Abstract Volume
14th Swiss Geoscience Meeting
Geneva, 18th – 19th November 2016

8. Rock mechanics, Rock physics and Geophysics
8. Rock mechanics, Rock physics and Geophysics

Marie Violay, Brice Lecampion, Claudio Madonna, Matteo Lupi, György Hetényi

Schweizerische Paläontologische Gesellschaft,
Kommission des Schweizerischen Paläontologischen Abhandlungen (KSPA)

TALKS:

8.1 Barnhoorn A., Verheij J., Frehner M.: Transition from elastic to inelastic deformation identified by seismic attenuation, not seismic velocity

8.2 Carrier A., Lupi M., Haddad A., Baron L., Linde N.: Bouguer anomaly inversion at the Nirano Mud Volcanic Field, Italy, to infer depth and density variations of hydrocarbon and mud reservoirs

8.3 Duran J.A., Obermann A.: 2D sensitivity kernels for monitoring weak changes on highly heterogeneous elastic medium

8.4 Häusler M., Schmelzbach C., Sollberger D.: A new seismic vector source: the Galperin source

8.5 Malvoisin B., Podladchikov Y.Y., Connolly J.A.D.: Role of metamorphic reactions on deformation and fluid flow: a new fully-coupled model

8.6 Pirot G., Linde N., Mariethoz G., Bradford J.: Geophysical data inversion with graph cuts under geological realism constraint

8.7 Somogyvári M., Jalali M., Bayer P.: Fracture network characterization using a stochastic transdimensional algorithm


POSTERS:


P 8.2 Wenning Q., Madonna C., Moulas E., Burg, J.P.: Petrophysical properties through a Grimsel granodiorite shear zone – Implications for geothermal reservoir evaluation and modelling

P 8.3 Ciardo F., Lecampion B.: Modelling of fluid injection into a frictional weakening dilatant fault


P 8.5 Nikolskiy, D., Lecampion, B.: Simulating fully three dimensional pressurized fracture propagation

P 8.6 Cornelio C., Violay M., Spagnuolo E.: Viscosity fluid influence on stick-slip motions

P 8.7 Dutler N., Valley B., Krietsch H., Amann F., Gischig V. & Evans K.: Stress Characterisation and stress modeling at the Grimsel Test Site for the In-situ Stimulation and Circulation Project
<table>
<thead>
<tr>
<th>Symposium 8: Rock mechanics, Rock physics and Geophysics</th>
<th>Platform Geosciences, Swiss Academy of Science, SCNATSwiss Geoscience Meeting 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>P 8.8 Blum T., Lecampion B.: Acoustic monitoring of laboratory hydraulic fracture growth under stress and pore pressure</td>
<td></td>
</tr>
<tr>
<td>P 8.9 Dombrovski E., Vogler D., Walsh S.D.C., Perras M.A.: Towards Replicating Rock Specimens: A Comparison of Tensile Fractures from 3D Printed and Natural Sandstones</td>
<td></td>
</tr>
<tr>
<td>P 8.11 Sprengel H., Ziegler M.: Analysis of surface roughness of Opalinus Clay extensional fractures</td>
<td></td>
</tr>
<tr>
<td>P 8.12 Orellana L.F., Violay M., Gramajo E., Henry P., Guglielmi Y., Amann F., Nusbaumm C.: Petro-physical characterization of the Main Fault at the Mont Terri Laboratory</td>
<td></td>
</tr>
<tr>
<td>P 8.13 Kakurina M., Guglielmi Y., Nussbaum C., Valley B.: Architecture of a fault zone in Opalinus Clay at the Mont Terri laboratory (Switzerland)</td>
<td></td>
</tr>
<tr>
<td>P 8.15 Hartung E., Caricchi L.: The physical properties of evolved melts and implications for melt segregation and the built-up of large silicic eruptions</td>
<td></td>
</tr>
<tr>
<td>P 8.16 Antunes V., Lupi M., Carrier A., Obermann A., Mazzini A., Ricci T., Sciarra A., Moretti M.: Seismic signals at the Nirano Mud Volcanic Field, Italy</td>
<td></td>
</tr>
<tr>
<td>P 8.17 Haddad A., Lupi M., Gonzalez Vidal D., Ganas A., Kassaras I.: Tectonic and fluid-driven seismic activity in Western Peloponnesse, Greece</td>
<td></td>
</tr>
<tr>
<td>P 8.20 Colavitti L., Hetényi, G.: 3-D shear-wave velocity model of the Central Alps using converted waves</td>
<td></td>
</tr>
<tr>
<td>P 8.21 Hadjadji A., Benaïssa Z., Benaïssa A., Boudella A.: Gray-scale Hough transform for seismic wavefield separation?</td>
<td></td>
</tr>
<tr>
<td>P 8.22 Schnydrig S., May D., Ueda K., Gerya T.: Topographic expressions of coupled surface process and 3Dtectonic models</td>
<td></td>
</tr>
</tbody>
</table>
8.1 Transition from elastic to inelastic deformation identified by seismic attenuation, not seismic velocity

Auke Barnhoorn¹, Jeroen Verheij¹ and Marcel Frehner²

¹ Department of Geoscience and Engineering, Delft University of Technology, Stevinweg 1, NL-2628 CN Delft (auke.barnhoorn@tudelft.nl)
² Geological Institute, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich

The transition from elastic to inelastic deformation occurs at the yield point in a stress-strain diagram. This yield point expresses the moment permanent deformation occurs and is marked by the onset of fracturing in the brittle field at relatively low pressures and temperatures or the onset of dislocation and/or diffusional creep processes in the ductile field at higher temperatures and pressures. Detection of this transition in materials under stress using an indirect measurement technique is crucial to predict imminent failure, loss of material integrity, or of approaching release of energy by seismic rupture.

Here we use a pulse transmission method at ultrasonic frequencies to record the change in acoustic wave form across the transition from elastic to inelastic deformation in a rock-fracturing experiment. In particular, we measure both the acoustic wave velocity (Figure 1B) and attenuation (Figure 1C) with increasing strain from the elastic regime all the way to macroscopic failure.

Our results (Figure 1) show that the transition from elastic to inelastic deformation coincides with a minimum in attenuation (Figure 1C). At the same time, the acoustic wave velocity continues to increase across the transition from elastic to inelastic deformation (Figure 1B). Therefore, the acoustic velocity is not a valid indicator for this elastic-to-inelastic transition.

However, we observe a minimum in attenuation for a range of different rock types (Barnhoorn et al., submitted) and this seems to be an almost universal feature. Therefore, the change in attenuation is a valid indicator for the onset of permanent deformation and fracturing.

Figure 1: Example of mechanical and acoustic data for Whitby shale. A) Axial stress-strain data with shear wave velocity with strain (B) and shear wave attenuation with strain (C), both measured during the uniaxial compression experiment. The strain at which the transition from elastic to inelastic deformation behavior occurs is indicated with the dashed vertical line.

In Figure 2 we propose a conceptual model to explain our observations. Below the minimum in attenuation, pre-existing microfractures close, leading to a reduction of attenuation. Above this minimum, formation of new microfractures occurs and attenuation increases. In other words, attenuation is a function of the fracture density.

That the acoustic velocity does not react in the same way to the change in fracture density (Figure 1B) may be explained by the fracture orientation. For randomly oriented pre-existing microfractures, the fractures perpendicular to the uniaxial compression direction close preferentially. This leads to a preferred fracture orientation parallel to the sample axis at the onset of permanent deformation. New microfractures also preferentially form parallel to the sample axis, accentuating this preferred fracture orientation. This leads to a seismic anisotropy with the fast direction parallel to the sample axis, which increases throughout the experiment (i.e., crossing the elastic-to-inelastic transition).
Figure 2: Conceptual model of fracture closure and opening of new fractures during a uniaxial compression experiment. The uniaxial compression results in a change in fracture density, but also in a change in fracture orientation from random to preferentially vertically oriented.

We propose that analysis of attenuation, not velocity, of acoustic waves through stressed materials may be used, for example, to detect imminent failure in materials, onset of crack formation in pipes or the cement casing in boreholes, or onset of fracturing in the near wellbore area. On a larger scale, attenuation monitoring may help predict the imminent release of energy by seismic rupture.

REFERENCE
Bouguer anomaly inversion at the Nirano Mud Volcanic Field, Italy, to infer depth and density variations of hydrocarbon and mud reservoirs

Aurore Carrier¹, Matteo Lupi¹, Antoine Haddad¹, Ludovic Baron², Niklas Linde²

¹ Département des Sciences de la Terre et de Géophysique, University of Geneva, Rue des Maraîchers 13, CH-1205 Genève (aurore.carrier@unige.ch)
² Institut des Sciences de la Terre, University of Lausanne, Quartier UNIL-Mouline, Bâtiment Géopolis, CH-1015 Lausanne

Mud volcanoes are often encountered in hydrocarbon provinces and considered as natural boreholes for sampling underlying reservoir formations. Mud volcanoes are still poorly investigated with geophysical methods. For example, little is known about their plumbing system or how fluids are transferred from the feeding reservoir to the surface.

To shed light on the underlying geometry of a logistically accessible mud volcanic system, the Nirano Mud Volcanic Field, Italy, we performed a gravity survey across the volcanic system. We used the gravimeter Scintrex CG5 and the GPS Leica 1200 to conduct two profiles striking N45° and N135°.

The Bouguer Anomaly analysed with wavelength filtering indicate at least a 2000m-deep reservoir, two mid-depth reservoirs (i.e., 600 m deep) and three shallow ones (i.e., 100 m deep). Using these observations and previous studies as prior information, the Bouguer anomaly is then inverted via a gradient-based least-squares method that uses the LSQR algorithm and account for data and model covariances. Inversion results suggest two subspheroidal reservoirs at about 1500 m depth that are tilted by 30° that are overlaid by two reservoirs at intermediate depths (i.e. 600 m deep). Density variations range from 100 to 200 kg/m³. Due to the difficulty to constrain both geometry and density of the investigated reservoirs, complementary information (i.e. seismic and electrical resistivity tomography) may be used to further improve the results.

Despite the degree of uncertainty of our investigations, this study represents the first attempt to provide a gravimetry-based geophysical image of the plumbing system of a mud volcanic field.

Figure 1. Top : Bouguer anomaly measured versus topography of the studied area (gray). Bottom : Two Bouguer Anomalies Lines Purple circles : mud volcanoes localization.
8.3

2D sensitivity kernels for monitoring weak changes on highly heterogeneous elastic medium

J. A. Duran¹, Anne Obermann¹

¹ Institute of Geophysics, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich
(alejandro.duran@sed.ethz.ch)

The main goal of most geophysical methods is an investigation and characterization of the subsurface. The most powerful geophysical tool hereby is the study of the passage of seismic waves through the Earth. The Earth is often assumed to be a simple stratified medium and the seismic waves will be reflected and refracted at the stratification boundaries. In classical seismic and seismology applications, this allows us to make direct conclusions about the subsurface from the traveltimes of the waves. However, the Earth is more complicated than the simple layer assumption and shows heterogeneities at different scales (mountain ranges (km), fractures (m), different grains (cm-mm)). These heterogeneities cause the late arriving waves to be multiply scattered within the medium, and wave propagation becomes very complex. These multiply scattered waves are called coda waves.

Besides their random character, coda waves are highly repeatable, such that if the medium remains unchanged over time, subsequent measurements of coda waveforms would be identical. Additionally, coda waves sample the medium very densely and become sensitive to even tiny perturbations of its mechanical (velocity, pressure, etc.) or structural (change of scatterer position, for instance due to fracturing) properties. This feature makes them ideal for monitoring purposes and has led to the development of the coda-wave interferometry (CWI) technique (Poupinet et al., 1984; Snieder et al., 2002; Snieder, 2006).

The technique makes use of coda waves to detect changes in the wave field due to a localized perturbation in the heterogeneous medium. This change is visible as a shift in the travel time between the perturbed and unperturbed wave fields. Pacheco & Snieder (2005) developed a sensitivity Kernel which describes the relation between a localized perturbation in an acoustic medium and the change in the travel time. Since then, the detection of temporal changes with coda waves has been successfully applied in different areas in seismology such as: landslides (Mainsant et al. 2012), fault zones (Poupinet et al., 1984; Brenguier et al. 2008b), volcanoes (Grêt et al. 2005; Brenguier et al. 2008a), hydrocarbon reservoirs (Meunier et al. 2001), injection induced changes (Obermann et al, 2015; Hillers et al. 2015), as well as civil engineering applications (Larose et al. 2015, Salvermoser et al. 2015).

Despite the success obtained by the theoretical development of this Kernel, an extension on elastic medium is needed for a more complete description of the multiple scattering phenomena.

In a heterogeneous elastic medium, P and S waves are constantly converted from one state to another. A discrimination of the intensity contribution for each state is possible by an analytical approach which leads to a derivation of sensitivity kernels for each state individually. This means that travel time changes caused by a perturbation in the P-wave and S-wave velocities can be individually analyzed.

In the current study we address this problem from a numerical perspective. We developed 2D finite difference simulations over a synthetic highly heterogeneous elastic medium. The heterogeneity of the medium is characterized by verifying the equipartition of seismic waves (Hennino et al. 2001).

Then, P and S wave fields are recorded individually and each Kernel (KP and KS) is built from the intensity of the waves. Relative strength of KP and KS is studied, the effect of the source mechanism on the kernels as well as the sensitivity of the waves at different time steps.
Figure 1. Spatial representation of the sensitivity kernel that describes the statistical time the waves spent in each part of the medium. The two peaks (R, S) indicate the position of the station pair. The time statistically spent in a region decreases with its distance to the stations (Obermann et al. 2013b).

REFERENCES
8.4

A new seismic vector source: the Galperin source

Mauro Häusler¹, Cedric Schmelzbach¹ & David Sollberger¹

¹ Institute of Geophysics, ETH Zurich, Sonneggstrasse 5, CH-8092 Zürich (cedric.schmelzbach@erdw.ethz.ch)

In the last decades, multicomponent seismic acquisition has experienced an increasing popularity in both exploration seismic surveying as well as in near-surface investigations (e.g., Hardage et al., 2011; Sollberger et al., 2014). Multicomponent measurements involve three-component (3C; vector) sources and/or 3C receivers and allow analysing the seismic wavefield in more detail than using single-component data only. For example, multicomponent data enable the analysis of shear waves to estimate elastic parameters for applications such as earthquake hazard and ground stability assessment. Furthermore, multicomponent data are critical for anisotropy and spatial seismic wavefield gradient studies.

Classic vertically-directed sources are, for example, a sledgehammer striking a steel plate and Vibroseis-sources. In order to excite horizontally polarized waves, shear beams and tilted or horizontal Vibroseis-sources have been employed. However, the source mechanism and source-to-ground coupling of these horizontally-directed sources may differ from vertically-directed sources, thus compromising a combined processing. Furthermore, horizontally-directed sources are usually more cumbersome in field operations. By hitting the two opposite sides of a metal wedge with 45°-inclined sides with a sledgehammer, a horizontal and a vertical source component can be obtained by either summing or subtracting the two records, which corresponds to a coordinate transformation (Figure 1a; Schmelzbach et al., 2016). Turning the wedge by 90° in the horizontal plane allows acquiring an additional transverse horizontal component. However, the re-positioning of the wedge is labour intensive and may change the source coupling. Furthermore, the total acquisition requires hits on four sites to obtain three directed source components; one vertical source-vector is redundant.

![Figure 1. a) Metal wedge source as used, for example, in Schmelzbach et al. (2016). b) The Galperin source, a metal-wood construction using the Galperin configuration. Blue arrows indicate the source vector orientations.](image-url)
With the motivation to develop an effective vector source with uniform source coupling for all three components, we designed a new source, called the Galperin source (Häusler, 2016). The acquisition principle is inspired by the Galperin receiver configuration known from, for example, the Streckeisen triaxial seismometer STS-2. The Galperin source consists of a three-sided steel pyramid that is struck with a sledgehammer (Figure 1b). The three normal vectors (corresponding to the source impact directions) are all orthogonal to each other with an angle of 54.74° to the vertical axis and separated by 120° in the horizontal plane. After acquisition, the seismic data is rotated into the Cartesian coordinate system to obtain source vectors parallel to all three coordinate axes. The Galperin geometry brings the advantage of identical impact patterns and consistent source coupling for all source components with three hits only.

To validate the Galperin source, we compared it to a metal plate and the metal wedge, all struck with the same sledgehammer. We found that the Galperin source compares well to these two sources when analysing, for example, amplitudes and phases, hodograms and frequency spectra. A possible limitation of the Galperin configuration is its sensitivity to errors in orientation, levelling and varying source strength. Synthetic-data studies indicate that the orientation and levelling error must not exceed 3° to keep the amplitude errors below 5%.

REFERENCES
8.5
Role of metamorphic reactions on deformation and fluid flow: a new fully-coupled model

Benjamin Malvoisin1,2 Yury Y. Podladchikov1, & James A. D. Connolly3

1 Institut des Sciences de la Terre, University of Lausanne, Géopolis, CH-1015 Lausanne (benjamin.malvoisin@unil.ch)
2 Centre d’hydrogéologie et de Géothermie, University of Neuchâtel, Rue Emile Argand 11, CH-2000, Neuchâtel
3 Institut für Geochimie und Petrologie, Department of Earth Sciences, ETH Zürich, Clausiusstrasse 25, CH-8092 Zürich

Metamorphic reactions do not only modify rock chemical and mineralogical compositions but they also have strong impacts on density and porosity. Therefore, the role of reactions on deformation and fluid flow has to be taken into account for modelling the evolution of metamorphic environments.

Here, we present a new model coupling reaction, deformation and fluid flow. Based on mass conservation and using a poro-viscoelastic rheology, new equations are derived for fluid pressure and porosity evolutions in reactive systems. The impact of reactions on density and porosity is predicted by using energy minimization calculations at the equilibrium. A delay in the achievement of equilibrium is introduced to model the effect of reaction kinetics. The validity of this model is demonstrated through the reproduction of the purely mechanic and equilibrium limits. Among the various parameters controlling the impact of reaction on deformation and fluid flow, the Clapeyron slope relating the evolution of porosity with pressure is shown to play a key role. This is well evidenced with the modelling of reacting porosity waves propagation in the crust providing a new complete mechanism for episodic tremor and slip events propagation.

8.6
Geophysical data inversion with graph cuts under geological realism constraint

Guillaume Pirot1, Niklas Linde1, Grégoire Mariethoz2 & John Bradford3

1 Institut des sciences de la Terre et de l’environnement (ISTE), University of Lausanne, UNIL-Mouline, CH-1015 Lausanne (guillaume.pirot@unil.ch)
2 Institut des dynamiques des surfaces terrestres (IDYST), University of Lausanne, UNIL-Mouline, CH-1015 Lausanne
3 Department of Geosciences, Boise State University, 1910 University Dr., Boise, ID 83725, USA

In hydrogeological applications, flow path and mass transfer are strongly influenced by the subsurface connectivity. When using geophysics to characterize an aquifer, it becomes important that geophysical inversion results are in agreement with the expected geological setting. Another important aspect in such applications is the quantification of uncertainty. To achieve these, we combine two concepts. Within a Markov chain Monte Carlo (MCMC) method that enables inversion of geophysical data and uncertainty quantification, we embed a multiple-point statistics algorithm which allows to generate complex geological structures. Compared to iterative pixel-based multiple-point statistics technique, patch-based multiple-point statistics techniques such as graph cuts considerably speed-up the algorithm. The efficiency of the algorithm has already been proven on synthetic cases.

Here we propose a first-ever field application by estimating the porosity field from ground penetrating radar data at the Boise Hydrogeophysical Research Site, Boise, Idaho. We consider two different prior models (training images): one multi-Gaussian and one outcrop-based that are in agreement with available porosity data. In both case, the posterior realizations honor the pattern characteristics of the related prior. Convergence of the multi-Gaussian model is much faster than for the outcrop-based prior model, but the latter is geologically more realistic and it better preserves the full porosity range of the prior.
8.7

Fracture network characterization using a stochastic transdimensional algorithm

Márk Somogyvári*, Mohammadreza Jalali*, Peter Bayer*

1 Department of Earth Sciences, ETH Zürich, Sonneggstrasse 5 CH-8092 Zürich (mark.somogyvari@erdw.ethz.ch)

Transport in fractured media is dominated by the geometry of the fracture network. While some geometrical properties of fractures like orientation and spacing can be easily captured from borehole logs, core images and outcrops, the assessment of the actual geometry of the fractured system (e.g. fracture length, height and width) is a great challenge, and could require the interpretation of transport related experiments. Existing interpretation methods are limited as they either approximate the fracture system as continuous media or provide fracture network realizations that are not conditioned to the measurements. Modern tomographic investigation methods in hydrogeology have proven to be able to provide insight into the distribution of the physical properties to infer the geometries of the fractures via introducing discrete fracture network (DFN) models which can be used for parametrization and rapid forward modelling. In this study we present a novel concept, using the reversible jump Markov Chain Monte Carlo (rjMCMC) method to characterize the fracture network geometry by interpreting tomographic tracer experiments in fractured aquifers.

A random initial DFN realization is generated using the statistical information on the fractured media, such as fracture intensity, fracture length distribution and fracture spacing. This fracture network is then evolved through an iterative stochastic inversion process. During each iteration a new DFN realization is proposed by updating the last accepted realization via deleting, adding or moving a fracture in the DFN. An implicit upwind finite difference method is used to simulate fluid and heat transport within the fracture network during the tomographic thermal tracer experiment – as the forward model of the inversion. To evaluate the proposed DFN realization, the Metropolis-Hastings-Green acceptance criterion is used which is the standard evaluation step of rjMCMC methods. A successful rjMCMC modelling requires large number of iterations and results in an ensemble of thousands of equally probable DFN realizations. From the ensemble of accepted realizations fracture probability maps are generated – showing the possible fracture locations thus highlighting the dominant transport conduits. Individual DFN realizations from the ensemble can be used for deterministic modelling whereas using the full ensemble it is possible to create stochastic flow and transport simulations for practical applications (e.g. risk assessment, efficiency studies).

Figure 1. Visual summary of the used reversible jump Markov Chain Monte Carlo method for discrete fracture network (DFN) reconstruction.
8.8

Coupled hydro-mechanical modelling of seismicity induced by gas production

Dominik Zbinden¹, Antonio Pio Rinaldi¹, Luca Urpi¹ & Stefan Wiemer¹

¹ Institut für Geophysik, ETH Zürich, Sonneggstrasse 5, CH-8092 Zürich (dominik.zbinden@sed.ethz.ch)

Induced seismicity due to natural gas exploitation has been observed at many sites around the world. It has been suggested that the pressure drop caused by gas production leads to compaction, which affects the stress field in the reservoir and the surrounding rock formations. This in turn can reactivate pre-existing faults and hence trigger earthquakes. Although these induced seismic events are often moderate in magnitude, some of them can be felt at the ground surface causing nuisance to the population and sometimes moderate damages to structures. A well-known example is the Groningen gas field in the Netherlands, where production-induced seismicity has caused damage to buildings close to the production site. Given the high public impact, it is crucial to understand the underlying processes during natural gas exploitation.

We carried out numerical simulations to better determine the conditions leading to fault reactivation. In our numerical model, gas is produced from a permeable reservoir, divided into two compartments by a low permeability fault zone and overlain by impermeable caprock. In contrast to previous modelling approaches, the fault in our model is serving as a bound for the gas reservoir, which is more realistic than assuming an unbounded, infinite reservoir. We used a simulator that couples multiphase fluid flow and geomechanics in order to account for gas and water flow within the reservoir and the fault. We performed a sensitivity analysis aimed at investigating different production scenarios and fault properties.

The results show that fluid flow plays a major role pertaining to pore pressure and stress evolution within the fault. Fluid inflow into the fault leads to bending of the stress path, causing rupture to occur at lower depletion levels and lower stresses than would be expected when neglecting fluid flow. In addition, the offset of the reservoir leads to uneven compaction, causing the shear stress in the fault to increase stronger compared to the case of a reservoir without offset. We also analysed the scenario of multiple production wells, and results show that simultaneous production does not prevent the fault to be reactivated. Actually, the rupture occurs at much higher stresses, because the contraction of the two offset reservoir compartments leads to an additional increase in shear stress in the fault. However, because the induced shear stress is opposing the tectonic stress in the upper part of the right reservoir compartment, the rupture is halted at the reservoir/caprock interface, leading to a smaller seismic event compared to the single well case.
P 8.1

An experimental study of the influence of pore water on dynamic rupture processes.

M.Acosta1, F.Passelegue2, A.Schubnel3 and M.Violay1.

1 LEMR, ENAC, École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland,
2 School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Manchester, UK,
3 Laboratoire de Géologie, Ecole Normale Supérieure de Paris, CNRS UMR8538, 24 rue Lhomond,75005 Paris, France.

Fluids play a fundamental role in controlling fault strength and earthquake nucleation, propagation and arrest (Sibson, 1973, 2000; Lachenbruch, 1980; Rice, 1992, 2006; Hickman et al., 1995). The understanding of how the presence of fluid in faults affects the seismic cycle in the upper continental crust remains poor, especially in the case of induced seismicity due to engineering applications (Hydraulic stimulations). To examine the influence of pore water on dynamic rupture processes in the context of deep geothermal reservoirs, we conducted stick slip experiments on thermally-treated, saw-cut westerly granite samples under triaxial loading (σ1>σ2=σ3) at confining pressures (σ3) ranging from 10 to 95 MPa and pore water pressures ranging from 0 to 94 MPa (Schubnel et al. 2011 and Passelègue et al. 2013, 2016). The samples were instrumented with four strain gages recorded at high frequencies and one thermocouple located close to the fault plane, that allowed measuring respectively dynamic shear stress drops and temperature elevation. The nucleation point of slip and rupture speeds were assessed during the experiments through an acoustic monitoring array. The method consists in recording particle motion at high-frequencies for each acoustic emission event and inversing the arrival times for each sensor of the array. We recorded more than 200 stick slip events. Preliminary results showed that at a given effective confining pressure (Pc-pf), the dynamic shear stress drops were about 20 to 30% higher and slip distances were about 30 to 40% longer in dry samples than in water saturated samples. Following the same tendency, higher temperature elevations were recorded during nominally dry experiments. These results highlight the importance of pore water pressure in frictional processes, and suggest that water might inhibit dynamic weakening and so, rupture propagation in granitic rocks.

P 8.2

Petrophysical properties through a Grimsel granodiorite shear zone – Implications for geothermal reservoir evaluation and modelling

Quinn Wenning1, Claudio Madonna1, Evangelos Moulas2 & Jean-Pierre Burg1

1 Geological Institute, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich
Corresponding Author: Q. Wenning (quinn.wenning@erdw.ethz.ch)
2 Institute of Geochemistry and Petrology, ETH Zurich, Clausiusstrasse 25, CH-8092 Zurich

This study focuses on measurements of elastic and fluid flow properties through a fault zone that first deformed ductilely and subsequently experienced brittle faulting. Measurements were performed on core material from the Grimsel Test Site (GTS) underground research laboratory. We measured the seismic velocities, porosity, and permeability, perpendicular and parallel to ductile foliation, systematically every 0.1 m in the 0.7 m transition zone between the host rock and the first fault core penetrated by the borehole. The studied fault zone consists of a foliated ductile transition zone grading from the host rock to the first ductile mylonitic fault core (also locally known as lamprophyres). A fractured damage zone (~3 m wide) formed between the first fault core and is bounded by another fault core at the base of the well. Foliation plane parallel p- and s-wave velocities and permeability systematically increase from the host rock towards the fault core. The positive correlation between foliation parallel velocity and permeability is contrary to what is typically shown in brittle fault damage zones. Although brittle deformation has persisted in recent times, antecedent ductile structures continue to control the matrix elastic and fluid flow properties instead of microfractures. The results demonstrate how physical characteristics of faults in crystalline rocks change in proximity to the fault core. The positive correlation between foliation parallel velocity and permeability is contrary to what is typically shown in brittle fault damage zones. Although brittle deformation has persisted in recent times, antecedent ductile structures continue to control the matrix elastic and fluid flow properties instead of microfractures. The results demonstrate how physical characteristics of faults in crystalline rocks change in proximity to the fault core. In addition, insight is shed on the transient changes as fault rock properties undergo ductile to brittle transitions. In such crystalline rocks the elastic and fluid flow properties have important implications for natural crustal processes and exploitation and use in geothermal energy and waste storage. The characterization of such a system is particularly important to geothermal resource evaluation and reservoir modelling.
Modelling of fluid injection into a frictional weakening dilatant fault

Federico Ciardo & Brice Lecampion

1 Geo Energy Laboratory – Gaznat Chair on Geo-Energy (GEL), École Polytechnique Fédérale de Lausanne (EPFL), EPFL-ENAC-IIC-GEL Station 18, CH-1015 Lausanne (federico.ciardo@epfl.ch)

Understanding the mechanism of nucleation of dynamic rupture is an important issue in seismology. It is the key factor in determining the seismic potential of pre-existing faults under long-term loadings. Furthermore, the activation of Mode II fracture by means of fluid injection is the way to enhance the permeability of deep geothermal reservoirs (Enhanced Geothermal Systems) whose efficacy rely on the shear-induced dilation.

Locally elevated pore pressure associated with fluid injection leads to a reduction of the fault frictional strength (product of the local normal effective stress and the slip-weakening friction coefficient) which may eventually falls below the background shear stress. As a result, a shear crack will start to propagate with an initially moderate velocity (quasi-static) as it is induced by fluid pressure diffusion. As slip accumulate, the quasi-static crack growth may become unstable due to the slip-weakening nature of friction, resulting in the nucleation of a dynamic rupture until residual frictional strength is reached (see Garagash & Germanovich, 2012). The size of such a dynamic rupture (associated with fluid injection) is intrinsically related to both the way the pore-pressure distribution evolves spatially and temporally along the fault and the initial background shear stress. Larger dynamic ruptures are actually obtained for lower overpressure that are spread over larger zones, while a dynamic rupture associated with larger (but more localized) peak overpressure reaches residual friction earlier. Moreover, for large values of overpressure (with respect to the initial effective stress state along the fault), the nucleation length is smaller for lower value of the background shear stress.

In this contribution, we investigate the effect of the shear dilatancy of the fault on the diffusion of pore pressure. Dilatancy may locally reduce pore-pressure depending on the ability of the fluid to flow in the newly created void space. Reduction in pore-pressure associated with dilatancy can result in increase of the fault shear resistance and thus can potentially arrest a dynamic rupture.

We formulate a 2D model of fluid injection in a shear dilatant fault exhibiting slip weakening friction. The model couples elastic deformation, shear weakening Coulomb friction with dilatancy and fluid flow along the fault. We develop a numerical scheme based on boundary element (Displacement Discontinuity Method) for elastic deformation and a finite volume scheme for fluid flow. We verify our solver first on the non-dilatant case by comparing our results with the solution of Garagash & Germanovitch (2012). We then investigate the effect of shear-dilatancy and its feedback on the nucleation of dynamic rupture.
REFERENCES

Figure 1. Sketch of frictional weakening dilatant fault under fluid injection.
P 8.4


Mahmoud Hefny¹, Alba Zappone²,³, Claudio Madonna¹, Andrea Moscariello⁴, Jean-Pierre Burg¹

¹ Geological Institute, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich
(mahmoud.hefny@erdw.ethz.ch)
² Swiss Seismological Service, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich
³ Institute of Process Engineering, ETH Zurich, Sonneggstrasse 3, CH-8092 Zurich
⁴ Department of Earth Sciences, University of Geneva, rue des Maraichers 13, 1205 Geneva

GEothermie 2020 (http://www.geothermie2020.ch) is an exploration program sponsored by the State of Geneva and SIG (Service industriel de Genève), to integrate the subsurface geological and geophysical data and evaluate the potential of geothermal energy production in the Geneva basin (Moscariello, 2016). Under the umbrella of this program, the Department of Earth Sciences at UniGeneva together with the Rock Deformation Laboratory at ETH Zurich have undertaken a joint research project focussed on physical properties relevant for the assessment of the geothermal potential. We present some preliminary results, including petrography and porosity measurements. Aim of the research is to characterise the influence of the mineral composition and texture on the seismic response of the key lithologies of the Molasse Basin.

Particular attention is given to the following aquifer/aquitard pairs:
- Hauptrogenstein/Effinger member (Lower Oxfordian)
- Upper Marine Molasse/Upper Freshwater Molasse
- Buntsandstein/Anhydrite Group
- Upper Muschelkalk/ Gypskeuper
- Lower Cretaceous/Lower Freshwater Molasse

The samples to test derive from borehole plugs of the Humilly (France) borehole, made available from TOTAL S.A.. 59 cylindrical samples of 25.4 mm diameter and > 30 mm length were collected. Where possible the cores were cut parallel and perpendicular to sedimentary banding or layering, in order to investigate rock anisotropy. Thin sections where prepared from the heads of the cylinders and represent the starting material for mineralogical and modal composition assessment. Further on, quantitative petrography and image analysis with the QEMSCAN at UniGeneva allows characterizing the rock microtexture. Bulk and grain density has been measured with the aid of a helium pycnometer. Porosity and permeability have been measured on the same sample set. These new measurements add substantially in asessesing the potential for geothermal challenges in the Geneva region.

This analyses will be followed by ultrasound velocity data (Vp and Vs) experimental tests on the same samples, at room temperature and at increasing pressure to reach reservoir conditions. The dataset that will be collected will help the interpretation of the seismic data available, and represent a complete and well constrained set of input parameters for numerical modelling of the Geneva basin subsurface.

REFERENCES
Simulating fully three-dimensional pressurized fracture propagation

Dmitry Nikolskiy1, Brice Lecampion

Geo-Energy Laboratory - Gaznat Chair on Geo-Energy, Ecole Polytechnique Fédérale de Lausanne, Switzerland
EPFL-ENAC-IIC-GEL, GC B1 391 (Bâtiment GC), Station 18, CH-1015 Lausanne
1 Corresponding author (dmitry.nikolskiy@epfl.ch)

We report the progress on a new computational technique for fully three-dimensional simulation of propagation of hydraulic fractures in the vicinity of a wellbore. One of the components of this technique is the boundary element code for modeling the elastic deformation of rock containing pressurized cracks developed previously by the first Author (see Nikolskiy, Mogilevskaya & Labuz, 2015). This code requires the use of only surface mesh, which facilitates its coupling with models of the fluid flow through the fractures. The code also features second order polynomial approximations of the boundary unknowns, which allow for accurate resolution of the cracks opening and sliding displacement near the tips and the stresses around these tips. The example of numerical solution of a problem of two pressurized cracks initiating from a borehole obtained with this code (the calculated boundary displacements) is given in Figure 1.

Figure 1. The boundary displacements (red) and displacement discontinuities (green) on two pressurized cracks initiating from a borehole.

In the present work, we further develop the code incorporating a fracture propagation algorithm that is capable of capturing the effects of mixed-mode loading (see Lazarus et al., 2001; Pham & Ravi-Chandar, 2016). In particular, we focus on the segmentation of the fracture front observed under combined opening (mode I) and anti-plane shear (mode III) load during fracture re-orientation from a wellbore. We discuss the importance of such fracture segmentation for the stimulation of unconventional reservoirs as well as for enhanced geothermal systems.

REFERENCES
P 8.6

Viscosity fluid influence on stick-slip motions

Chiara Cornelio\(^1\), Marie Violay\(^1\), Spagnuolo Elena\(^2\),

\(^1\) Laboratory of Experimental Rock Mechanics, EPFL, Station 18 CH 1015 Lausanne (chiara.cornelio@epfl.ch)
\(^2\) Sezione di Sismologia e Tettonofisica, Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, Italy

The Enhanced Geothermal System (EGS) offers a great potential for developing the use of geothermal energy, allowing the creation of hydrothermal reservoirs in deep and hot geological formations, where energy production was impossible due to a lack of fluid or permeability. In order to guarantee the economic flow rates of the system, this technology allows to improve the permeability of the rock pumping high-pressure fluid from an injection well.

With the injection of fluid, the stress equilibrium of the rock formation could change and lead to enhanced seismic activity. Thus making necessary to investigate the physical and chemical role of pore fluid (i.e., water pressure, flow rate water chemistry, and water density and viscosity) on the fault stability and lubrication, in order to optimise the hydraulic stimulation in a EGS.

With this purpose, a first serie of experiment has been set up in dry and wet conditions using fluids with different viscosity for direct shear tests and rotary shear tests on precut samples of Westerly granite. Normal stress varied from 0.3 MPa to 10 MPa. Slip velocity was set at ~ 0.008 mm/s. Water and glycerol with different concentrations (0% and 80%) have been used for the wet tests thereby the kinematic viscosity ranges between about 1 mm\(^2\)s\(^{-1}\) to 50 mm\(^2\)s\(^{-1}\). Glycerol has been chosen because it is fully miscible with water and is not considered as a lubricant.

First results showed differences in stick-slip motions that occur with the different configurations. The amplitude of stress drops are larger for wet conditions than for dry one, in particular it grows as the viscosity increases. At the same time, the viscosity of the fluid layer negligibly affects the macroscopic frictional resistance, reducing the mean static friction coefficient of only 10% above the dry condition.
Stress Characterisation and stress modeling at the Grimsel Test Site for the In-situ Stimulation and Circulation Project

Nathan Dutler\(^2\) now at 1, Benoit Valley\(^1\), Hannes Krietsch\(^2\), Florian Amann\(^2\), Valentin Gischig\(^2\) & Keith Evans\(^2\)

\(^1\) Centre for Hydrogeology and Geothermics, University of Neuchâtel, Rue Emile-Argand 11, CH-2000 Neuchâtel
\(^2\) Geological Institute, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich

The controlled creation of permeability at great depth is a major challenge for the development of deep geothermal projects in Switzerland and worldwide. The interplay between an interconnected fracture network and the in-situ stress field governs the permeability creation processes. The In-situ Stimulation and Circulation (ISC) project taking place at the Grimsel Test Site (GTS) aims at enhancing our understanding of these processes. A good comprehension of the in-situ stress field is a prerequisite to design the ISC experiment.

Thus, a stress characterization campaign was performed in the target rock mass for the ISC experiment, which includes overcoring, and hydraulic fracturing methods. The stress determination from various methods do not agree on all stress parameters. The micro-seismicity cloud recorded during hydraulic-fracturing indicates the minimum principal stress is sub-horizontal and orientated in NNE direction, similar to the results of other measurements conducted in the vicinity (e.g. Pahl et al., 1989), although there are also indications of local heterogeneity of the stress field. This contribution presents results of numerical stress models based on the geological model that attempt to match and explain the observations made during the stress measurement campaign and possibly explain some of the observed discrepancies. The stress models permit an evaluation of the effect on the stress field of such factors as topographic and tectonic loading on the regional scale.

The modelling work was performed using the 3D distinct element code 3DEC from ITASCA. As a first step, an isotropic elastic model was developed that reproduced the results derived in earlier numerical studies at the GTS (Konietzky and Marschall, 1996; Ziegler et al, 2016). Tectonic loading was simulated by imposing shortening of the distance between opposite boundaries. Shortening in directions striking 105-285° (MOD105) and 150-330° (MOD150) was needed to reproduce the measurements from hydraulic-fracturing and overcoring respectively. In total four different constitutive models were applied: isotropic elastic, transversal elastic, linear plastic and bilinear plastic. The transversal elastic model indicates that anisotropy does not have a major influence compared to the results of the isotropic elastic models. The linear plastic behaviour represented by Byerlee’s law for a normal tectonic regime provides questionable stress tensor results up to a depth of 1000 m. The bilinear plastic behaviour represented by a combination of Byerlee’s law and micro-crack initiation threshold delivers similar stress tensors as the isotropic elastic models.

The stress model fails to explain the hydraulic fracture orientation inferred from the alignment of micro-seismic events monitored during the hydraulic fracturing tests. The stress models with a regional loading directions striking 150-330° fits best with the overcoring measurements from field campaign. The model leads to a maximum principal stress magnitude between 19.3 and 24.9 MPa with a dip direction of 142° and a dip of 12°. The intermediate axis is located sub-horizontal with a magnitude of 11.7-12.3 MPa. Dip and dip direction are both around 41°. The minimum principal stress has a magnitude between 9.1 and 9.3 MPa with a dip of 46° and 246° azimuth which is also in general agreement with the overcoring results. Generally, the models show the predominance of the topographic influence on the stress state at the GTS, and tend to validate the overcoring stress measurement results, because the tectonic loading is more consistent with the large-scale stress direction from the World Stress Map. Currently, the observed orientations of the hydraulic fractures remain unexplained.
Figure 1: A and B have a $k_{inh}$ of 0.85. The shortcuts in the legends are for the elastic isotropic behavior (ELA), the linear plastic behavior (PLA1) and the bilinear plastic behavior (PLA2). The dashed lines indicate the results for MOD105 and the solid ones for MOD150. The transparency color bars in A display the most reliable observed magnitude range from the measurements.

REFERENCES
Acoustic monitoring of laboratory hydraulic fracture growth under stress and pore pressure

Thomas Blum & Brice Lecampion

° Geo-Energy Laboratory – Gaznat chair on Geo-Energy, Ecole Polytechnique Fédérale de Lausanne, EPFL-ENAC-IIC-GEL, Station 18, CH-1015 Lausanne (thomas.blum@epfl.ch)

Fluid-driven fracturing is used in a wide range of applications, including oil and gas extraction, geothermal energy recovery, and CO₂ sequestration. In order to efficiently fracture the targeted rock formation, theoretical models provide estimates of the fracture size and shape. Carrying properly scaled laboratory experiments, on the other hand, allows to validate theoretical predictions by providing complete datasets of individual experiments performed under controlled conditions, and therefore to better understand the physics of fluid-driven fracturing. The DelFrac Consortium at TU Delft pioneered this field by building an acoustic monitoring setup inside a triaxial press applying three independent stresses on a cubic specimen (Groenenboom, 1998).

At the Geo-Energy Lab, we intend to further investigate the solid and fluid mechanics of hydraulic fractures by building a novel experimental setup in our EPFL facility. The fracturing setup will consist in a triaxial frame designed to accommodate cubic-shaped specimens of up to 250 mm in length, and to apply up to 20 MPa independently on each axis. We will also have the ability to pressurize a pore fluid up to 5 MPa inside the frame in order to simulate in-situ conditions. Our current high-pressure pump can inject fluids with a maximum pressure of 51 MPa and a flow rate ranging from 1 μL/min to 90 mL/min through a high-pressure line and a cased wellbore inside the specimen.

We will monitor the growth of the fracture with a combination of compressional and shear piezoelectric transducers for a total of 64 units, that can be used to both generate and measure acoustic energy. We use a function generator connected to a high-power amplifier to generate an excitation signal, which is then routed to one of 32 excitation transducers through a multiplexer. The other 32 transducers are connected to a high-speed acquisition board in order to simultaneously record the measured ultrasonic signals. By carefully placing the transducers on all six faces of the specimen to be fractured, we expect to record transmitted, reflected and diffracted acoustic events (Figure 1). We intend to use these three types of event in order to estimate the spatial extent of the fracture, as well as its thickness along raypaths. Transmission measurements, where the wave travels across the specimen, provide fracture thickness information (Groenenboom & Fokkema, 1998; Kovalyshen et al., 2014). Diffraction events, where the wave propagates to the tip of the fracture and then towards the side of the block, carry information about the tip position, and in turn give an estimate of the fracture size (Groenenboom et al., 2001). Reflection events, where the acoustic energy is reflected back toward the same side of the block, let us discriminate between dry and fluid-filled fracture in the case where a fluid lag is present at the fracture tip.

With these unique laboratory capabilities, we plan to investigate complex fracturing problems that have not yet been investigated in laboratory experiments. This includes the case of fluid-saturated porous materials, where the porosity and properties of both injection and pore fluids have a strong influence on fracture growth, but also the case of fracture propagation in anisotropic or inhomogeneous materials, as well as the effects of mixed-mode fracturing with fracture reorientation, as well as the influence of existing fractures.
Figure 1. Schematic of the ultrasonic monitoring configuration. T: transmitted wave, R: reflected wave, D: diffracted wave.

REFERENCES
Towards Replicating Rock Specimens: A Comparison of Tensile Fractures from 3D Printed and Natural Sandstones

Elisaveta Dombrovski1,2, Daniel Vogler1, Stuart D.C. Walsh3, Matthew A. Perras1

1 ETH Swiss Federal Institute of Technology Zurich, Department of Earth Sciences, Zurich, Switzerland
2 Technical University of Munich, Faculty of Civil Environmental and Geo Engineering, Munich, Germany.
3 Stone Code Pty. Ltd., Sydney, Australia

Recent advances in 3D printing technology have the potential to replicate the physical characteristics of natural sandstones, enabling the manufacturing of reproducible rock specimens. This process could be used to replicate heterogeneous specimens to perform destructive testing with different tests and testing configurations. In a first stage, a sand based printed material was examined to determine if its behaviour was similar to natural sandstones. For this purpose, we compare the tensile failure behavior of 3D printed and natural sandstone specimens.

We tested two different grain sizes of the same 3D printed material and three natural sandstones to compare: (1) tensile strength; (2) strain path to failure; (3) fracture surface roughness after failure; and (4) failure mode as analyzed with digital image correlation.

Tensile strength and failure modes of 3D printed sandstone and weak natural specimens was found to be comparable. Crack propagation paths during failure as measured with surface roughness of the 3D printed specimens were similar to those of natural specimens of comparable tensile strength. The findings of this study suggest similar grain- and macro-scale failure behaviour was found between the 3D printed and natural sandstone specimens and this 3D printed material could be a useful analogue material for future studies.
Numerical modeling of seismic attenuation in realistic fractured media

Jürg Hunziker¹, Marco Favino², Eva Caspari¹, Beatriz Quintal¹, Rolf Krause² & Klaus Holliger¹

¹ Applied and Environmental Geophysics Group, Institute of Earth Sciences, University of Lausanne, Switzerland
² Institute of Computational Science, Università della Svizzera italiana, Switzerland

Imaging of fractures is important for geothermal and hydrocarbon exploration as well as for nuclear waste disposal and CO₂ storage. As the fracture thickness is much smaller than the seismic wavelength, direct imaging of fractures with seismic methods is generally not possible. Indirect imaging is, however, potentially possible, because seismic waves experience velocity dispersion and attenuation in fractured media due to wave-induced fluid flow (WIFF).

Numerical upscaling experiments allow us to better understand the velocity dispersion and attenuation of seismic waves caused by WIFF. To this end we apply a compressibility test to a representative sample of the subsurface region of interest. The fractured numerical sample is compressed under undrained conditions vertically along its upper boundary with the lower and lateral boundaries remaining fixed. Fractures are modeled as a highly compliant and highly porous material embedded in a much stiffer and much less porous background material. The P-wave velocity dispersion and attenuation can then be obtained by solving the quasi-static poroelastic equations (Biot, 1941) in the space-frequency domain. Shear tests are used in a similar manner to obtain the S-wave velocity dispersion and attenuation.

So far, such numerical experiments have been limited to simple fracture models (e.g., Quintal et al. (2014), Rubino et al. (2013,2014)). Here, we present a new finite-element code called Parrot that allows us to model realistic 2D fracture geometries. This code is based on the Multiphysics Object Oriented Simulation Environment (MOOSE). Instead of creating a mesh with element boundaries coinciding with fracture boundaries, we create a mesh of rectangular elements, which are adaptively refined at fracture locations but otherwise independent of the geometry of the fractures. Note that our approach does not necessarily require structured meshes. Here, we just have chosen structured meshes as they are trivially to generate. This allows for a fast mesh generation that does not require user interaction, making the code amenable for the simulation of realistic, stochastic fracture networks.

We compare our results with those of the Comsol Multiphysics software for two interconnected fractures (Fig. 1a). The agreement between the two sets of results in terms of attenuation is very good (Fig. 1b). The small differences are most likely due to the different meshes. An example of a realistic fracture network is depicted in Fig. 1c. As for the case of only two fractures, the attenuation exhibits two peaks (Fig. 1d), one at low frequencies due to WIFF between the fractures and the background, and one at high frequencies due to WIFF between connected fractures. As there are not so many connections between the fractures in the second example, the low-frequency attenuation peak has a much higher amplitude than the one at higher frequencies.

In the future, we plan to use this code to explore relations between WIFF effects and the effective permeability of realistic, stochastic fracture networks featuring different statistical properties. An extension of this code to 3D is currently under development.
REFERENCES

Analysis of surface roughness of Opalinus Clay extensional fractures

Holger Sprengel¹, Martin Ziegler¹

¹ Department of Earth Sciences, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich
(sholger@student.ethz.ch, martin.ziegler@erdw.ethz.ch)

Opalinus Clay is the target rock formation for the high-level nuclear waste repository in Switzerland. Rock mass characterization experiments in Opalinus Clay at the Mont Terri underground rock laboratory have shown that tunnel excavation leads to formation of an Excavation Damage Zone (EDZ) around the underground galleries (e.g. Nussbaum et al., 2011). This EDZ contains newly formed brittle fractures of which some are extensional fractures aligned about tangential to the tunnel walls. Shortly after tunnel excavation rock mass support measures are installed in order to limit tunnel convergence and rock mass damage. Characterization and assessment of the system behavior of EDZ fractures and confining stress, e.g., due to tunnel support and/or later swelling of bentonite backfill, is highly relevant for the long-term storage of radioactive waste and repository safety since the EDZ fractures may form release paths for radionuclides. The impact of EDZ fractures on repository integrity has been subject to a wide range of scientific investigations at the Mont Terri underground rock laboratory and other research laboratories until today.

Mechanical and hydrological rock mass behavior is strongly influenced by the roughness of rock fractures (e.g. Grasselli and Egger, 2003; Scesi and Gattinoni, 2007). This study investigates the effect of suction pressure (and corresponding saturation) on the roughness of (1) newly-formed Opalinus Clay extensional fractures and of (2) fractures under confining pressure. The study aims at increasing our understanding of the fracture sealing processes, which are relevant for the long-term disposal of radioactive waste.

We used artificial fractures formed by Brazilian indirect tensile strength tests as analogues for extensional EDZ fractures (Figure 1a; Ulusay and Hudson, 2007). The fractures were produced parallel and perpendicular to bedding planes. To be able to analyze the influence of the suction pressure on the fracture roughness, sample material from the same sampling location at the Mont Terri underground rock laboratory was desaturated artificially to obtain five different water contents (>97 %, 85 %, 66 %, 43 %, 15 %) using oversaturated salt solutions. 3D models of the fracture surfaces were created by the use of a photogrammetric scanner (GOM ATOS Core 300). Calculated surface models with resolutions on the order of 0.5 mm were used to determine different roughness parameters, such as $Z_2$S (Belem et al., 2000) and the standard deviation of the asperity height, to characterize the surface morphology quantitatively (Figure 1b). The scans were carried out before and after fracture-perpendicular compressive loading, simulating confining stress buildup during gallery closure. Different magnitudes of confinement were applied. We will present and discuss our investigation concept and laboratory loading equipment (Figure 1c), and aim at showing first results of the Opalinus Clay fracture roughness investigations.

---

Figure 1. a) As analogue for EDZ extensional fractures new fractures were artificially formed by the Brazilian indirect tensile strength test. Tensile stress occurs perpendicular (red arrows) to the loading direction (black arrows). b) Both fracture surfaces were scanned by an optical 3D scanner. High resolution 3D models of the fracture surfaces (top) were used to calculate digital surface models (bottom) of each fracture surface. These were then used to determine surface roughness parameters. c) During a second experimental step fracture closure was simulated by uniaxial compressive loading of mated fractures, perpendicular to the mean orientation of the fracture. Strain between both sample parts was measured. After loading the fracture’s roughness was investigated a second time.
REFERENCES

P 8.12
Petro-physical characterization of the Main Fault at the Mont Terri Laboratory

Luis Felipe Orellana¹, Marie Violy¹, Eduardo Gramajo¹, Pierre Henry², Yves Guglielmi³, Florian Amann⁴, Christophe Nusbaumm⁵.

¹ Laboratory of Experimental Rock Mechanics, École Polytechnique Fédérale de Lausanne, Route Cantonale 1015, CH-1018, Lausanne (felipe.orellana@epfl.ch)
² Aix Marseille Université, CNRS, Collège de France, IRD, CEREGE UMR7330, 13545 Aix-en-Provence cedex 4, France
³ Earth and Environmental Sciences Area, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
⁴ Department of Earth Sciences, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich.
⁵ Federal Office of Topography (SWISSTOPO), Seftigenstrasse 264, CH-3084 Wabern

Opalinus clay has been widely studied in the context of deep geological disposal. Its favorable hydro-mechanical properties made it a suitable material for the storage of nuclear waste. One of those key properties is its low permeability, being practically impermeable.

This work focuses on the petro-physical characterization of the Main Fault zone at the Mont Terri Laboratory, in Switzerland. The objective of the study is to constrain the cap rock sealing efficiency. The petro-physical properties were determined from sample measurements in the laboratory. Permeability was measured by transient pressure pulse method using fluid at chemical equilibrium with the rock. Connected porosity was measure using the triple-weight method and helium pycnometry. Porosity topology was assessed by mercury porosity technique. Preliminary results suggest that porosity along the fault structures suggest a layered system. Fault core was ~21% porosity and dominated by small pores of size lower than 14 nm. Surrounding damage zone presented porosity values lower than 15%, and nano-pores of about 16 nm. Permeability far from the fault zone is in the order of $1 \times 10^{-20}$ and $1 \times 10^{-19} \text{ m}^2$, if measured perpendicular and parallel to bedding respectively.
P 8.13

Architecture of a fault zone in Opalinus Clay at the Mont Terri laboratory (Switzerland)

Maria Kakurina¹, Yves Guglielmi², Christophe Nussbaum³, Benoît Valley¹

¹ Center for Hydrogeology and Geothermics, University of Neuchâtel, Rue Emile-Argand 11, CH-2000 Neuchâtel (maria.kakurina@unine.ch)
² Lawrence Berkeley National Laboratory, University of California, 1 Cyclotron Rd, CA 94720 Berkeley
³ Swisstopo, Seftigenstrasse 264, CH-3084 Wabern

Opalinus Clay formation exposed in the Mont Terri underground rock laboratory gives an excellent opportunity to investigate the architecture of an unweathered clay fault zone. Since 20 years, about 150 experiments have been performed in Mont Terri in order to investigate the hydrogeological, geochemical and mechanical properties of argillous formations. The FS (Fault Slip) experiment aims at better understanding the stability of clay faults. This experiment has been conducted by injecting fluids in the upper, middle and lower parts of the main tectonic structure of the Opalinus Clay, so-called the Main Fault, using the SIMFIP probe (Guglielmi 2016). The present work contributes to a highly-detailed structural analysis of three FS fully cored and logged 35-to-50m long and 1.7-to-4.3m spaced boreholes intersecting the entire fault zone.

The Main fault core consists of a thrust zone of about 4.0-5.0 m wide, that includes scaly clay and non-scally fabrics intersected by various density of secondary fault planes (Figure 1). The fault rocks are classified in 7 different fault facies: 2 scaly clay facies and 5 fractured rock facies:

- Scaly clays, including shear zones, microlithons, S-C bands and microfolds, mainly occur in larger zones at top and bottom of the Main Fault boundaries, and also as isolated lenses in the middle. The scaly clay facies 1 comprises a scaly fabric that has a relative low “tensile strength” since it can be easily broken by hands. The scaly clay facies 2 consists of larger microlithons, that are intersected by thin shear zones, and cannot be easily disintegrated.

- The fractured facies 1 is characterized by mainly non-deformed zones rarely intersected either by moderately SSE-dipping system or by low-angle SW-dipping fault planes. The fractured facies 2 consists of a sequence of the SSE-dipping faults intersected with the SW-low-dipping fault planes usually associated with calcite mineralisation. Slickenside analysis of SSE-dipping faults with well-striated surfaces indicates that the slip direction has a top-to-NNW shear sense, while the SW-low-dipping fault planes – NW shear sense. The fractured facies 3 includes moderately inclined N- to NNE-striking faults with mainly NW shear sense. The fractured facies 4 is specified by the rhombohedral undeformed blocks with low to moderately SSE-dipping fault planes with NW slip direction. It was noted that the higher the inclined angle of the fault plane, the larger are the shining strias. The fracture facies 5 is characterized by the very densified SSE-dipping fractures with a very shiny and well-striated surface with NNW slip direction. This facies usually occurs closed by the scaly clays. The three fault systems observed in the fractured facies have been identified in the galleries of the rock laboratory (Nussbaum et al. 2011).

These structural facies have been differentiated in order to correlate the structural features between the boreholes. Indeed, such a complex variability of the fractured zones as well as the continuity of the borders of the Main Fault are hard to correlate even with highly detailed geological data within the relatively small volume of the experiment. This high heterogenity within the fault zone is likely to impact the fault rock response to fluid injection and its reactivation. It has been recently shown in Tournemire underground rock laboratory (France), that the rupture in faulted clay rich rocks is mainly associated with the reactivation of preexisting discontinuities(Guglielmi et al. 2015). It results in high potential instability of some fault planes to stress variability induced by galleries excavation, that are very important questions in many industrial applications and, therefore, need to be studied.
Figure 1. a,b - Experimental location in Mt-Terri URL; c – Map of the boreholes geometry in the FS experiment zone, d – Cross section of the Main Fault geometry

REFERENCES


Porosity and permeability reduction in conduit wall rock. A transition from localized cataclastic pore collapse to distributed viscous flow.

Michael Heap¹, Marie Violay², and Fabian Wadsworth³

¹ Géophysique Expérimentale, Institut de Physique de Globe de Strasbourg (UMR 7516 CNRS, Université de Strasbourg/EOST), 5 rue René Descartes, 67084 Strasbourg cedex, France.
² Laboratory of Experimental Rock Mechanics, École Polytechnique Fédérale de Lausanne, Station 18, CH-1015, Lausanne, Switzerland.
³ Earth and Environmental Sciences, Ludwig-Maximilians-Universität, Theresienstr. 41, 80333 Munich, Germany.

The permeability of volcanic conduit walls can govern the outgassing and explosivity of eruptions. The destruction of the porosity and permeability of the materials within this zone could therefore promote explosive behaviour.

To examine the mechanisms of porosity and permeability loss in the region of the conduit margin zone, we conducted high-pressure (effective pressure of 40 MPa), high-temperature (up to 800 °C) triaxial deformation experiments on porous andesite. Porosity change was measured during deformation.

Mechanical and micro-structural observations (at experimental constant strain rate of $10^{-5} \text{s}^{-1}$) indicate that andesite deforms by cataclastic pore collapse at temperatures that do not exceed the glass transition ($T_g = \sim 740$ °C) of the amorphous groundmass phase. Localized cataclastic pore collapse produces bands of crushed pores orientated sub-perpendicular to the maximum principal stress. In this regime, porosity is only reduced within the bands; the host rock porosity remains unchanged. Although these features may disrupt the outgassing of the nearby magma-filled conduit, it is unclear whether they will form a coherent low-permeability barrier. At temperature higher than $T_g$, the deformation is distributed throughout the sample and no localized bands develop. This change in deformation mechanism is accompanied by a substantial reduction in strength and a substantial increase in porosity and permeability loss, the result of widespread viscous pore flattening and closure. A low-porosity, low-permeability viscously compacted layer within the conduit wall will severely inhibit the outgassing of the nearby magma-filled conduit and could allow pore pressure to build up to that preparatory for the next Vulcanian explosion.

Our study therefore highlights that small changes in the temperature can result in a change in deformation micromechanism that drastically alters the mechanical and hydraulic properties of the wall rock adjacent to the conduit, with implications for pore pressure augmentation and explosive behavior.
P 8.15

The physical properties of evolved melts and implications for melt segregation and the built-up of large silicic eruptions

Eva Hartung & Luca Caricchi

1 Department of Earth Sciences, University of Geneva, Rue de Maralchers 13, CH-1205 Geneva (eva.hartung@unige.ch)

The extraction of residual melt from crystallising magmas is a mechanism commonly considered to precede the eruption of crystal poor magmas. A detailed petrographic, geochemical and structural study of the Takidani pluton suggests that a porphyritic granitic unit near the roof of the intrusion was produced by the extraction of residual melt from magma crystallised to about 50 wt.%

The rheological properties of magma and residual melt depend on temperature, pressure, chemistry, water, crystal and bubble content, and the rate of deformation. In this study we calculate the physical properties of magma and residual melt during the progressive crystallization of magma with the composition of the Takidani granodiorite. Given the compositional similarity, the variation of chemistry and crystallinity as function of temperature was obtained from the experiments of Costa et al. (2004).

As a first step, we have calculated the density, viscosity and bubble volume fraction at 200MPa and different temperatures for water saturated melts. The water content at saturation for the residual melt increases with decreasing temperatures from 6.0 to 7.0 wt.%. The total initial volume of the magma and dissolved water triples from 1000°C (near liquidus) to 700°C (near solidus) because of water exsolution. However, the volume of the magma itself only increases by about six percent, while the density decrease from 2.30 to 2.17 g/ccm. The viscosity of the residual magma increases from about 2.4 to 4.2 between 1000°C and 800°C, and to about 5 at 700°C. In comparison, the viscosity for anhydrous melts increases exponentially from 5.2 to 13.1 from 1100°C to 700°C.

In the second step we will calculate the relative viscosities of the residual melt for a two- and three-phase system after the models of Pistone et al. (2012) and Truby et al. (2014), respectively. In addition, we will calculate the rheological properties for a water-undersaturated melt and discuss the implication for magma transport of silicic melts in the upper crust.

In summary, calculations of physical properties for magmas with different initial water contents will be presented to determine if the extraction of residual melt during magma crystallisation was triggered by the achievement of a particular set of physical properties of the residual melt.

REFERENCES
Seismic signals at the Nirano Mud Volcanic Field, Italy

Verónica Antunes¹, Matteo Lupi², Aurore Carrier³, Anne Obermann², Adriano Mazzini³, Tullio Ricci³, Alessandra Sciarra⁴, Milena Moretti⁴

¹ Department of Earth Sciences, University of Geneva, Rue des Maraîchers 13, CH-1205 Geneva (veronica.antunes@unige.ch)
² ETH Zürich, Erdbebendienst (SED), NO H 63, Sonneggstrasse 5, CH-8092 Zurich
³ Centre for Earth Evolution and Dynamics (CEED), University of Oslo, ZEB-bygningen, Sem Sælandsvei 2A, Blindern, NO-0371 Oslo
⁴ Istituto Nazionale di Geofisica e Vulcanologia (INGV), Via di Vigna Murata, IT-605-00143 Rome

Mud volcanoes are geological systems characterized by elevated fluid pressures at depth. For this reason, mud volcanoes are often considered ideal natural laboratories to investigate the effects of passing seismic waves on fluid-saturated geological systems. We deployed a network of 7 temporary seismic stations around the Nirano Mud Volcanic Field, Italy, to capture the local effects of remote earthquakes. We notice that the seismic noise is increasing after the passage of the seismic waves. This is possibly indicating changes in the (shallow) fluid flow regime within the mud plumbing system.

Additionally, during the three months long deployment we repeatedly recorded drumbeat signals beneath the mud volcanic field. The signals were characterized by a high-frequency content in the range of 10-25 Hz. We attempt to locate and characterize the source generating such recurrent seismic signals. The amplitude of the events varies across the stations suggesting a conduit located in the NE-most part of the mud volcanic field.
Tectonic and fluid-driven seismic activity in Western Peloponnese, Greece

Antoine Haddad¹, Matteo Lupi¹, Diego Gonzalez Vidal², Dr Athanassios Ganas³, Ioannis Kassaras⁴

¹ Crustal Deformation and Fluid Flow Group, University of Geneva, Rue des Maraîchers 13, CH-1205 Genève. antoine.haddad@unige.ch – matteo.lupi@unige.ch
² Earth Sciences department, University of Concepción, Victor Lamas 1290, concepcion – Chile diegogonzalezv@udec.cl
³ Research Director, National Observatory of Athens Lofos Nymfon, Thission P.O Box 20048 11810 Athens – Greece aganas@gein.noa.gr
⁴ Assistant Prof. Professor (Assistant) - University of Athens - Department of Geophysics and Geothermy Greece · Athens kassaras@geol.uoa.gr

The interaction between fluid flow and seismic activity is modulated by the state of stress of the crust. Fluid-rich geological environments are often characterised by elevated pore pressure at depth. The heterogeneous distribution of pore pressure may be an important aspect to identify regions prone to generate fluid-driven seismic swarms.

This study investigates fluid-driven seismicity in the Western Peloponnese area (Fig.1) that is considered an ideal natural laboratory due to the abundance of crustal fluids and frequent occurrence of earthquakes. The basin is composed of thick Jurassic-Eocene carbonate and clastic sedimentary sequences underlain by Triassic evaporites (Fig 2.) that under tectonic stress penetrate through cataclastic zones generating diapiric structures. They likely control fluid migration/concentration processes. (Etiope et al. 2006).

To capture the evolution of such fluid-driven seismic sequences we deployed a seismic network spanning 200 km from north to south and more than 100 km from east to west. The network is composed of 14 temporary and 7 permanent seismological stations (Fig.1).

Fluid-driven seismic sequences are often characterised by temporary permeability enhancements and may localise in regions affected by increase lithostatic pore pressures at depth. We couple numerical fluid flow models with accurate earthquake locations to highlight whether in this part of Western Peloponneses seismic sequences/swarms may be fluid driven as the result of anomalous P-T variations in the crust.

REFERENCES
Lupi, M., S. Geiger, and C. M. Graham (2010), Hydrothermal fluid flow within a tectonically active rift-ridge transform junction: Tjornes Fracture Zone, Iceland, J. Geophys. Res. B Solid Earth, 115,
Mind the (seismic) gap: the 1714 Bhutan earthquake

György Hetényi¹, Romain Le Roux-Mallouf², Théo Berthet³, Rodolphe Cattin³, Carlo Cauzzi⁴, Karma Phuntsho⁵, Remo Grolimund⁴

¹ University of Lausanne, Institute of Earth Sciences, UNIL-Mouline Géopolis, CH-1015 Lausanne, Switzerland
² Géosciences Montpellier, Université de Montpellier, Place E. Bataillon, F-34095 Montpellier, France
³ Department of Earth Sciences, Uppsala University, Villavägen 17, S-75236 Uppsala, Sweden
⁴ Swiss Seismological Service, ETH Zürich, Sonneggstrasse 5, CH-8092 Zürich, Switzerland
⁵ Shejun Agency for Bhutan’s Cultural Documentation and Research, Changangkha, Thimphu, Bhutan

The region of Bhutan is thought to be the only segment of the Himalayas not having experienced a major earthquake over the past half millennium. A proposed explanation for this apparent seismic gap is partial accommodation of the India-Asia convergence further south across the Shillong Plateau, yet the seismic behavior of the Himalayan megathrust is unknown.

Here we present historical documents from the region reporting on an earthquake in 1714 AD and geological evidence of surface rupture to constrain the latest large event in this area. We compute various earthquake scenarios using empirical scaling laws relating magnitude with intensity and rupture geometry. Our results constrain the 1714 AD earthquake to have ruptured the megathrust in Bhutan, most likely during a M7.5-8.3 event. This finding reclassifies the apparent seismic gap to a former information gap, and implies that the entire Himalayan arc has a high level of earthquake potential.
P 8.19

Effect of tilt angle on the inter-hemispherical asymmetries: Study of the variations of the temperature and the electronic density

Sabrina Tair 1, Frédéric Pitout 2, Yasmina Yahiat 1 & Naima Zaourar 1

1 Faculté des Sciences de la Terre, Géographie et Aménagement du Territoire, Université des Sciences et de la Technologie Houari Boumediene, BP 32 El Allia 16111 bab ezzouar Alger, Algérie (sabrina_tar@yahoo.com)
2 Institut de recherche en Astropysique et Planétologie, 9 avenue du Colonel Roche, BP 44346, 31028 Toulouse cedex 4, France

Geomagnetic activity is controled by the angle (Φ), called tilt angle, which makes the magnetic axis of the Earth with regard to the perpendicular for the ecliptic. Indeed, if the equipotentiality of the lines of force of the ground magnetic field, in particular large-scale, is source of a symmetry between the combined regions, the causes of asymmetry between hemispheres are not rare. This asymmetry is due on one hand, in the slope of the axis of rotation of the Earth from the point of view of the ecliptic, leading a seasonal effect and on the other hand, in the slope of the axis of the geomagnetic dipôle with regard to the geographical axis, which leads a diurnal effect. The seasonal effect due to the differences of conductivity between the polar summer and winter ionospheres is translated by a strong disparity between the capacities of the north and south hemispheres to close the magnetospheric currents, also leading to an asymmetry of electric fields and convection of the plasma.

In our study, we exploit average minutes of the Density and the electronic Temperature of the electric field during the period 2002 - 2004, measured by the probe Langmuir PLP aboard the satellite CHAMP. We also use the index of the radio flow which represents the variations of the solar flow «ultraviolet ray» in a 10,7 cm wavelength. This flow has no influence on the structure of the atmosphere, but suits to represent the temperature variations observed in the thermosphere.

To show the influence of the slope of the magnetic axis (seasons) on the differences between hemispheres, we put a selection criterion of data according to the variability of the tilt angle and examined the relation enter the variation of the solar flow (F10.7) and the parameters of the electric field various intervals.

After a decomposition of the electric field values, measured by the probe Langmuir PLP aboard the satellite CHAMP, according to the variability of the angle of inclination (Φ), we show a correlation enter the sign of the tilt angle (Φ) and the inter-hemispherical asymmetries. These results are obtained from the cards of the average minutes of the meridian variation of the temperature and the density of electrons for the low heights.

The tilt angle plays a fundamental role on the geomagnetic activity which depends on the sign of this angle. Indeed, we were able to reveal a visible seasonal effect (asymmetry for the high latitudes marked by an increase of the effect Joule in the north hemisphere when (Φ) is positive and in the southern hemisphere when (Φ) is negative and less visible when the angle of inclination is zero.

REFERENCES:
Rother, M. 2000 : CH-ME-2-PLP corrected magnetic field in ECEF/NEC system. Information System and Data Center, GeoForschungszentrum Potsdam, Germany. doi:10.5880/ISDC.
The Alpine geological chain represents the consequence of the collision and subduction process involving the European plate and the Adriatic (or Apulian) microplate, which is a promontory of the African plate. The whole process that initiated the formation of Alp orogen started during the Lower Eocene, about 55 million years ago. Although they represent a relatively young mountain belt, the structure of Alps is very complex both at the surface and at depth. Actual information about deep crustal structure has been provided through P-wave velocity models obtained combining active and passive seismic investigations (e.g. Wagner et al. 2012; Diehl et al. 2009 and references therein).

The aim of this work is to exploit converted waves (that represent the analogue of reflectivity from active seisms) and complementary geophysical investigations (e.g. gravity) to deliver a whole 3-D shear-wave velocity model of the crust. The first application is focused on the Central Alps, where active seismic data is widely available for control and also for comparison.

A 3-D model is very useful because orogenic structures are not frequently cylindrical and vary greatly laterally; therefore, it is indispensable to develop a new technique to try to improve structural images and to determine different lithologies and remark the geometry of discontinuities present in the Earth.

Here we adopt the technique of ‘receiver function’ RF (Langston, 1977) which has been developed during the last 40 years and is nowadays largely used for structural investigations based on passive seismic experiments.

We perform a new analysis of receiver functions using a data set composed of about 20 years of high-quality data from permanent broad-band stations of the Swiss Seismological Service. To get homogeneous coverage of the entire Central Alpine tectonic domain, we also added data from permanent broad-band stations operating in neighbouring countries. We selected data from teleseismic events in the 30-90° epicentral distance range and we chose a threshold magnitude of 5.2. By applying the H-$\kappa$ stacking technique (Zhu & Kanamori, 2000), using timing of direct and multiple P-to-S converted phases derived from the crust-mantle interface, we compute the crustal features of Moho depth and average $V_p/V_s$ ratio for tectonic units and we compare the results obtained with those of Lombardi et al. 2008 using the same approach.

Our main goal is to develop a new technique to construct a fully 3-D Vs model from RFs, by applying a joint inversion strategy of converted waveforms sampling the study area.

The inversion method can either proceed directly, or can use a priori information such as existing Moho depth and high-quality 3-D P-wave velocity model (e.g. Diehl et al. 2009): in this case the inversion can focus on $V_s$ (or $V_p/V_s$ ratio). With our method, we aim to build an at least three-layer model including, for instance, sediments, upper crust and lower crust. S-wave information guarantees a much better correlation with rock density and mechanical properties than P-wave model only, reducing effectively the interpretation ambiguities.

The resulting model will be interpreted by taking into account the lithology and the physical properties of the main tectonic units of the region considered.

Finally, we plan to combine our results with the existing gravity anomaly data, controlled source seismology (CSS) profiles acquired during the years, studies of local earthquake tomography (LET) and geological data.

REFERENCES


P 8.21

Gray-scale Hough transform for seismic wavefield separation?

Asma Hadjadj1, Zahia Benaissa1, Abdelkader Benaissa1 & Amar Boudella1

1 University of Sciences and Technology Houari Boumediène, Geosciences Faculty, BP 32, EI Alia, Bab-Ezzouar, 16000 Algiers, Algeria. E-mail: zabendz@yahoo.fr

In a Vertical Seismic Profile (VSP) recording, the useful signal is composed of the superposition of a downgoing wavefield with positive apparent velocities, and an upgoing wavefield with negative apparent velocities. To make best use of them, they need to be separated. Several methods exist to perform this separation, each with its advantages and disadvantages (Kommedal & TJostheim, 1989). The most frequently used in the industry are median filtering which remains, however, unsuitable when amplitude preservation is critical, and (f-k) filter which needs a regular sampling.

In this study, we propose a new method based on the gray-scale Hough transform (GSHT) (Lo & Tsai, 1995; Kesidis & Papamarkos, 2000) which is an extension of the conventional Hough transform used to detect straight lines and other curves (Hough, 1962; Duda & Hart, 1972). The technique, we suggest here, directly maps the gray-scale VSP image, including the downgoing and upgoing linear events, in image coordinate space (x,t,g) to the gray Hough parameter counting space (θ,ρ,g), where r and q are, respectively, the distance and the orientation with respect to the x-axis of the normal vector to the line, and g represents the gray value. In this new space, the downgoing events appear in the negative angles θ quadrant and the upgoing in the positive quadrant.

The inverse GSHT algorithm, we developed, is then performed to extract the lines that satisfy the filtering conditions: θ negative for the downgoing VSP wavefield and θ positive for the upgoing VSP wavefield (Fig.1).

The experimental results on synthetic and real VSP datasets are convincing (Hadjadj et al., submitted). The wave separation is well performed, even in the presence of loud noise levels, with signal to noise ratio improvement and amplitude preservation.

REFERENCES


Hadjadj, A., Benaissa, Z., Benaissa, A. & Boudella, A. submitted: VSP wavefield separation using the gray-scale Hough...
transform: synthetic data. A.J.G.
Lo, R. & Tsai, W. 1995: Gray scale Hough transform for thick line detection in gray-scale images. Pattern Recognition 28, 647-661.
Topographic expressions of coupled surface process and 3D-tectonic models

Stephanie Schnydrig¹, Dave May¹, Kosuke Ueda¹ & Taras Gerya¹

¹ Department Erdwissenschaften, ETH Zürich, Sonneggstrasse 5, CH-8092 Zürich (schnyadr@student.ethz.ch)

The coupling between dynamics in the Earth’s interior and surface processes over geodynamic time scales is widely accepted. Tectonic processes such as plate collision set up topography and in response surface processes redistribute significantly large volumes of sedimentary material. This may induce tectonic feedback due to the dynamic loading and unloading of the underlying crust.

To study the interaction between topographic evolution, surface processes and lithosphere/mantle dynamics, a 3D thermo-mechanical model (I3ELVIS: Gerya and Yuen, 2007) is fully coupled with a surface process model. To this end, we test and employ a new 2D surface process model, FDSPM, which affects the physical surface of the model. It uses a diffusion-advection law to model erosion and sedimentation that approach a physical description of surface processes. Firstly, we evaluate the applicability of our landscape evolution model for large scale geodynamics. We also assess the most appropriate mathematical description to model the physics of erosion and sedimentation in large scale problems. Secondly, the role of surface processes on topographic expression is examined, i.e. we explore how surface processes modify large scale topographies. And lastly, we examine the influence of erosion and sedimentation on the behaviour of the lithosphere and the mantle flow dynamics, examined for the case of drip-type, convective removal of lithospheric mantle (Fig. 1).

Based on a comparison with analytical solutions, we show that the FDSPM code is accurate and stable. Further, a linear diffusion model appears sufficient to capture the feedback under reasonable geological assumptions, and behaves virtually identical to a critical-slope non-linear diffusion model, while both outperform gross-scale, prescribed, erosion/sedimentation formulations.

Coupled models (Fig. 1) show that the steady-state elevation is similar for very different efficiencies of long-range surface redistribution, despite the fact the amount of uplift and exhumation varies significantly. The role of feedback is demonstrated by the decay time of topography, which is at least one order of magnitude longer in the case of active erosion-uplift feedback, as compared to static analytical predictions (Fig. 1b). Even for lowest effective diffusivity values, the erosional decay effects dominate over gravitational collapse (c.f. Jadamec et al., 2007). The developing stratigraphy is in agreement with principal observations from the Miocene Arizaro Basin in Argentina, which is indeed thought to have formed in response to partial lithospheric removal (DeCelles et al., 2015).

REFERENCES


P 8.23

**Constraints on the extent and kinetics of eclogitization processes in the Indian lower crust**

Chanard K., Hétenyi G., Baumgartner L., Licul A., Herman F.

Earthquakes occurring in the Indian lower crust underthrusting Tibet can be related to the mineral transformations of subducted crustal rocks to denser eclogites. These intermediate-depth earthquakes are most likely linked to physical processes accommodating the significant volume change caused by dehydration reactions during eclogitization. However, while described by laboratory experiments and field samples, the kinetics of metamorphic reactions at large scale is not well known.

We propose to constrain the extent and kinetics of eclogitization processes in the Indian lower crust, at large spatial scales, by combining Bouguer anomaly data with 2-D thermokinematic and petrological modeling. We derive lithospheric density profiles by coupling thermokinematic modeling with a realistic multi-layer petrological model depending on mineralogical composition, pressure and temperature. The density estimates are then used to compute the associated Bouguer anomalies, which are then constrained by observed data along profiles perpendicular to the Himalayan arc. We explore model parameters (model geometry, mineralogical composition, water content) to best fit observations along 10 profiles spanning from NW India to Bhutan and discuss lateral variations in eclogitization processes along the Himalayan arc, in relation with seismic activity in the region.

P 8.24

**Laboratory earthquakes triggered during eclogitization of lawsonite bearing blueschist**

Sarah Incel1, Nadège Hilaire2, Loïc Labrousse3, Timm John4, Damien Del dicede5, Thomas Ferrand5, Yanbin Wang5, Joerg Renner6, Luiz Morales7 & Alexandre Schubnel1

1 Laboratoire de Géologie de l’ENS - PSL Research University - UMR8538 du CNRS, 24 Rue Lhomond, 75005 Paris, France (incel@geologie.ens.fr)
2 CNRS - UMET, Université Lille 1, 59655 Villeneuve d’Ascq, France
3 Université Pierre et Marie Curie, 4 place Jussieu, 75252 Paris, France
4 Freie Universität Berlin, Malteserstr. 74-100, 12249 Berlin, Germany
5 GeoSoilEnviroCARS, University of Chicago, Argonne, IL 60439, USA
6 Ruhr-Universität Bochum, Universitätsstraße 150, 44801 Bochum, Germany
7 GeoForschungsZentrum Potsdam, Telegrafenberg, 14473 Potsdam, Germany

The origin of intermediate-depth seismicity has been debated for decades. Almost all of these events occurs within the upper plane of Wadati-Benioff double seismic zones believed to represent subducting oceanic crust. We deformed natural lawsonite-rich blueschist samples under eclogite-facies conditions (1 < P < 3.5 GPa; 583 K < T < 1121 K), using a D-DIA apparatus installed at a synchrotron beam line continuously monitoring stress, strain and strain rate, phase proportions, and acoustic emissions (AEs). Two distinct paths were modelled: i) high pressure paths (> 2.5 GPa) under which lawsonite and glaucophane became gradually unstable while entering the stability field of lawsonite-eclogite ii) a low pressure path (< 2 GPa) without entering the lawsonite-eclogite stability field, but crossing the breakdown reaction of lawsonite and entering the stability field of epidote-blueschist and later eclogite-amphibolite. Upon entering the Lws-Ecl stability field samples exhibited brittle failure, accompanied by the radiation of AEs. In-situ X-ray diffraction and microstructural analysis demonstrate that fractures are topologically related to the formation of omphacite. Amorphous material filling out the fractures was detected by transmission-electron microscopy without evidence for free-water. Since the newly formed omphacite crystals are small compared to the initial grains, we suggest that grain-size reduction (transformational faulting) during the transition from lawsonite-blueschist to lawsonite-eclogite leads to brittle failure of the deviatorically loaded samples. In contrast, we find no microstructural evidence that the breakdown of lawsonite, and hence the liberation of water leads to the fracturing in the samples.