of the inverted structure has likewise been analysed with digital image correlation techniques thanks to overhead and lateral photographs of the models taken at regular intervals of time with computer-controlled high-resolution cameras. Hence, it has been possible to analyse how the anticline grew and where the strain was located during the inversion in each model. Photogrammetric techniques have been also used to create point-clouds from the surface of the model constraining the growth of the salt-cored anticline as shortening progressed.

The results show that, during inversion, partial decoupling occurs between the basement and the supra salt unit, which folds to accommodate tectonic deformation (Figure 1). Regardless of the modelled parameter, the geometries of the salt anticline are quite similar. The inversion of the half-graben develops a doubly plunging anticline towards the two glasses bounding the sandbox, with a gently to moderate curved fold hinge resulting from the salt migration towards the central part of the model (compare anticline geometry in figure 1a and 1b). Regarding the salt flow, Couette, Poiseuille and hybrid flow patterns have been recognized (Figure 1), and therefore, it has been possible to identify in which areas of the basin the salt flow is dominated by the overburden load and in which the flow is controlled by the relative movement between the overburden and the rigid basement. Finally, the comparison between the models and the Mid Polish Swell has not only confirmed the feasibility of forming such salt structures through tectonic inversion but also has provided some insights into the characteristics of the amount of inversion required to form salt-cored anticlines with geometries like those observed in our natural prototype. Furthermore, the experimental results have been useful in inferring the basement fault's position simply from the geometry of the salt anticline, a practical result for basins containing

salt units since seismic signal attenuation produced by these levels hinders the study of the basement structure.

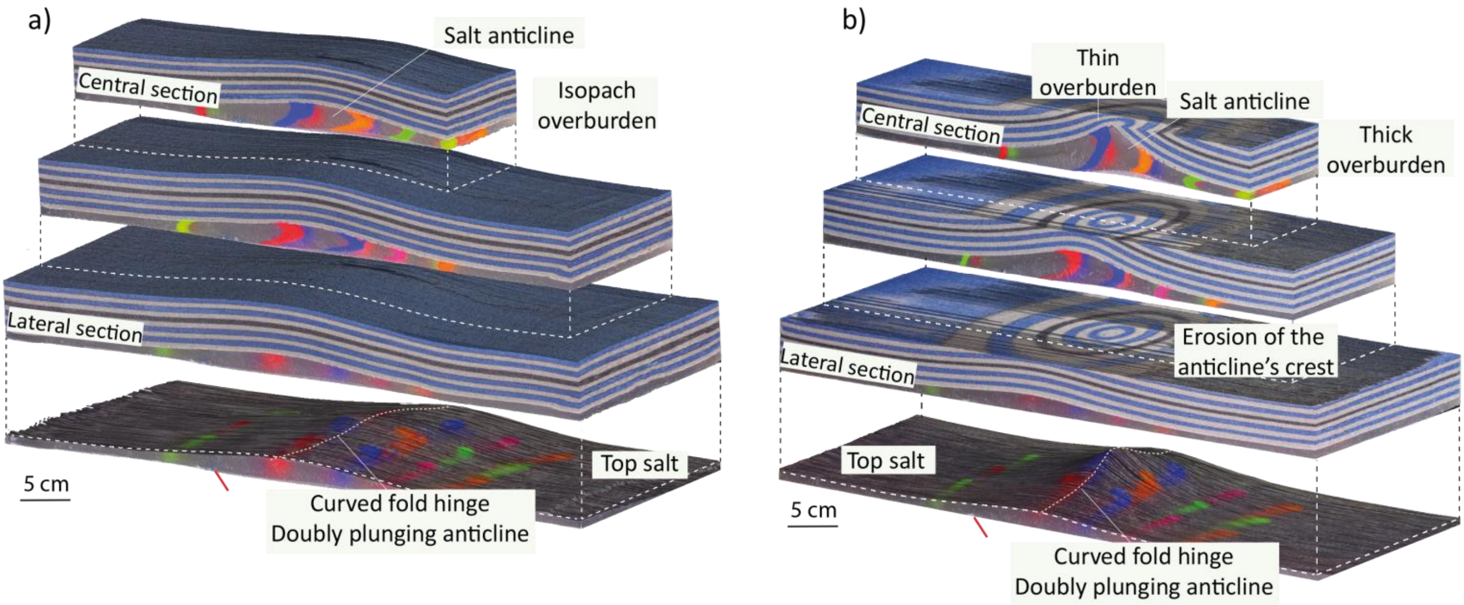

Figure 39 : 3D voxels of the baseline model PB01 (Fig. 1a) and the model PB04 with erosion (Fig. 1b) showing the doubly plunging anticline at top of salt and different longitudinal and transverse cross-sections illustrating the along-strike structural style.

Fatbox - a comprehensive toolbox for fault network analysis

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Abstract
Characterization of complex fault systems is vital for understanding the tectonic history and present-day deformation of specific regions as well as analyzing associated seismic hazard or potential for subsurface use. Three main approaches have been used to study fault network evolution through space and time: (1) Complementary to natural systems, accessible on the field or using remote sensing imagery, the modeling approach provides interesting inputs. (2) Analogue models are a classical tool, intrinsically 3D, that are limited in terms of theological complexity and that offer precise result in a short time. (3) Numerical models are able to reproduce complex rheology in 2D or 3D in an entirely controllable setup and direct access to relevant variables like stress tensor or strain rate, with resolution limited by computational efficiency. Given the often very large numbers of faults within a given target area or model, the development of an automatic method for fault extraction, tracking and analysis can facilitate spatiotemporal analysis and reveal details that were inaccessible before at such high resolution.

Here we present the Fault Analysis Toolbox [Fatbox], an open-source Python-based library designed to extract and characterize fault networks from both observational data, or from analogue and numerical modeling results. The faults can be extracted semi-automatically by specifying very few parameters related to image processing. Alternatively, the structural analysis can be built on a manually digitized fault network. The fault systems are described using networks, composed of nodes linked by edges. This structure allows first to capture natural fault and fracture systems in all their complexity, and second to follow the evolution of the networks both temporally and spatially. The structural analysis is fully automated and provides access to the strike, dip angle, dip direction, extension, throw, and displacement. This information can be used to generate displacement length profiles, rose plot of strike, spatial distribution, length histograms.

Fatbox provides a set of more than 150 functions and 15 recipe scripts to adapt to the user's specific needs and immediately perform topological geometric and structural analysis in an intuitive, consistent and reproducible way.
The library extracts and analyzes structures visible in the topography which extend the scope of future applications to data derived for example from bathymetry, hydrologic networks, landslides mapping, using natural data or models results.

The role of rheological contrast in strike-slip fault interactions.

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Abstract
Strike-slip faults in nature typically have complex architectures, consisting of numerous spaced segments separated by steps or consisting of anastomosing, linked fault zones. Understanding fault interaction and linkage is important due to their multiple applications in geothermal resources, hydrocarbon exploration, and especially from a seismic hazard perspective. Previous studies have described strike-slip fault interaction as a function of loading, stress disturbances, geometry of the previous structures and the rheology. Crustal rheological contrasts have an impact on the Coulomb friction coefficient, thereby conditioning the segmentation, displacement and orientation of the regional stress field.

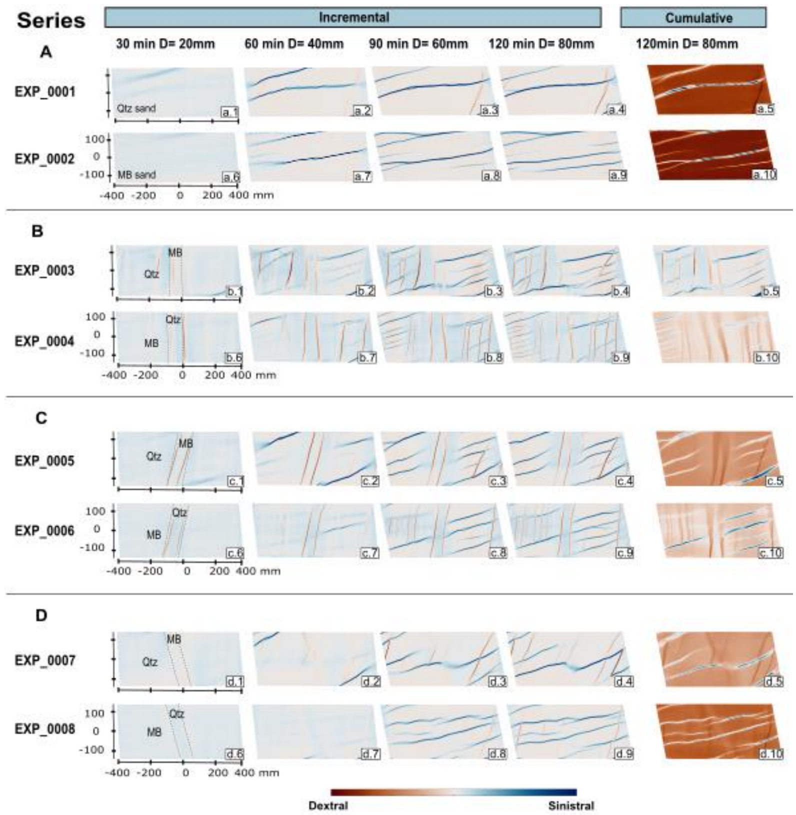

Figure 40. PIV analysis of analogue modeling experiments; Qtz = quartz sand; MB = microbeads

In this study we used scaled analogue models to assess the role of *vertical* rheological contrasts in distributed strike-slip shear experiments using quartz sand (Qtz) and/or microbeads (MB), which have internal friction angles of c. 36° and c. 22°, respectively. These brittle materials represent upper crustal rocks and overly a viscous layer representing the lower ductile crust. Experiments have been organized in 4 series, testing first the two types of brittle materials independently (Fig. 1, A) and then by adding a c. 5 cm wide, central band of either quartz or microbeads (Fig 1, B), which in the last two series (Fig 1, C & D) was oriented in different directions with respect to the shear direction. Our results show that the variation of materials and the orientation of the vertical rheological contrast have an effect on the orientation and behaviour of strike-slip faults. This may be an important factor to be considered in the study of major active faults cutting different rock types.

Patterns of deformation in accretionary wedges during accretion cycles with different settings of décollement configuration

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Abstract

Accretionary wedges at plate subduction zones are developed by repetition of an accretion cycle which starts with frontal accretion and ends with basal accretion (underthrusting). The location of deformation in the accretion wedge is correlated with the accretion cycle, which migrates from the outer (frontal) part to the inner part. This kind of cyclic pattern of deformation is crucial for understanding the kinematics and dynamics at plate subduction zones. To examine how deformation styles and thrust activity evolve during the accretion cycles, we performed sandbox analog modeling with several different settings of *décollement* configuration.

In this study, we performed 2-D, large-shortening (1 m) analog sandbox experiments to examine how the strain patterns are affected by different settings of *décollement* configuration. Four settings (Types 1–4) of the incoming sediment layers were examined in this study, which include Type 1, continuous, single *décollement*; Type 2, continuous, double *décollement*; Type 3, discontinuous, single *décollement*; and Type 4, discontinuous, double *décollement*. Serial side-view digital photographs were quantitatively analyzed with an open-source DIC software to characterize the accretion cycles, underthrusting/ underplating, and reactivation of pre-existing thrusts (out-of-sequence thrusts).

The reference models with single *décollement* (Type1) were dominated by periodic cycles of frontal accretion with landward propagation of strain, uplift, and reactivation of the pre-existing thrusts, which progressively increased in strength and then approached the critical state (Figure 1). Each cycle was composed of preparation (Phase 0), initiation (Phase 1), accretion (Phase 2), and reactivation (Phase 3). Through frontal accretion, the wedge accumulated the strain internally with landward migration of the basal coupled area along the plate interface, which caused uplift and reactivation of the landward preexisting thrusts in the wedge (hardening). When a new frontal thrust emerged at the deformation front (Phase 1), the basal coupling suddenly ceased (softening). Through this cycle, the entire accretionary wedge progressively increased in strength while experiencing hardening and softening and approached the critical state. The double *décollement* models (Type 2) showed a similar accretion cycle to Type 1 models, but it consisted of a combination of shallow-rooted and deep-rooted frontal thrusts, meaning that the *décollement* stepped up and down between the interbedded and basal weak layers. This promoted sediment underthrusting at the frontal part of the wedge during the early phase of the accretion cycle and favored the connection of pre-existing deep-rooted thrusts with shallow-rooted thrusts. A frictional interruption in the basal *décollement* (Type 3 or 4 models) produced a combination of a steep-taper inner wedge and a gentle-taper outer wedge and disturbed the wavelengths of the accretion cycle. The single *décollement* models (Type 3) were dominated by high-angle out-of-sequence thrusts, while underplating was significantly promoted in the double *décollement* model (Type 4) where the interbedded *décollement* acted as a low-angle, smooth-surface megathrust.

These results shed light on the impact of properties and homogeneity of the incoming sediment and the plate interface on the deformation zone in accretionary wedges through multiple accretion cycles. Comparisons of our results with natural subduction zones will contribute to understand the mechanisms and dynamics of the deformation process and the strength evolution in natural subduction zones.

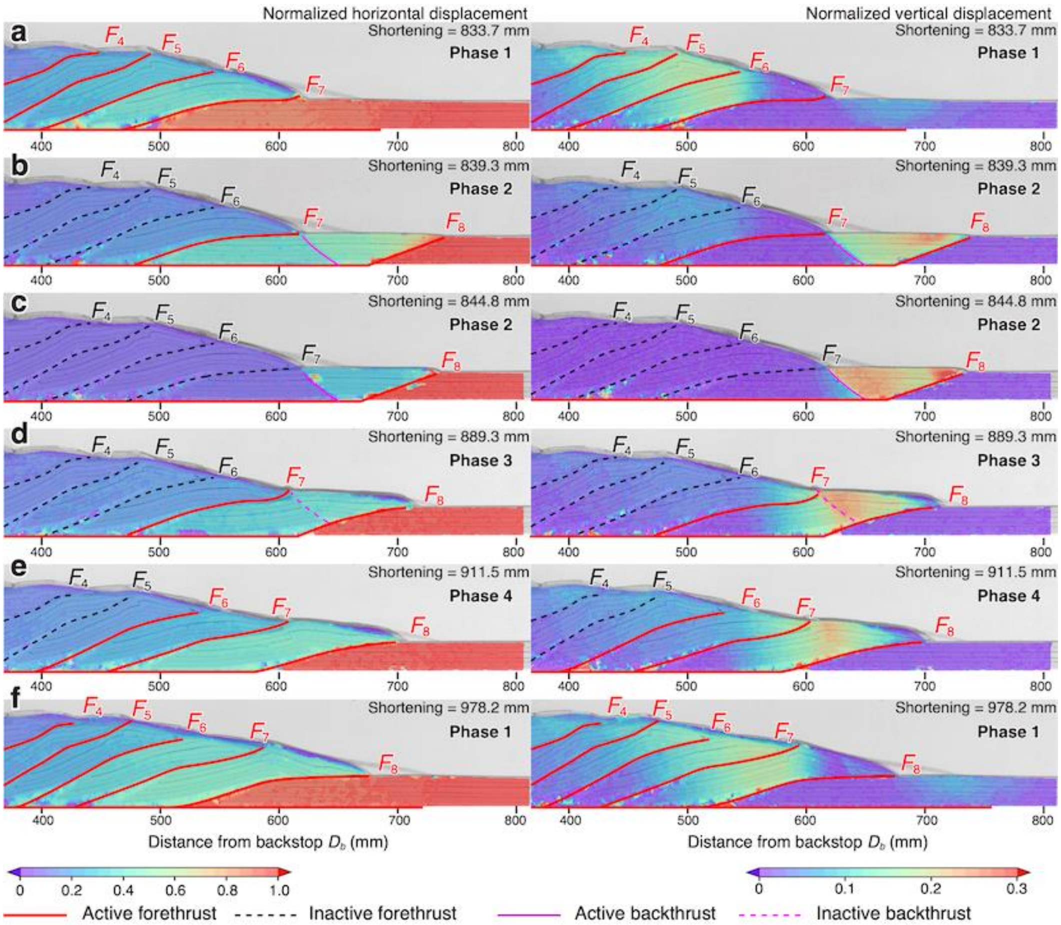

Figure 41: Sequential images of the normalized horizontal (left) and vertical displacement (right column) showing an accretion cycle in the continuous, single décollement model (Type 1)

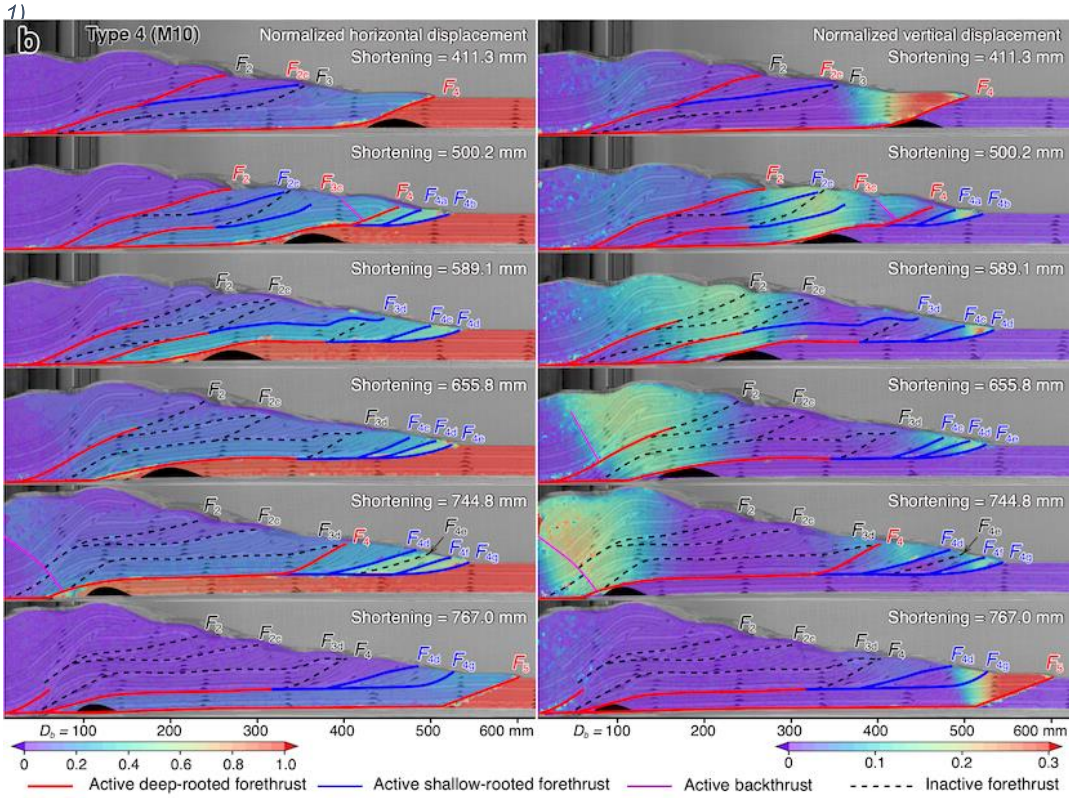

Figure 2: Sequential images of the normalized horizontal (left) and vertical displacement (right column) showing an accretion cycle in the discontinuous, double décollement model (Type 4).

GPU-based finite difference solution of 3D stress distribution around continental plateaus in spherical coordinates

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Abstract
On Earth, different geodynamic features form in response to a tectonic event. Collisional environments can form continental plateaus, such as the Tibetan plateau, which are characterized by an unusually large crustal thickness. The crustal thickness and topography variations between the plateau and the neighboring lowlands generate lateral variations of gravitational potential energy (GPE). These GPE variations cause the thickened crust to flow apart and thin by gravitational collapse. Although plateau and lowland are largely in isostatic equilibrium, the spatial GPE variations must be balanced by horizontal differential stresses, which prevent the plateau from flowing-apart instantaneously. The distribution and magnitude of these stresses around plateaus, especially around corners for three-dimensional (3D) spherical geometries relevant on Earth remain unclear. Due to the ellipticity of the Earth, the lithosphere is mechanically analogous to a shell, characterized by a double curvature. The mechanical characteristics of a shell can be fundamentally different to the ones of plates, having no curvature in their undeformed state. The quantification of the magnitude and spatial distribution of strain, strain-rate and stress inside a deforming shell is important to understand the dynamic processes around plateaus, but technically challenging since it requires high-resolution and high-performance computing.

The aims of this study are to quantify the impact of the crustal and mantle viscosity, the impact of a power-law flow law, the impact of curvature and the impact of the corner region on the resulting stress field. To achieve this, we use a simplified plateau geometry and density structure implemented in a spherical coordinate system. The curvature is modified by varying the radius of the coordinate system, without altering the initial geometry. We particularly focus on stress magnitudes and distributions in the corner regions of the plateau.

Here, we present numerical calculations solving the Stokes equations under gravity, using a combined linear and power-law viscous flow law. We employ the pseudo-transient finite difference (PTFD) method, which enables efficient calculations of high-resolution (700x200x200 grid cells) 3D deformation processes by implementing an iterative implicit solution strategy of the governing equations. The main challenges for the PTFD method are to guarantee convergence, minimize the required iteration count and speed-up the iterations. We implemented the PTFD algorithm using the Julia language. The Julia packages ParallelStencil.jl and ImplicitGlobalGrid.jl enable optimal parallel execution on multiple CPUs and GPUs and ideal scalability up to thousands of GPUs.

Uplift constraints from analogue modelling of basin inversion:

Application to the Trento platform, eastern Southern Alps

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Introduction
During the Cenozoic evolution of the Alps, the Adriatic plate is traditionally considered as a rigid indenter. The internal structure of the northernmost part of the Adriatic microplate in the eastern Southern Alps of Italy and Slovenia, referred to as Dolomites Indenter (DI), however, demonstrates significant internal deformation at least from the Miocene on. The DI contains the structural memory of Jurassic extension resulting in a platform-basin geometry and subsequent shortening is accommodated within a WSW-ENE striking, S-vergent fold-and-thrust belt (Fig. 1a). Focusing on the western (i.e., Trento) platform within the DI, we argue that compositional heterogeneity in the crust linked to Permian intrusives and extrusives (i.e., Athesian Volcanic Complex, AVC) together with inherited basement structures are key for understanding crustal deformation and surface uplift patterns associated with basin inversion.

Experimental setup
The brittle upper crustal scale analogue experiments consist of quartz sand and the differentiation of the crust into 2 platforms and 2 basins, a result of crustal extension, was pre-scribed by implementing initial, pre-shortening thickness variations between platforms and basins (Fig. 1b-e). This platform-basin configuration was shortened parallel to the basin axes (Fig. 1b-e). Compositional heterogeneity is assumed to have strengthened locally the upper crust, which is implemented by varying the thickness (Fig. 1c) and shape (Fig. 1d) of the western model platform (WP), representing the northern Trento platform in the DI. Pre-existing basement faults are accounted for by pushing the deformable model over a fixed, 0.3 cm thick basal plate (Fig. 1e). The northern border of the fixed basal plate simulates N-dipping Permian normal faults, bordering the AVC to the south (Selli, 1998).

Preliminary results
Our analogue modelling results indicate that WP variations in thickness, shape, and basal plate forcing, lead, compared to the reference model (Fig. 1b, Model 1 in Fig. 2a-c) with simple platform-basin geometry, to (i) overall fewer thrust sheets (2 to 3 instead of 4), (ii) footwall cut-offs of the frontal thrust further in the hinterland, and to (iii) longer and flatter flats of the frontal thrust (Fig. 2d-f). Regarding the topographic evolution, a variation in, e.g., shape leads to similar uplift of thrust sheets I and II (Model 3, cross-section f-f' in Fig. 2e-f). For the case of basal plate forcing, modelling results show strain localization at the margin of the basal plate and stronger uplift within the southern WP and limited to zero uplift of the northern WP. Compared to the DI, the latter underlines documented little vertical movement north of the Valsugana fault system since the Jurassic. Based on our modelling results, we infer that differential uplift N and S of the Valsugana fault system, could be the result of a stronger northern Trento platform confined by normal faults.

Outlook
As the presented study is an excerpt of a larger research project (Sieberer et al., 2023), our findings from crustal-scale analogue modelling will be combined with close-meshed thermochronological data which cover the entire Dolomites Indenter. Additionally, a combination with results of lithospheric-scale

analogue and of numerical modelling will further help to display the complex tectonic evolution of this highly stressed crustal fragment of the eastern Southern Alps.

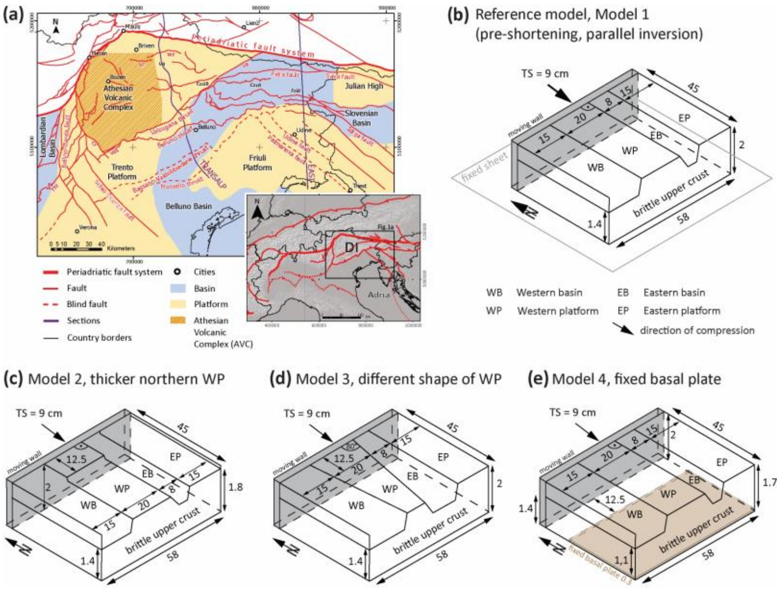

Figure 42 : (a) Late Triassic/Jurassic platform-basin configuration projected over the present-day geography and overlain by the tectonic map of the Dolomites Indenter. Modified from Sieberer et al. (2023). (b-e) Simplified sketches of the geometric and kinematic modelling setup of the reference model and its variations.

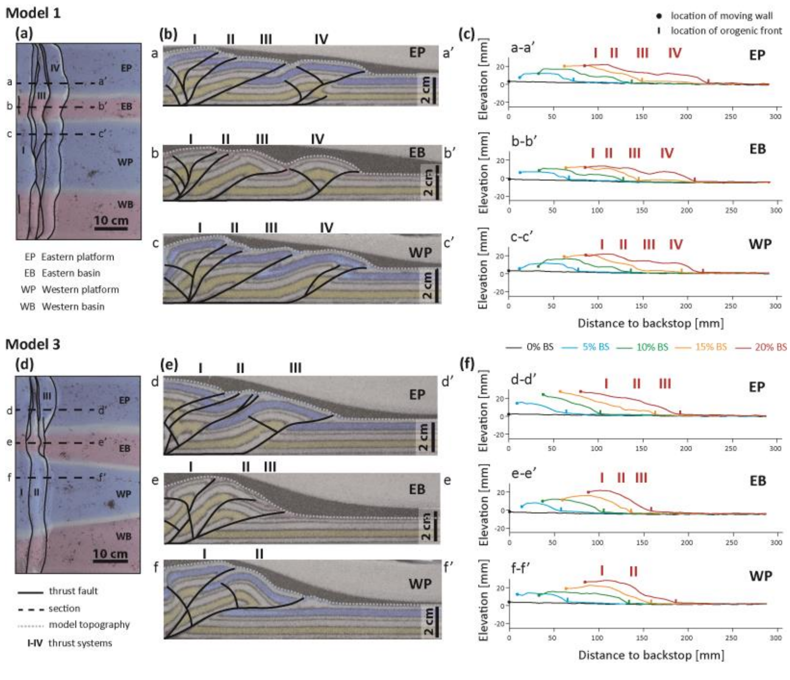

Figure 43 : Experimental results of the reference model (model 1) and a variation in terms of shape of the western platform (model 3) shown by (a, d) top-view pictures, (b, e) cross-sections, and (c, f) topographic profiles at several time steps during the model run. Abbreviations: BS = bulk shortening.

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Modes of reactivation of pre-existing rifted basins by forced subduction initiation

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Abstract

Basin inversion is widely observed in the past decades, it refers to the basin which undergoes the transition from the extensional to compressional stress regime. Previous studies indicate that basin inversion can cause the uplift and erosion of basin structure, which is conflicted with a lot of observations showing that even under compression, subsidence of the basin can also occur. Here we use a 2D numerical model to investigate the responses of the rifted basin to the compression at the onset of subduction, our results show that: 1) With the inception of subduction, the whole basin can keep subsiding almost during the whole process; 2) The subsidence of the basin exhibits periodic characteristics, and there is an "reactivation stage" which can be displayed through the change of subsidence rate; 3) The inherited wavelength of rifting basin's sag induced rheological heterogeneities controls the rates and location of subsidence and uplift. Our model results show that even under compression and undergoing a change of stress regime, the subsidence of the whole basin can also be the response of basin inversion, this indicates that the judge of basin inversion should consider more about the broader tectonic setting.

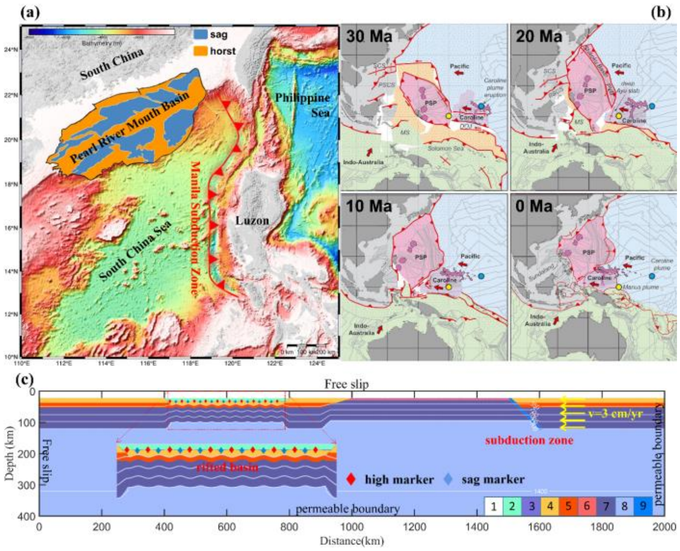

Figure 44 : Tectonic setting, evolution history of Pearl River Mouth Basin (PRMB), and model design. (a) Tectonic setting of PRMB. (b) The reconstruction of Philippine Sea and East Asian plate since 30 Ma (edited from Wu et al., 2016). (c) Initial setup of model including both rifted basin and subduction zone.

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Fault zone porosity evolution in analogue experiments based on 3D X-ray micro-tomography

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Abstract

Characterizing the properties of granular materials is key for understanding fault nucleation and development in scale models and their bearings on natural fault systems. In this study we quantify fault porosity evolution in relation to fault displacement for contractional tectonic systems using X-ray 3D micro-tomography.

A series of upper crust-scale analogue experiments consisting of dry quartz sand (Willingshofer et al., 2018) have been performed where the amount of shortening has been varied to produce thrust faults with variable off-sets, ranging from 0.2-2.8 cm. Geometrically and kinematically, our setup shows some similarities to that of Malavieille et al. (1983) where the model material is placed on two plastic sheets, with the mobile sheet being pulled below the overlaying stationary sheet. This basal kinematic condition triggers localization of deformation at the velocity discontinuity (VD) and the formation of conjugate thrusts with variable off-set. After wetting, drill-cores, which penetrated the fault structures, have been extracted from the experiments and imaged with a ZEISS Xradia 610 Versa 3D X-ray Microscope located in the EPOS-NL Multi-scale Imaging and Tomography Facility (MINT) at Utrecht University. Image analysis was performed using the Aviso software package.

The results of this study show that porosity of intact (non-faulted) samples at great distance to the fault structure is ~39%. Across the faults, porosity increases to ~40% in low off-set faults (0.2 cm displacement) and to ~45% in high offset faults (2.8 cm of displacement). Porosity in faults increases quickly during early phases of fault development and decays with increasing displacement, which is consistent with decompaction behavior of granular materials upon fault formation (Mandl et al., 1977; Lohrmann et al., 2003). Our results bear important implications for the evolution of porosity and permeability of faults in analogue experiments and natural systems.

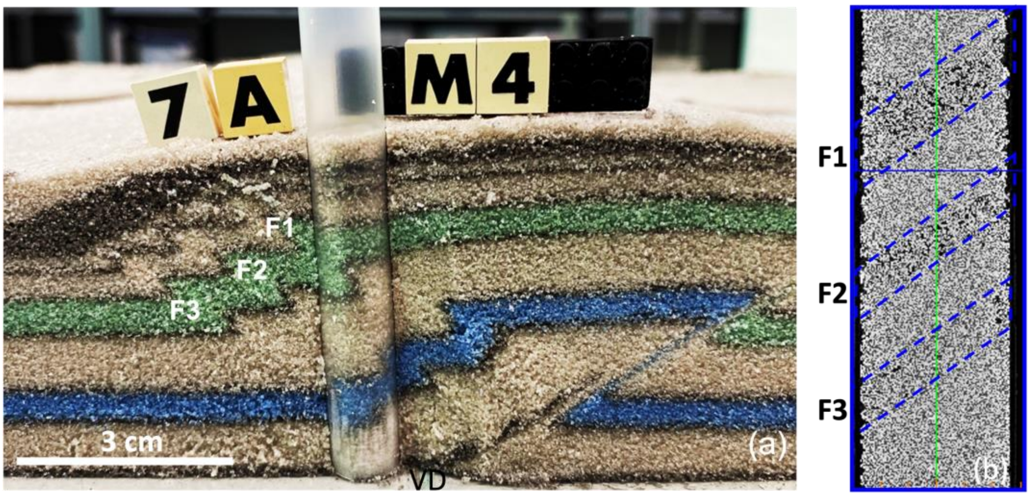

Figure 45: Result of contractional analogue model (a) where a drill-core has been extracted across faults F1-F3. (b) Image showing faults F1-F3 as high porosity zones based on micro-CT scanning. VD=velocity discontinuity.

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Geodynamic models, spatial data, and subsurface uncertainty assessment - Some conceptual thoughts

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Abstract
While one of the main objectives of geodynamic models is to understand the mechanisms at stake in earth processes and their controlling parameters, they do not easily allow for honoring spatial observations. In analog models, the number of experiments which can be practically made always remains limited. Numerically, many experiments can be run and the data conditioning can be formulated as an inverse problem. However, its resolution is highly computationally demanding especially for dense spatial data sets. An alternative strategy to bridge the gap between geodynamic modeling and spatial data is to infuse the spatial features learned from geodynamic models into (geo)statistical models. This may be done under the theoretical framework of spatial random fields in 2D or 3D grids, using for instance multi-point statistics or GANs. However, these approaches can be limited by the grid resolution and tend to poorly reproduce large-scale connections between geological objects. An alternative is to simulate geological objects, but again conditioning can be very computationally challenging when objects are large regarding the data spacing and when complex interactions exist between objects. In this presentation, we consider, therefore, the problem of “joining the dots” between sparse spatial observations, e.g., regrouping fault traces identified on seismic sections into faults, or associating samples between stratigraphic sections. We show some examples illustrating how process-based models can be used to infer complex statistical relationships between sparse data. Finally, we discuss some of the research challenges associated with this approach, including representativity, the automatic identification of geological objects on analog models and the possible role of the temporal dimension.

Numerical Modelling of Focused fluid Flow in Ductile/Plastic Rock:

Effects of Geological Heterogeneity and Material Properties

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Abstract

This study explores the coupling of solid deformation and fluid migration in geodynamical simulations and subsurface engineering operations through two-phase flow equations. While simple models have been employed to investigate the impact of material properties on fluid-rock systems, realistic models considering geological heterogeneity are limited due to the complex nonlinear nature of these systems. In this work, we present a viscoelastic numerical model that employs a hydromechanics coupling approach using an efficient pseudo-transient solver. This model allows for the simulation of focused fluid flow with sharp material boundaries.

Initially, we investigate the influence of a less permeable block on the propagation of channelized fluid flow by varying the permeability factor and block size over multiple orders of magnitude. Our findings reveal that while an obstacle does not entirely halt the localized channels, it does divert and decelerate their progression. A wider block enables channels to pass through at a slower pace, whereas a narrower block deflects the channels towards the sides. Furthermore, we examine the dynamics of fluid channels encountering a sharp geological boundary characterized by significantly lower permeability. We incorporate realistic geological materials by adjusting the bulk viscosity and permeability exponent for different substances within our models. This approach allows for the consideration of more authentic scenarios, including intraformational and top-sealing layers relevant to CO2 storage and natural fluid migration (e.g. Fig. 1).

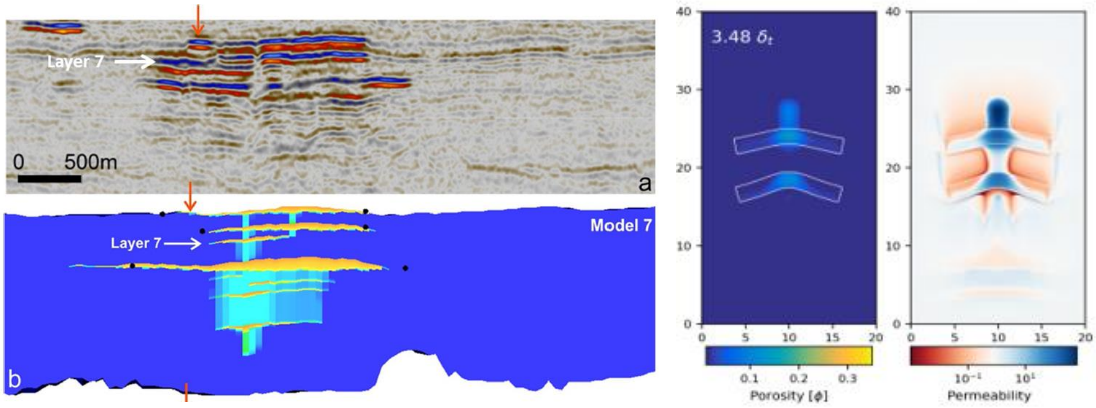

Figure 46 : Seismic image and conceptual model of CO2 plumes at Sleipner and a numerical mode with multiple material layers..

The results obtained from this research contribute to a deeper understanding of the complex behavior of fluid-rock systems with geological heterogeneity. The developed numerical models and the insights gained can aid in the assessment and optimization of subsurface engineering operations, particularly those related to fluid flow and deformation in ductile/plastic rocks.