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6. Geophysics and Rockphysics

Marcel Frehner, Klaus Holliger

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6.1

Fault zone porosity determination by joint interpretation of 3D seismic and gravity data for geothermal exploration - application in the St. Gallen geothermal project

Altwegg Pierrick[1], Schill Eva[1] & Abdelfettah Yassine[1]

[1] *Centre for Hydrogeology and Geothermics (CHYN), University of Neuchâtel, Emile-Argand 11, CH-2000 Neuchâtel (pierrick.altwegg@unine.ch)*

In recent years, most of the geothermal projects developed in Switzerland and neighboring regions or underway are targeting the exploitation of deep aquifers. Indeed, in a setting of sedimentary basin, these reservoirs are frequently present beneath highly populated areas. In this geological context, fault zones are frequently the target of the project because faulting zone increases the rock fracture density. This local increase of fracture density can result in an increasing of permeability within the aquifer, and thus the flow rate that it is possible to extract from it. This can be inferred through the transmissivity of the rock, which is related to its effective porosity. An increase of this porosity should result in a lowering of the rock bulk density which can be measured by gravimetry.

However and in this case, the resulting gravity anomaly is of relatively small intensity. In order to characterize the associated gravity anomaly due to the change of rock density, it is necessary to remove any other gravity signal present in the measured gravity values. Thus after the stripping step, the final residual (or misfit) is only influenced by the targeted structures. To do so, we modeled the geological structures and calculated the gravitational effect of the model using a forward modeling. Even if gravity can be used to determine the geometry of the geological model, it is not widely used because it presents a nonlinear problem. That's the reason why other method such as 3D seismic must be used, when data are available, such as in St Gallen geothermal project.

The geothermal project of the city of St. Gallen, which targets a fault zone in the potentially aquifer formations of Mesozoic lying at more than 3 km deep, was good and rare opportunity. A large 3D seismic survey was conducted early 2010 and the results give a 3D model of the regional geological structures.

In order to characterize the local increase of rock permeability, a high precision gravity measurements campaign was done in the St Gallen region. Our gravity results have been combined with the data from the Swiss Atlas of Gravimetry (Olivier et al., 2010) to allow a better determination of the connected porosity in the targeted area.

Based on the 3D geological model from the 3D seismic, a forward gravity map of the region has been computed and then compared to our residual gravity map. The comparison indicates that the regional 3D structural model is not sufficient to explain the entire residual anomaly (Fig. 1a) and that some structures that were not modeled, such as Permo-Carboniferous Graben and quaternary deposits have a significant gravity effect. Consequently these two structures have been added to the 3D model, their gravity effect calculated and subtracted to the residual gravity (Fig. 1, b & c). As there was no other known geological structures from which the gravity effect could be resulted in the residual anomaly, we consider that this final residual anomaly was due to a lowering of the bulk rock density in the fault zone. This end was modeled, its gravity effect calculated and subtracted from the previous stripping result (Fig. 1, d). We found that this residual anomaly corresponds to a bulk rock density change comprised between 4 and 6% (Fig. 1, d). However this value is equal to the porosity only if rock is not saturated. So if the rocks are saturated, it corresponds to a porosity comprised between 6.5 and 9.5%.

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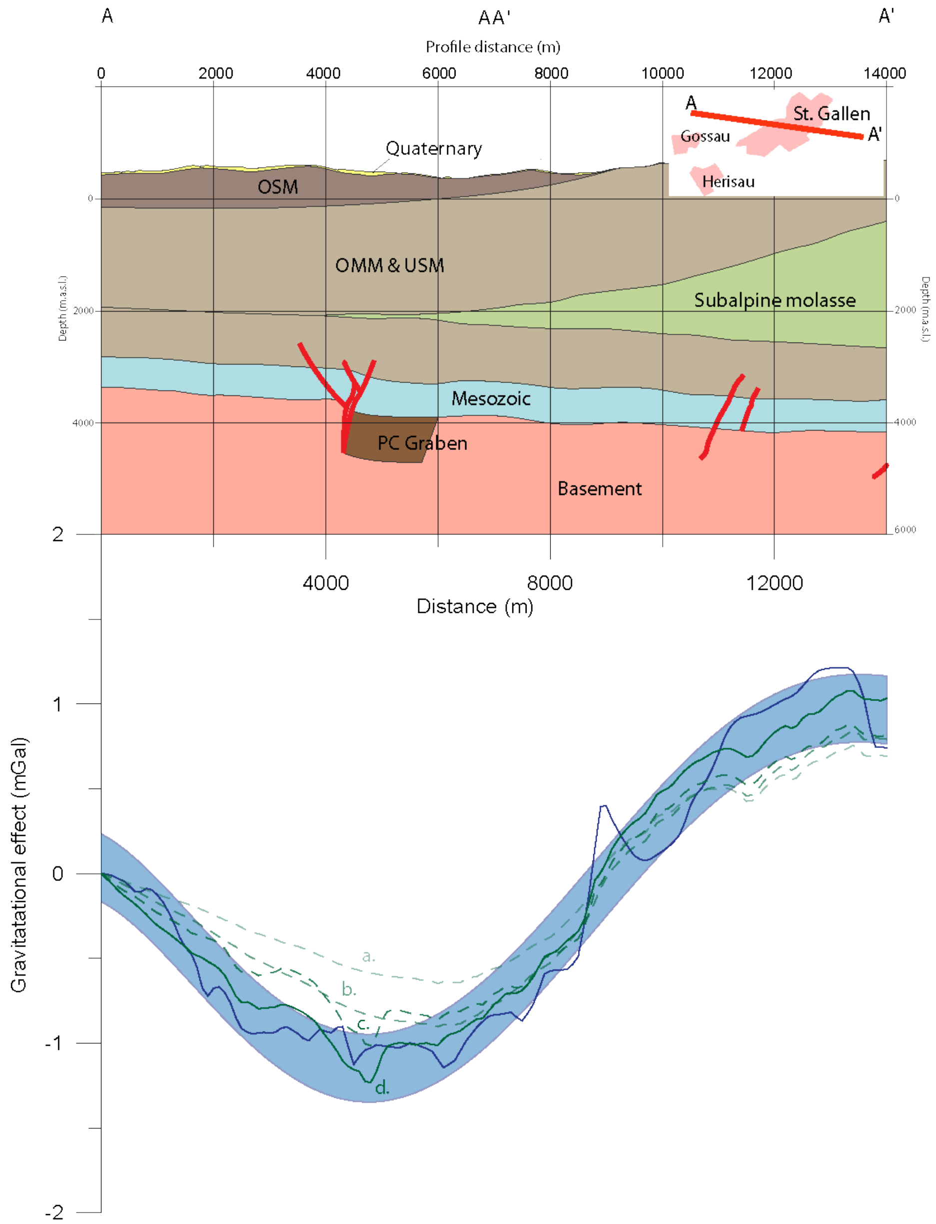

Fig 1. Top: model and localization, bottom, different steps of stripping: a. Effect of the geological model established using 3D seismic data. b. The effect of the Permo-Carboniferous graben is added to (a.). c. Quaternary deposits effect is added to (b.). d. The effect of the fault zone assuming a diminution of 5% of the density due to fracturing is added to (c.). The light blue area represents the assumed residual anomaly, the thin blue line being the measured value.

6.2
Seismic and magnetic anisotropy of the Finero Peridotite (Ivrea Zone)

Biedermann Andrea Regina[1], Erni Michaela[1], Hirt Ann Marie[1], Pistone Mattia[2] & Zappone Alba[3]

[1] *Institut für Geophysik, Eidgenössische Technische Hochschule Zürich, Sonneggstrasse 5, CH-8092 Zürich*
[2] *Institut für Geochemie und Petrologie, Eidgenössische Technische Hochschule Zürich, Sonneggstrasse 5, CH-8092 Zürich*
*** Schweizerischer Erdbebendienst, Sonneggstrasse 5, 8092 Zürich (alba.zappone@sed.ethz.ch)

The Ivrea-Verbano zone (north-western Italy and southern Switzerland, Alps), provides one of the most spectacular out-cropping sections through rocks of lower crustal provenance .This crustal cross-section has not been affected by the Alpine deformation, except for very localized retrograde metamorphism structures. Therefore, the Ivrea-Verbano zone provides the unique opportunity to improve our understanding of the lower and upper continental crust and the primary metamorphic and magmatic processes that generated the current assembly of rocks.

The Ivrea-Verbano zone consists of an original sequence comprised of metasedimentary gneisses and schists, metabasites and minor marbles and quartzites; a large volume of mafic rocks has intruded at the base of the crustal section. At the base of the section, there are also mantle-derived peridotites (i.e. Boudier et al., 1984, Quick et al., 1995), the emplacement of which is still on debate.

From south to north, three major peridotites crop out: the Balmuccia Peridotite in Val Sesia, the Premosello Peridotite in Valle d'Ossola and the Finero Peridotite in Val Cannobina. The last one is distinctive due to the presence of hydrous minerals, such as phlogopite (up to 15 vol.%) and hornblende (up to 20 vol.%), which were produced by dramatic metasomatism (Zanetti et al., 1999; Grieco et al., 2001). The concentrations of Sr, Rb and Ba and $^{87}Sr/^{86}Sr$ ratios indicate a significant amount of crustal contamination (Grieco et al., 2001), but there is still controversy as to its origin.

To date, there is a lack of data on seismic and magnetic properties of such peridotites that underwent metasomatic under-crustal processes. The difficulty to obtain reliable measurements on this kind of rocks is related to the difficulty in finding rock samples that do not contain serpentine minerals (weathering); even a minimum amount of serpentine has a large influence on the magnetic and seismic properties of the whole aggregate.

In this study we present a combination of experimental results on both seismic and magnetic properties in the peridotites from Finero, with the intent to investigate the influence of those hydrous minerals on the overall seismic behaviour of the Finero peridotite body. We also correlate seismic and magnetic anisotropies and their relation to the deformation.

The studied samples are virtually free from serpentine; their modal composition has been determined using electron microscopy techniques. Samples, selected on the basis of phlogopite and hornblende content, have been used to measure ultrasonic wave velocities, using the pulse transmission technique (Birch, 1961) at confining pressure and temperature, simulating in situ conditions. Vp absolute values confirm literature data (i.e. Ullemeyer et al, 2010); seismic anisotropy is dominated by the phlogopite and hornblende content.

Anisotropy of magnetic susceptibility (AMS) has been measured both in low and high magnetic fields. High-field measurements allow for the separation of paramagnetic and ferromagnetic contributions to the magnetic anisotropy, which can be related to silicates and iron oxide inclusions, respectively. Magnetic anisotropy is often used as a proxy for mineral fabric. The low-field AMS is dominated by the ferromagnetic component and does not show any preferred orientation of the principal susceptibility axes. The paramagnetic sub-fabric, however, is clearly related to the rock texture. All samples except one have their minimum susceptibility parallel to the pole of the foliation plane. The degree of anisotropy is similar to that expected for olivine in most samples. Samples contains a large amount of hornblende, have more pronounced anisotropies.

These results will be used to understand the role of metasomatic fluids on the seismic and magnetic physical properties of lower crustal peridotites and how magnetic and seismic anisotropies can help us understand deformation in these rocks.

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6.3

Talc lubrication of faults at seismic velocities: comparison between the rate and state approach and a fluid constrain.

B. Cordonnier[1], N. Tisato[1], S. Boutareaud[1], T. Hirose[2]

[1] *Geologisches Institut, ETH, Zurich, Switzerland*

[2] *Japan Agency for Marine-Earth Science and Technoloy (Jamstec)*

Exposures of fossil or active mature faults at the Earth's surface show that in the shallow crust most of co-seismic slips occur within a clay-rich gouge material. Field observations, theories and laboratory experiments show that the thermo-poro-mechanical properties of this gouge slip zone significantly influence the dynamic fault strength by controlling the efficiency of the slip-weakening.

Talc can represent a fault gauge material which explain weak zones among the all seismogenic zone (e.g., San Andreas fault in USA; Zuccale fault in Italy). However, the mechanical behavior of talc at seismic velocities remains purely speculative.

We compare here two comportmental law, one relates the strain and semi empirical rate and state equation while the second is based on a visco-elastic approach. The latter is compared to rotary-shear friction experiments conducted on dry and water saturated natural talc gouge, at 0.01, 0.13 and 1.31 m s^{-1} slip-velocities and 0.3 - 1.8 MPa normal stress.

At 0.13 and 0.01 m s^{-1} the experimental results always display i) a strengthening behaviour with time, ii) the development of a mm-thick Principal Slip Zone (PSZ), and iii) a re-orientation of grains parallel to the sense of shear. From litterature, such strengthening mechanisms remain still unclear.

At 1.31 m s^{-1} the results evidence i) a weakening behavior, ii) the development of a mm-thick PSZ, and iii) progressive re-orientation of the grains parallel to the sense of shear for the central part of the gouge. In dry conditions, the slip-weakening is attributed to solid lubrication of the gouge in the central part of the PSZ (i.e., frictional sliding between favourably C-oriented (001) planes of forming talc lamellae). Under wet conditions, the slip-weakening is also attributed to fluid lubrication of the gouge in the central part of the PSZ (i.e., shear of a thin film of fluid between talc grains).

A previous work has already explained these effects as a structural self-organization of the PSZ grains to provide minimum dynamic friction during strain rate localization. The observations for dry conditions suggest that grains are subjected to sliding and rolling regimes during the same experiment. The association of sliding and rolling friction suggests strain partitioning during the slip-weakening, and so powder lubrication as a possible additional weakening mechanism for dry conditions.

With this work we propose a granular flow approach from visco-elastic comportmental laws. A linear visco-elastic type equation is thus applied to fit our results with parameters obtained from the experiment and physical properties measurements. The strengthening gets consequently explained as a simple relaxation process of the material. The weakening arises from the formation of slifind-rolling structures affecting the physical parameters of the material.

6.4

Analysis of seismic attenuation mechanisms in unconsolidated surficial sediments

Marco Milani*, J. Germán Rubino*, Ludovic Baron*, Rolf Sidler* and Klaus Holliger*

[1] *Applied Geophysics Group, University of Lausanne, Amphipôle Building, CH-1015 Lausanne, Switzerland (marco.milani@unil.ch, german.rubino@unil.ch, ludovic.baron@unil.ch, rolf.sidler@unil.ch, klaus.holliger@unil.ch)*

The attenuation of seismic waves is an important material parameter, which contains potentially valuable information on key hydraulic and geomechanical properties of the probed medium. An inherent and important complication arising in the interpretation of such measurements is, however, that there are multiple physical mechanisms contributing to the dissipation of seismic energy, such as wave-induced fluid flow at the micro-, meso-, and macroscopic scales as well as scattering and inelastic effects, and that their relative contributions and importance is generally unknown and difficult to unravel. To address this problem for the practically particularly relevant case of unconsolidated surficial alluvial sediments, we analyze multi-frequency sonic logs with dominant source frequencies ranging roughly between 1 kHz and 30 kHz. To obtain reliable estimations of attenuation, appropriate corrections for near-field and geometrical spreading effects are fundamental requirements. In order to estimate these effects, we model our experimental setup using a 3D poroelastic simulation code in cylindrical coordinates. After having applied corrections, this broadband dataset, in conjunction with a comprehensive suite of complementary logging data, allows for building a realistic rock physics model, which in turn provides the basis for simulating the various seismic attenuation mechanisms and for assessing their relative importance.

6.5

Geophysical monitoring of the Excavation Damaged Zone during a gallery excavation in the Opalinus Clay (Mont Terri underground rock laboratory, Canton of Jura)

C. Nussbaum,[1] P. Bossart[1], D. Gibert[2], Y. Le Gonidec[3], F. Nicollin[3], A. Maineult[2], K. Wieczorek[4], J. Wassermann[5], N. Lesparre[6], J.-F. Thovert[7], P.M. Adler[8], B. Lavielle[9]

[1] *Federal Office of Topography swisstopo, CH-2882 St-Ursanne, Switzerland*
(Corresponding author: christophe.nussbaum@swisstopo.ch)
[2] *Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Univ. Paris Diderot, UMR 7154 CNRS, F-75005 Paris, France*
[3] *Géosciences Rennes, Université de Rennes 1, UMR 6118 CNRS, F-35000 Rennes, France*
[4] *Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, D-38122 Braunschweig, Germany*
[5] *Universite de Cergy-Pontoise, Laboratoire Geosciences Environnement, Cergy, France*
[6] *Systems and Computer Engineering, Carleton University, Ottawa, Canada*
[7] *Institut PPRIME, SP2MI, BP 30179, F-86962 Futuroscope cedex, France*
[8] *Université Pierre et Marie Curie, Sisyphe, 4 place Jussieu, 75252 Paris cedex 05, France*
[9] *Centre d'Etudes Nucléaires de Bordeaux Gradignan, Université Bordeaux 1, UMR 5797 CNRS, F-33175 Gradignan, France*

At the Mont Terri underground rock laboratory we excavated the rock mass of the "EZG-08 segment" located at the junction between the advancing face of Gallery 08 (Ga08) and the existing end-face of Gallery 04 (Ga04). This offered a unique opportunity to monitor the Excavation Damaged Zone (EDZ), simulating the short-term "excavation phase" of a repository. Different geophysical methods (i.e. electrical tomography, active and passive seismic monitoring, spontaneous potential monitoring) were applied from the Ga04 end-face, to observe the evolution of the rock mass of the "EZ-G08 segment" during the progress of the excavation (Fig. 1A). The geophysical dataset was complemented by noble gas measurements, structural data of the fracture network (mainly composed of pre-existing tectonic fault and of scarce EDZ micro-fractures) and its reconstruction means statistical approaches.

During and after the gallery excavation process we detected and located in time and place a large number of microseismic events (MSEs) (Le Gonidec et al. 2012). Most of the MSEs were induced in the excavated face Ga08. Only a few MSEs were located inside the rock mass itself, and these were arranged close to a SE-dipping fault, which seems to have been reactivated by the excavation process. According to laboratory experiments performed by Amann et al. (2011) on Opalinus Clay samples, the first MSEs can be related to microcrack initiation in the tensile failure mode. This stage was also clearly reflected by the increase of the measured resistivity. When the tunnel face of Ga08 was getting closer to the tunnel face of Ga04, the growth and coalescence of EDZ microcracks lead to macroscopic shear failure, associated with a decrease of the MSEs, which mainly occurred along bedding plane structures and pre-existing tectonic faults.

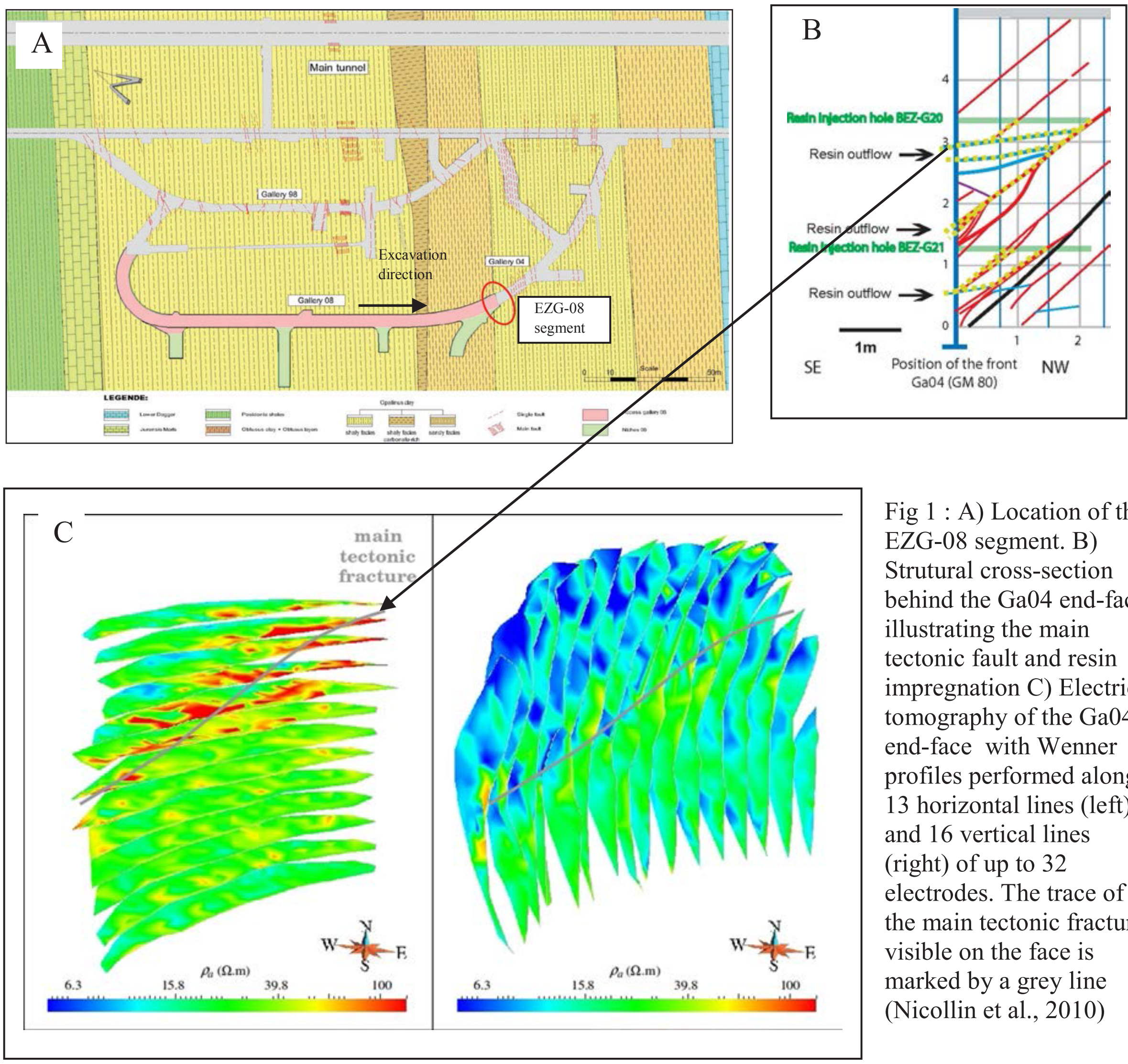

Fig 1 : A) Location of the EZG-08 segment. B) Strutural cross-section behind the Ga04 end-face illustrating the main tectonic fault and resin impregnation C) Electrical tomography of the Ga04 end-face with Wenner profiles performed along 13 horizontal lines (left) and 16 vertical lines (right) of up to 32 electrodes. The trace of the main tectonic fracture visible on the face is marked by a grey line (Nicollin et al., 2010)

The short-term pore pressure response monitored during the excavation of the "EZG-08 segment" revealed rapid negative pore pressure changes in the gallery walls, followed by pore pressure increase deeper within the rock mass. Pore pressure measured directly at the tunnel wall was substantially below the in-situ pore pressure. These low pore pressures could be due to a desaturation process. The presence of many tectonic faults in the Ga04 end-face, reactivated by the excavation of Gallery 04 in 2004, together with the EDZ microcracks, had enhanced the penetration depth of the desaturation zone up to 2m. This was demonstrated by resin-impregnation experiments performed for the microstructural characterisation of the EDZ fracture network (Fig. 1B). Fig 1C illustrates the influence of a reactivated tectonic fault on the electrical resistivity on the Ga04 end-face (Nicollin et al. 2010). Möri et al. (2010) showed that degree of saturation and depth penetration may be due to seasonal variations in relative humidity in the tunnel. During the excavation of the "EZG-08 segment," performed in Summer 2008, the humidity content in the ambient air was close to 100%. We suggest that the presence of air at atmospheric pressure within the fracture network created a suction effect. The slow decrease of resistivity measured after the excavation phase may be interpreted as consequence of slow re-saturation of the fracture network triggered by suction within the unsaturated zone.

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6.6

3D-Seismic for Geothermal Energy in St. Gallen

Brian Steiner[1]

[1] Interoil E&P Switzerland AG, Seefeldstrasse 287, 8008 CH-Zürich
(brian.steiner@interoil.ch)

Geothermal energy has gained rising interest in Switzerland during the last few years. Geothermal energy is reliable, sustainable, and environmentally friendly. In the last 20 years near-surface geothermal energy (d < 400 m) has become a standard energy source for heating houses. Contrarily, deep geothermal energy (d > 400 m) is not a standard energy form yet. Deep geothermal energy has the potential to continuously and nearly inexhaustibly provide energy. Initiative has been taken to promote and provide electrical power and heat from deep geothermal energy in some urban regions. Riehen (Basel-Stadt) is already connected to deep geothermal energy. Basel-Stadt, Zürich Triemli and St. Gallen are some of the pioneers in exploring the potential of deep geothermal energy in Switzerland (géothermie.ch, 2010; energeia, 2012).

Deep geothermal energy can be extracted either by producing hot water from an existing aquifer (hydrothermal) or by extracting heat from a basement rock (petrothermal). Particularly for hydrothermal projects careful exploration is important due to reduce the risk of drilling in the wrong location. Current knowledge about the deep subsurface satisfies rough estimation of possible aquifers or hot rock volumes only. An efficient and adequate future energy supply demands a close localization of a promising target zone. To plan a borehole one should know in advance, at which spot of a specific layer it should be placed to maximize the extraction of energy. An important tool to illuminate the subsurface at the desired depth of 3 to 6 kilometers is reflection seismic. The Swiss midland is covered with a loose grid of 2D-seismic lines. Depth maps produced from 2D-seismic data are not very accurate due to lack in signal directivity and surface coverage (Figure 1). Developments in seismic field equipment, seismic data processing and interpretation makes 3D-seismic applicable to large-size industrial projects at a reasonable cost. It allows a very accurate and detailed mapping of geological structures in the deep subsurface (Figure 1). This advantage is essential to narrow down a potential target zone.

The city of St. Gallen is aiming for a geothermal power plant that produces heat and electricity. A 3D-seismic survey was carried out at the beginning of 2010 (Figure 2, surface area ca. 270 km2). This was a crucial step that helped in mapping the fault systems at target level and to define an optimal location for drilling. The first step was planning and designing the 3D-seismic survey. The acquisition parameters had to be chosen so that enough energy could be recorded from the deepest target level. The ideal grid-layout had to be adapted to the road network and to deal with obstacles like railway lines. Permission from authorities and land-owners had to be requested early enough. Good planning is an essential first step for the success of a 3D-seismic campaign. At this point, St. Gallen is now preparing to drill to the most promising targets at the level of the Malm, the Muschelkalk and possibly a fractured basement.

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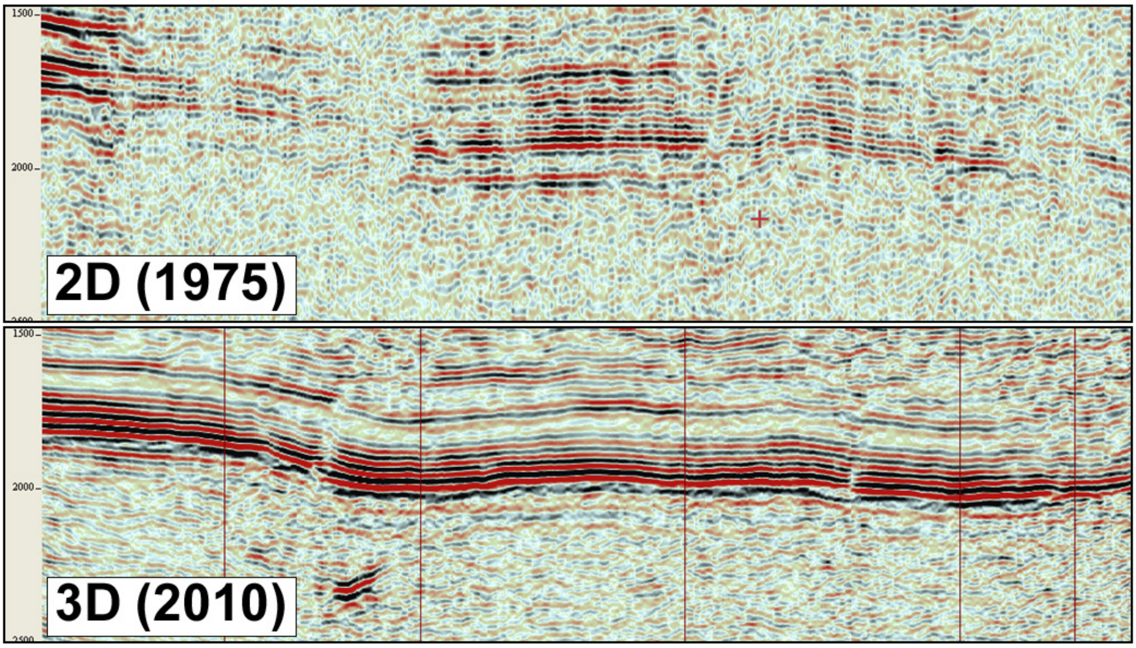

Figure 1. The image from 3D-seismic (below) renders a clearly more continuous structure of the reflector than the image from 2D-seismic (top). Geothermieprojekt St. Gallen, St. Galler Stadtwerke, 2010.

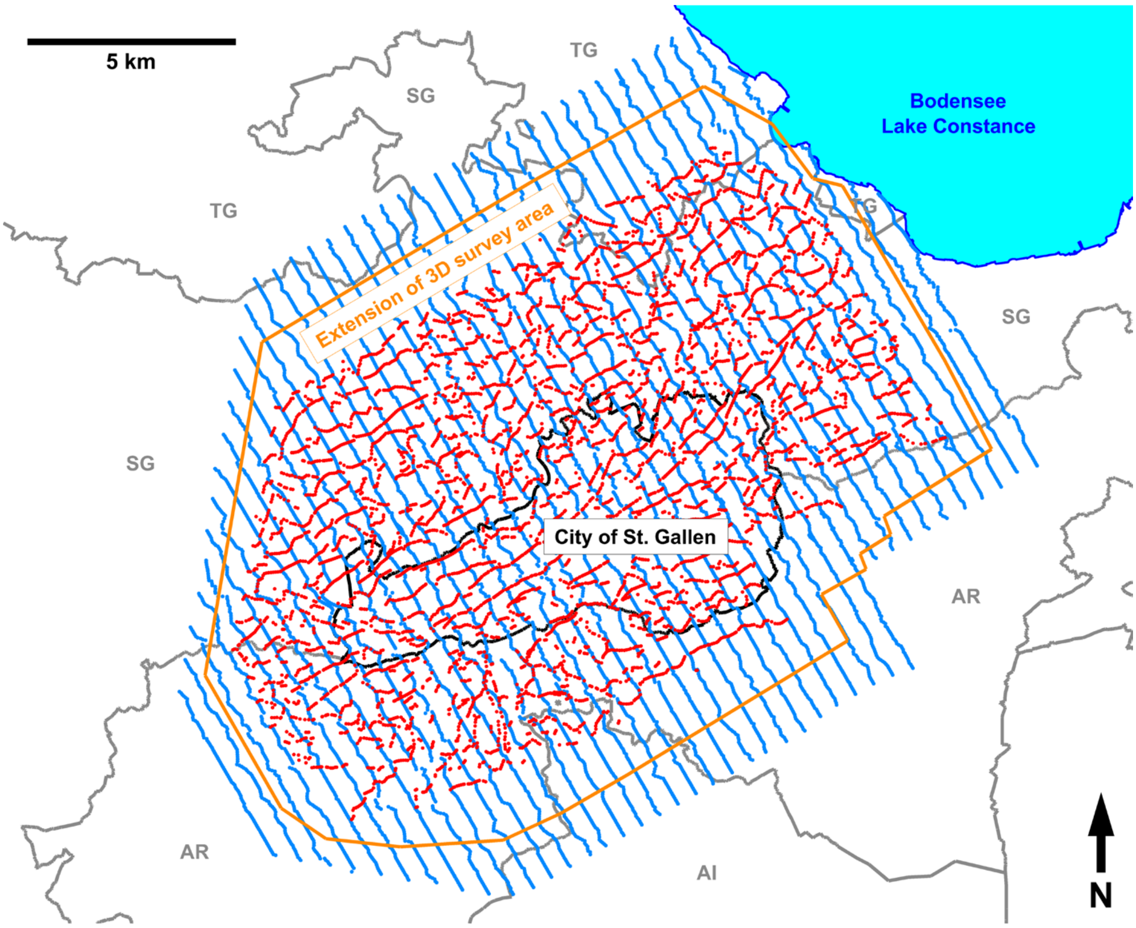

Figure 2. The 3D-seismic layout covers the northern part of canton St. Gallen and some of the neighboring cantons. Red points indicate source locations (vibration, explosions). Blue lines indicate recording lines (geophones). Geothermieprojekt St. Gallen, St. Galler Stadtwerke, 2010.

6.7

How stress affects Berea sandstone seismic-wave-attenuation

Tisato Nicola[1], Madonna Claudio[1], Erik H. Saenger[1]

[1] *ETH Zurich, Soneggstrasse, 5, CH 8092 Zurich (nicola.tisato@erdw.ethz.ch)*

Seismic wave attenuation (Q^{-1}) in the bandwidth 1-100 Hz can help to understand the saturation of crustal and reservoir rocks (e.g. Chapman et al., 2006). Attenuation for frequencies <100 Hz in partially saturated porous media have been studied by several authors. White (1975), Mavko and Jizba (1991), and Pride et al. (2004) described i) patchy saturation, ii) squirt flow and iii) wave-induced fluid flow, respectively. The latter theory has been modelled for instance by Gurevich and Lopatnikov (1995) and by Quintal et al. (2011). In addition, experimental studies focused on attenuation in the bandwidth 1-100 Hz have been conducted by several authors (e.g. Peselnick and Liu, 1987, and Batzle et al. 2006). All these efforts improved the knowledge about the attenuation mechanisms in partially saturated rocks. However, the mechanisms responsible for attenuation and its dependence with the stress applied on partially saturated rocks are still not fully understood, and there are still many lithologies and physical conditions for which experimental data do not exist. In addition numerical models, like Quintal et al. (2011), need to be calibrated.

In this contribution we describe a series of seismic wave attenuation measurements as function of frequency (1-100 Hz) and confining pressure (0-20 MPa) for two partially saturated Berea sandstone specimens (samples). For the same lithology the longitudinal and transverse wave speeds at ultrasonic frequency (~1 MHz), as function of confining pressure, have been also measured and will be presented here.

The quality factor of dry samples confined with a pressure lower than 20 MPa is constant and around 100 over the entire bandwidth. On the other hand the same samples, but partially saturated (e.g. 60% with water), show a dependence of attenuation on saturation and stress (Fig. 1). Thanks to the i) calibration performed with aluminum, ii) the data related to dry samples and iii) the calculation made to evaluate the open-boundary condition effect (Dunn, 1986) we ruled out the possibility that the frequency dependent attenuation observed is the result is an artefact related to the apparatus (Peselnick and Liu, 1987) or the sample (Dunn, 1986).

To conclude we can state that the results show a frequency and stress dependence attenuation which could be explained with i) squirt flow (Mavko and Jizba, 1991), and ii) in part with patchy saturation (White, 1975) related attenuation. The variation of attenuation, as function of confining pressure, could be explained by cracks aspect ratio reduction and bulk module increasing. Longitudinal and transverse wave speeds measured on a similar sample also indicate that crack like voids close for confining pressure <20 MPa.

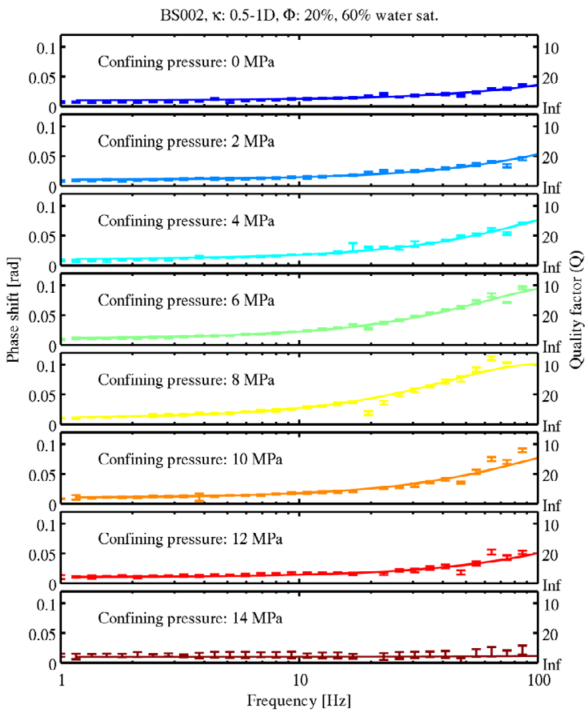

Figure 1. Q of 60% water saturated Berea sandstone sample for confining pressures between 0 and 14 MPa.

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6.8

Seismic-induced stick-slip friction in simulated granular layers

Wu Wei

Ecole Polytechnique Fédérale de Lausanne (EPFL), School of Architecture, Civil and Environmental Engineering, Laboratory of Rock Mechanics (LMR), CH-1015 Lausanne, Switzerland

Stick-slip friction has been long recognized as a mechanism of earthquakes (Brace & Byerlee, 1966). Several laboratory experiments have been performed to explore quasi-static fault slips at a range of slip rates, with and without fault gouges, and under the effects of temperature, normal and pore pressures. The slip durations in most of these studies are longer than 0.01s, which agrees with a variety of fault-slip observations (Peng & Gomberg, 2010). In nature, dynamic triggering has been found as the origin of most of seismic events (Ujiie et al., 2009), such as seismic-induced landslides and blast-induced collapses. The instantaneously triggered stick-slip friction also significantly contributes to fault instabilities, however, has been subjected to less attention.

The experimental study investigates the seismic-induced stick-slip friction on a simulated granular fault zone using a novel dynamic direct shear apparatus. The rock fault model consists of two thin norite plates with a thickness of 30 mm and 120 mm in width, namely the incident plate (1000 mm in length) and the transmitted plate (500 mm in length). The short side of the transmitted plate contacts the center part of the incident plate long side as a frictional interface. The normal load is fixed on the other short side of the transmitted plate. A layer of crushed norite is used as the granular gouge and sandwiched in the simulated fault.

The experimental results show a generated plane P wave propagates in the incident plate and drives stick-slip friction in the simulated granular layer. The frictional slip is rate-dependent at high shear rates. The amplitude of the induced shear wave recorded in the transmitted plate depends on gouge thickness, loading rates and normal loads. The experimental study extends our understanding of fault instability from quasi-static to dynamic triggering with the observation of seismic wave radiation.

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P 6.1

Delineation of the Permo-Carboniferous graben in the crystalline basement of Switzerland using gravity

Abdelfettah Yassine[1] & Schill Eva[1]

[1] *Centre for Hydrogeology and Geothermics (CHYN), University of Neuchâtel, Emille-Argand 11, CH-2000 Neuchâtel (yassine.abdelfettah@unine.ch)*

Although many are suspected from seismic observations, few and far between Permo-Carboniferous (PC) graben at the top of the Variscian basement in Switzerland are confirmed by wells. Challenges in localization of PC troughs using seismic data include (Marchant et al., 2005): i) Uncertainty in the origin of the characteristically weak reflections below the Mesozoic in the absence of boreholes. ii) Where PC deposits are present, the little expressed base Mesozoic reflection can be mistaken for an internal PC reflection, and iii) the structural interpretation is often uncertain, as faults below the Mesozoic cannot be traced along marker horizons on the seismic sections. These difficulties are also comprehensible in the new Atlas of the Swiss Molasse Basin (Sammaruga et al., 2012).

Gravity studies have been proven to be a good exploration tool for the investigation of the troughs. It was this method which permitted the first regional interpretation on the extension of the Northern Swiss trough (Klingelé and Schwendener, 1984). Unfortunately, since the 80-ties, the gravimetric exploration method was not used further to better understand the PC graben in Switzerland subsurface. In this study, we have investigated the application of 2D and 3D geology for gravity forward modeling as well as the application of Butterworth filters of different wavelength. Real application was conducted in the northern part of Switzerland under the Molasse basin.

In order to systematically assess the potential of the gravity data to detect and characterize PC troughs in the Molasse basins, 2D and 3D conceptual models were set up. Synthetic gravity data sets were generated for these models using a homogeneous basement density of 2670 kg m^{-3}. According to different types of measurements, a range of density for the PC graben is obtained (Klingelé and Schwendener, 1984), resulting mainly in the 3 scenarios: (1) an extreme density contrast of -220 kg m^{-3} (PC density ρ_{PC} = 2450 kg m^{-3}), which is slightly smaller than the value obtained from gamma-gamma ray density logs in the wells of Böttstein and Weiach, (2) an intermediate density contrast of -100 kg m^{-3} (ρ_{PC} = 2570 kg m^{-3}) obtained from gravity measurement (BHGM) in the same wells, and (3) a small density contrast of -50 kg m^{-3} (ρ_{PC} =2620 kg m^{-3}) is assumed as worst case scenario.

Gravity forward modeling is carried out using developed and unpublished Finite Element (FE) code. The FE modeling allows approaching the geological geometry using tetrahedrons shape. To simulate the real conditions, the gravity stations are located on the real topography. After computing a gravity effect of the 3D geological model, we get a complete Bouguer anomaly. Since, and as expected from the geology, the Bouguer anomaly is strongly dominated by the gravity effect of the Molasse sediments, where the slightly bended Mesozoic sediments are inclined by about 2-5 ° towards the Alps and the Tertiary filling of the molasses basin is deepening following this geometry.

A code using Butterworth filter was developed and applied on the computed Bouguer values to eliminate this trend (Abdelfettah and Schill, 2012). This filter is characterized and controlled mainly by two parameters: (1) cut-off frequency or wavelength and (2) the filter order. The advantage of this filter is that we can easily use different wavelength to i) delineate and characterize different negative anomalies at depth, and ii) to choose an adequate residual anomaly which provides the comparable gravity response with the conceptual model. Depth and size of the origin of the anomalies are indicated among others by the wavelength of the filter. With increasing wavelength, we are able to visualize increasing larger or deeper structures until approaching the Bouguer or residual anomalies. Moreover, the filter order parameter can be also changed to delineate a very small variation, for instance, in the case of low density contrast between the PC graben and the basement. With increasing filter order the horizontal density contrast is emphasized.

Gravity modeling was conducted on the basis of 2 and 3D geological models in order to understand the gravity variation with increasing depth of the top of the grabens. It reveals high potential in the delimitation of the Permo-Carboniferous troughs by the combination of both. Assuming a similar geometry for these graben structures, gravity data processing traces these structures at different depth using a Butterworth filter with different wavelength to calculate a residual gravity anomaly. Filtered Bouguer anomaly with different wavelengths is an essential tool to detect and trace the horizontal and vertical extension of the PC troughs. The sensitivity studies on the conceptual geological models reveal that the negative anomaly related to PC grabens persists through the different steps of Butterworth filter with varying wavelength. The different wavelengths provide insight into different vertical levels of the trough and thus, allow describing 3D geometry of the graben structures. Finally, the application of the filters to real measurements reveals the distribution of the PC grabens in the northern part of Switzerland where it was confirmed by wells. It, however, shows that the tracing of the geometry is more complex, since long wavelengths risk to take up also other more regional structures, such as in this case the deepening of the Molasse basin, which introduces a broader negative anomaly overlying the expected narrowing of the PC graben at depth.

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P 6.2

Localization of temperature anomalies in Soultz area (Upper Rhine Graben): insights from gravity, magnetics and slip and dilation tendency analysis

Baillieux Paul [1], Schill Eva[1], Abdelfettah Yassine[1] & Dezayes Chrystel[2]

[1] Centre for Hydrogeology and Geothermics (CHYN), University of Neuchâtel, Emille-Argand 11, CH-2000 Neuchâtel (paul.baillieux@unine.ch)
[2] BRGM, Geothermal Department, 3, avenue C.-Guillemin, BP 36009, 45060 Orléans cedex 2, France

The recently developed new 3D geological model of Soultz area (Baillieux et al., 2011; Dezayes et al., 2011) is used as a basis for understanding the localization of temperature anomalies at a regional scale. Gravimetric, magnetic and slip and dilation tendency analyses are used to investigate the implication of structural patterns of the 3D geological model, density and magnetic variations, and stress patterns associated to hydrothermal circulation along the faults. A mean temperature anomaly of 30°C at top basement is found to be linked to a light and magnetic granodioritic pluton offering a rather high radiogenic heat production. Three temperature anomalies above 60°C at top basement show similar patterns: they are located along N-S directed fault with a west dipping signature in the western side of horst structures (Fig. 1).

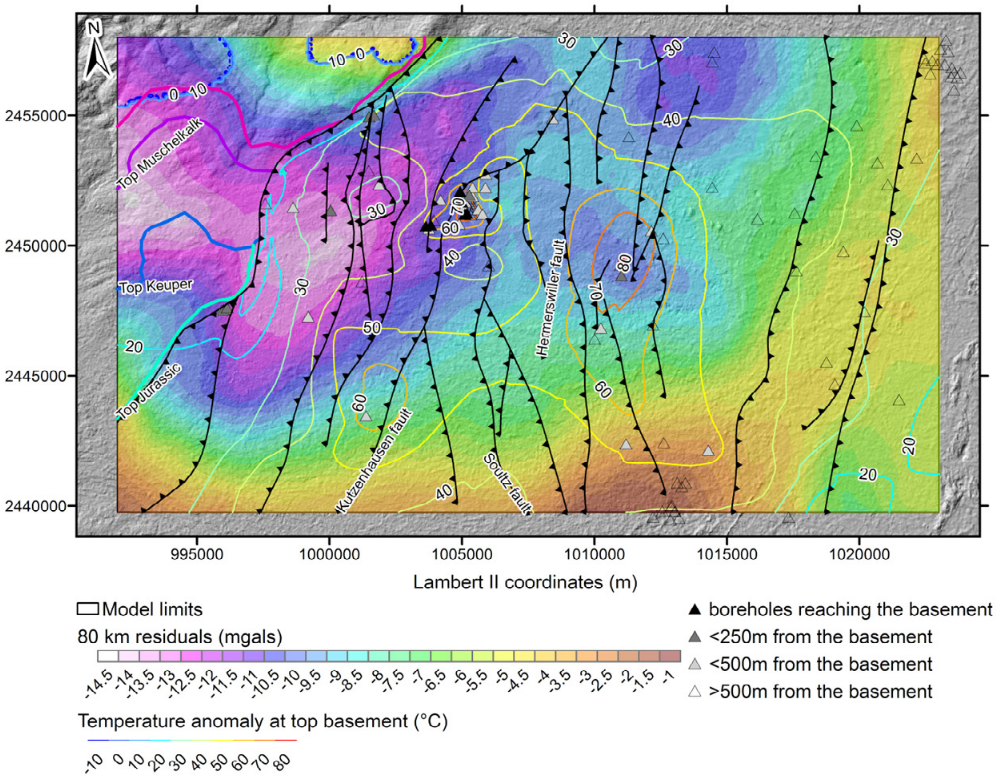

Fig. 1: Residuals anomaly after 80 km Butterworth filter (Abdelfettah & Schill, 2012), surface features from the 3D model (fault system, horizons) and contours of temperature anomaly at top basement (°C)

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P 6.3

Attempt to identify the fault associated with the great Mw=6.2 Earthquake of Visp 1855

Cyrill Baumann[1], Luis Angel Dalguer[1], Jan Burjaněk[1], Clotaire Michel[1] & Donat Fäh

[1] *Schweizerischer Erdbebendienst, ETH Zürich*

The Valais area in the Swiss Alps shows the largest seismic hazard in Switzerland. During the past 500 years, the Valais region experienced six earthquakes around magnitude 6 or larger. Those earthquakes occurred with a periodicity of about 100 years, the most recent one in 1946. The Valais presents rough topography, unstable and steep slopes, deep sediment-filled valleys and wide glacier- and snow-covered areas that potentially increase the seismic risk level due to earthquake-induced phenomena such as strong site- and topographical effects, liquefaction, landslides and snow avalanches. In addition, important critical facilities of Switzerland, such as hydroelectric power plants and chemical plants have been built in the Valais, making the region even more exposed to damaging earthquakes. On July 25, 1855 the strongest earthquake in Switzerland in the last 300 years struck the region of Visp, with an estimated moment magnitude of 6.2 (ECOS09). It caused an epicentral intensity of VIII and therefore heavy damage (Fäh et al. 2003a, Kozak & Vanek, 2006). There was a large aftershock activity within the following months and years, with intensities up to VII. The reconstruction of the damage field showed largest damages between Visp and Stalden, which may suggest the location of the epicenter (Fritsche, 2008). The general nature of the damage field and the geological structure suggests that the responsible fault is close to the surface and also supports the thesis of a normal fault striking along the Valley of Visp (north-south) and dipping to the west (Créalp, 1999). Several further geological observations support the thesis of a fault between Stalden and Visp. Joris (personal communication) observed a neo-tectonic fault approximately 2Km southeast of Visp near Unterstalden. Further indications come from the examination of a fault, which was discovered during the construction of the tunnel Eyholz and a historical geological map in which a transversal fracture between Unter- and Oberstalden is mapped. We applied a passive seismic investigation method, which is based on the assumption that the fault of interest is surrounded by fractured rock. When seismic waves penetrate the damage zone consisting of fractured rock, energy is absorbed, which leads to a decrease in amplitude of the seismic waves. The loss of energy finally leads to a decrease of seismic velocity. The damage zone, the zone in which the seismic velocity is reduced, is called low velocity zone (LVZ). The attempt is to detect reduced amplitudes in the power spectra of the seismic traces at seismic stations, which could be an indicator of a LVZ. We performed several seismic surveys during day and night, usually measuring about 3 hours. The number of sensors was in average 10 and the maximum spacing between them around 15m. Data acquisition was carried out with LE-3D/5s seismometer sensors and digitized with Quanterra Q330. Our measurements confirmed the existence of signature in the power spectra of the seismic noise that may correspond to a LVZ as defined above. This signature is observed along the trace of the expected fault that reinforces the existence of it. These observations together with geomorphological indications support the thesis of a fault in the corresponding investigation area.

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P 6.4

Magnetic fabrics and anisotropy in rock-forming minerals

Biedermann Andrea Regina[1], Hirt Ann Marie[1], Pettke Thomas[2]

[1] Institute of Geophysics, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich (andrea.biedermann@erdw.ethz.ch)
[2] Institute of Geological Sciences, University of Bern, Baltzerstrasse 1-3, CH-3012 Bern

Magnetic susceptibility is a material property that is often anisotropic in rocks. The anisotropy of magnetic susceptibility (AMS) can be used as a proxy for the mineral fabric qualitatively and possibly quantitatively. To obtain a quantitative estimate of mineral fabric it is necessary to know the intrinsic anisotropy of the constituent minerals. Compared to other fabric techniques, determining the magnetic fabric is fast and has the advantage that not only the material surface is sampled, but the whole volume. AMS has also been used to determine e.g. the flow direction in magma or river deposits, or reflect the strain ellipsoid during tectonic events. However, this method can be applied more effectively if we understand what minerals have the strongest contribution to the susceptibility of the bulk rock.

All minerals in a rock contribute to the magnetic susceptibility and hence its anisotropy. We determined single crystal AMS in the common rock-forming minerals olivine, amphiboles and pyroxenes. Both low- and high-field AMS were measured. Analyzing high-field data allows for separation of paramagnetic and ferromagnetic contributions to the AMS, i.e. contributions arising from the silicate lattice or iron oxide inclusions, respectively. The paramagnetic component is related to the arrangement of cations, particularly Fe, in the crystal structure and therefore reflects the crystal orientation. Ferromagnetic inclusions, e.g. magnetite or hematite, are generally randomly distributed.

Samples in this study are natural crystals and were chosen so as to cover a wide range of chemical compositions within each mineral group. Crystal chemistry was measured using laser ablation inductively coupled plasma mass spectroscopy (LA-ICP-MS) and data were used to establish a relationship between iron content and AMS parameters. We were mainly interested in the paramagnetic contribution to the AMS. For example, in olivine the maximum principal susceptibility of the paramagnetic component is parallel to the crystallographic c-axis, whereas the intermediate and minimum principal susceptibilities are parallel to a or b at room temperature (Figure 1). At 77 K, all minimum axes are parallel to the crystallographic b-axis. Chemical analysis shows that the samples can be divided into two groups: those with 3-5 wt.% FeO and those with 7-9 wt.% FeO. The first group shows a switching of the minimum and intermediate axes at room temperature compared to low temperature, whereas directions do not change with temperature in the second group. Further, the shape of the AMS ellipsoid is more prolate in the first group. The degree of anisotropy appears not to be affected by iron content as long as this is less than 8 wt.% FeO (Figure 2). Similar relationships are established for amphiboles or pyroxenes. Thus, the paramagnetic fabric in e.g. peridotites, amphibolites or pyroxenites is an indicator for preferred crystal orientation. On the other hand, if the orientation distribution function in a rock is known, our results can be used to model the bulk rock AMS.

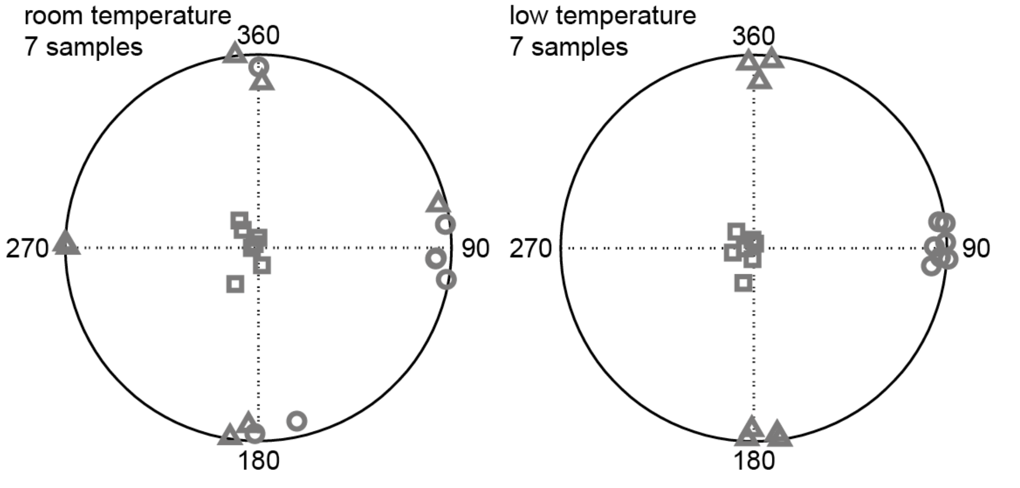

Figure 1: Lower hemisphere, equal area stereoplots of principal AMS directions in olivine single crystals. Squares show the maximum principal axes, triangles and circles intermediate and minimum axes of the paramagnetic component, respectively. Low temperature AMS measured at 77 K.

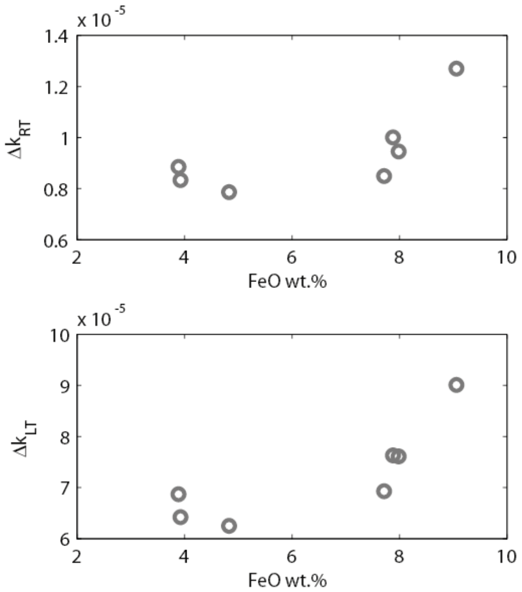

Figure 2: Relationship of anisotropy degree Δk and iron content both for room temperature and 77 K.

P 6.5

Brittle onset of monodispersed magmatic suspensions: impact of the particle shape.

Cordonnier B. , Kaus B. , Manga M. , Caricchi L. , Pistone M., Castro J. , Hess K.-U. , Dingwell D.B., Burlini L.

Geologisches Institut, ETH, Zurich, Switzerland

The brittle-ductile transition remains a central question of modern geology as rock failure is the main parameter in mitigating geological risks, such as, for volcanic eruptions, the transitions from effusive to explosive eruptive style. Although numerical simulations are the only way to fully understanding the physical processes involved, we are in a strong need of an experimental validation of the proposed models.

We first recall some experimental results obtained under torsion and uni-axial compression on both pure melts and crystal-bearing magmas. Torsion experiments were performed at high temperature (600 to 900 degC) and high pressure (200 to 300 MPa) using a Paterson-type rock deformation apparatus (ETH Zurich). We characterized the brittle onset of two phases magmas from 0 to 65 vol% crystals. The strain-rates span 5 orders of magnitude, with a change in the behavior of the material from viscous to brittle (10^{-5}- 10^{0} s^{-1}). The materials tested are a standard borosilicate glass (NIST717), a natural crystal bearing rhyolitic melt (Mt Unzen volcano) and a suspension of haplogranitic synthetic sample with corundum particles.

To characterize the physical processes leading to failure in the experiments, we performed 2D and 3D numerical simulations on monodispersed rigid spheroids with eccentricities ranging from 10^{-2} to 10^{2}. The model is numerically solved with Finite Elements Methods. The pre-processing, processing and post-processing are all performed under MATLAB. For the largest meshes, the computation has been performed with the help of the BRUTUS cluster at ETH Zurich. For solving the system of equation we used the MILAMIN solver and extended it from 2-D to 3-D by the use of Crouzeix-Raviart type elements. MILAMIN is a native MATLAB implementation, which takes advantage of Tim Davi's SuiteSparse package. Here we solve the incompressible Stokes equations. We tested random to structured configurations (Simple Cubic, Body Centered Cubic and Face Centered Cubic) for different particle orientations from random to aligned. These numerical simulations allow us to estimate the stress concentration in magmas due to the presence of the crystals.

Our results first confirm the hydrodynamics effects on the flow of elongated particles. The calculated apparent viscosity of the material versus the crystal fraction confirms an early increase for the suspensions viscosity with elongated particles. More importantly, the stress localization due to the particles suggests that the melt will start cracking for a relatively lower bulk stress. Finally, the experimental trend is supported by the numerical simulations, which highlight the importance of the critical packing fraction in addition to the maximum packing fraction.

The combination of experimental results and numerical modeling allow us to characterize the physical processes responsible for the failure of particle bearing suspensions and characterize the effect of fraction and shape on the brittle-ductile transition.

P 6.6

VLF Measurement in the cristallin area, new survey in the EGS research project in Black Forest

Di Tommaso Gennaro[1], Abdelfettah Yassine[1] & Schill Eva[1]

[1] Centre for Hydrogeology and Geothermics (CHYN), University of Neuchâtel, Emille-Argand 11, CH-2000 Neuchâtel (dtg.ditommaso.g@bluewin.ch)

The exploitation of the shallow geothermic sites for systems of heating and cooling was accentuated and showed its advantages during the last years. Nevertheless, the questions concerning the electric exploitation of major geothermics continue to be the object of many work of research and development. Contrary to other generating stations of the clean energy, the major projects in the geothermics are characterized by the high and an important risk factor for technical and financial investment costs. This is why accurate geological knowledge, until several hundred meters of depth, is necessary. The research project EGS (Geothermal Enhanced System) in the south of the Black Forest had the aim to develop a methodology integrating several geophysical exploration methods, in order to better identify and to characterize geothermic sites, with lower costs and hence reduce the financial risk.

An alternative and/or complementary method to the already existing geophysical methods, is the VLF measurements (Very Low Frequency). It can be used in order to better characterize the geothermal sites, and thus helping the planning of the project. This method was tested for the localization and the characterization of the vertical and sub-vertical contacts of structure and also for the identification of fault zones in the crystalline rocks. To achieve this, a test measurements on a gas pipeline were carried out and the results were discussed. After this test, the method is employed in wide zone of the investigation in Black Forest. The VLF Method, or EM-VLF, use the terrestrial radio transmissions in the radio frequency band between 10 and 30 kHz to measure the value of the magnetic field, whose amplitude and phase are influenced by the geology of the subsurface. The interpretation of these data which gives access to the anomalies of electric conductivity of the vertical and sub-vertical contacts under ground, makes it possible to better characterize the faults and the faulted zones. Two device of VLF data acquisition VLF were used; VLF-Car and a portable devices. The first was used to cover a long distance to carry out the recognition studies. The second device used to realize more detailed measurements and for a small distance.

Both instruments are suitable for the characterization of the horizontal and sub-horizontal electrical conductivity contrast, but the VLF-Car method proved to be effective in Hotzenwald area with an optimized time.

P 6.7

Seismic response of the active instability above Preonzo (TI)

Valentin Gischig[1], Jan Burjanek[1], Jeffrey R. Moore[2], Simon Loew[2]

[1] *Swiss Seismological Service, ETH Zürich, Sonneggstrasse 5, CH-8006 Zürich, (gischig@sed.ethz.ch)*
[2] *Geological Institute, ETH Zürich, Sonneggstrasse 5, CH-8006 Zürich*

Recent passive seismic recordings in unstable rock slopes have revealed that the seismic response within instabilities is distinctly different than on adjacent stable ground. Ground motion is strongly amplified at distinct frequencies and polarized primarily in the direction of rock mass movement. At the slowly-moving slope instability above Randa (VS), site-to-reference amplification factors of up to seven at a frequency of 3 Hz were derived from ambient noise measurements and recordings of regional earthquakes. Similarly, localized amplification reached a factor of about seven at 1.6 Hz at Walkerschmatt (VS), an inactive instability characterized by widely open tension fractures. These observations are interpreted as eigenmode vibration of individual blocks delineated by highly-compliant tension fractures.

We recently performed new ambient noise measurements at the active slope instability above Preonzo (TI), a few weeks after the catastrophic failure of 15 May 2012. That failure involved roughly 200’000 m^3 of rock, which is about half the estimated total unstable volume. The remaining unstable rock mass is dissected by a network of tension fractures, with apertures of several decimetres, that break the rock mass into blocks a few meters to decameters in length. Fracture opening rates since failure have decelerated to values of much less than 1 mm/day, except for one strongly tilting block at the May 2012 scarp that moves at around 1 mm/day (information late August 2012).

Twelve seismic stations were installed on the accessible bench behind the scarp, with four stations positioned on stable ground and two of these close to the tension fracture forming the back boundary of the instability. The remaining instruments were installed on different unstable blocks with the aim of observing spatial heterogeneity in the seismic response. The stations continuously recorded ambient noise over a period of about one hour. By chance two distant earthquakes were also recorded, with epicentres in northern Italy. Polarization analysis showed strong directionality of ground motion at ~3 Hz for all stations except the two farthest from the instability boundary.

Maximum polarization is oriented in the main direction of slope movement. Relative amplification with respect to the stable ground was also estimated and reached factors of 30 at 3 Hz within the instability. Local amplification characteristics vary considerably among the different stations. In comparison to the two less-active slope instabilities investigated previously, measured amplification at Preonzo is extraordinarily high.

We argue that the seismic response of rock slopes may be a diagnostic measure of instability and perhaps also of the degree of destabilization. We stress that amplification of the wavefield within unstable rock masses is a site effect making slope instabilities more vulnerable to triggering by nearby earthquakes.

P 6.8

Geophysically based estimations of rock/air/ice/water contents and validation with ground truth data at three alpine permafrost sites

Hilbich Christin[1], Scapozza Cristian[2,3], Lambiel Christophe[2]

[1] *Département Géosciences, Unité Géographie, Université de Fribourg, Chemin du Musée 4, CH-1700 Fribourg (christin.hilbich@unifr.ch)*
[2] *Institut de géographie et durabilité, Université de Lausanne, Anthropole, CH-1015 Lausanne*
[3] *Institute of Earth Sciences, University of Applied Sciences and Arts of Southern Switzerland (SUPSI), CP 72, CH-6952 Canobbio*

During recent years geophysical monitoring approaches in permafrost regions have evolved quickly regarding the observation of changes in the ice and unfrozen water content of the subsurface over short and long time periods. Relative changes in electrical resistivities or seismic velocities provide rough estimates of spatio-temporal changes in the subsurface. Additional information on the distribution of high and low ice contents within 2-D subsurface sections are provided by electrical resistivity tomography (ERT) monitoring and refraction seismic tomography monitoring, in contrast to 1-D temperature monitoring in boreholes. Furthermore, the spatial variability of the temporal changes can be adressed. However, as straightforward relations between observed resistivity or velocity and ice content do not exist, absolute quantification of ground ice degradation is still impossible from the consideration of relative resistivity/velocity changes alone.

An approach to estimate volumetric fractions of ice, water, and air within the pore volume of a rock matrix by jointly using complementary data sets from geophysical surveys was introduced by Hauck et al. (2011). The so-called four-phase model (4PM) uses coincident ERT and seismic data sets to relate the physical properties of the subsurface to the measured electrical resistivities and seismic velocities. Due to inherent ambiguities in the model the approach is still limited to specific cases and often allows only a rough estimation of the quantities of the solid (ice), liquid (water), and gaseous (air) constituents of the available pore volume.

One of the major drawbacks of the current 4PM approach is that it is underdetermined and one of the four phases (usually the porosity) has to be prescribed based on rough estimations. However, as the porosity of a subsurface section will not change over the period of several years, the calculation of temporal changes in ice, water and air contents may give a more reliable indication on the subsurface characteristics than the estimation of total fractions. Applying the 4PM to time-lapse ERT and seismic data sets and regarding only the temporal change in the fractional composition will thus reduce the uncertainties and gain higher confidence in the calculated values.

In this contribution, a further step towards the reduction of the uncertainties of the 4PM is presented. Based on a unique data set of observed porosity and ice content data determined from borehole geophysical measurements at three permafrost sites in the Swiss Alps, measured porosity values could be used to constrain the 4PM. The calculated ice contents could then be validated with the observed ice contents in the boreholes. Based on this study the performance of the 4PM is evaluated and an estimate of the reliability of the 4PM results can be given.

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P 6.9

Laboratory experiments of seismic wave attenuation from 0.01 Hz up to 100 Hz.

Madonna Claudio[1], Tisato Nicola[1] & Saenger Erik H. [1]

[1] *Geologisches Institut, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich (claudio.madonna@erdw.ethz.ch)*

Seismic velocities are sensitive to pore fluids and pore shapes. Thus, seismic attributes can provide qualitative and quantitative information on underground structures and processes.

Among these attributes, seismic attenuation can be valuable to identify the pore
fluid type and to monitor sub-surface reservoir processes. There is currently an enormous lack of attenuation data for many lithologies under various physical conditions and dramatic ambiguity on theories explaining attenuation mechanisms and velocity dispersion. Laboratory experiments are required to close the data gap and validate theories.

One goal of this research was to create a laboratory apparatus to understand attenuation with respect to rock type, anisotropy, fluid type and fluid saturation. The Seismic Wave Attenuation Module (SWAM) was developed to experimentally measure the attenuation in extensional-mode (Q^{-1}_E) and the Young's modulus inside a pressure rig (Paterson). The sub-resonance method was employed to measure attenuation in the seismic frequency range. It allows performing measurements at low strain magnitudes (ε < 10-6) for which the rock behaves as a Linear Time Invariant (LTI) system. A series of measurements on different materials in a dry condition and saturated with different fluids is presented (Fig. 1). Berea sandstone, Fontainebleau sandstone, Crab Orchard sandstone and shale rocks were tested at 10 MPa confining pressure.

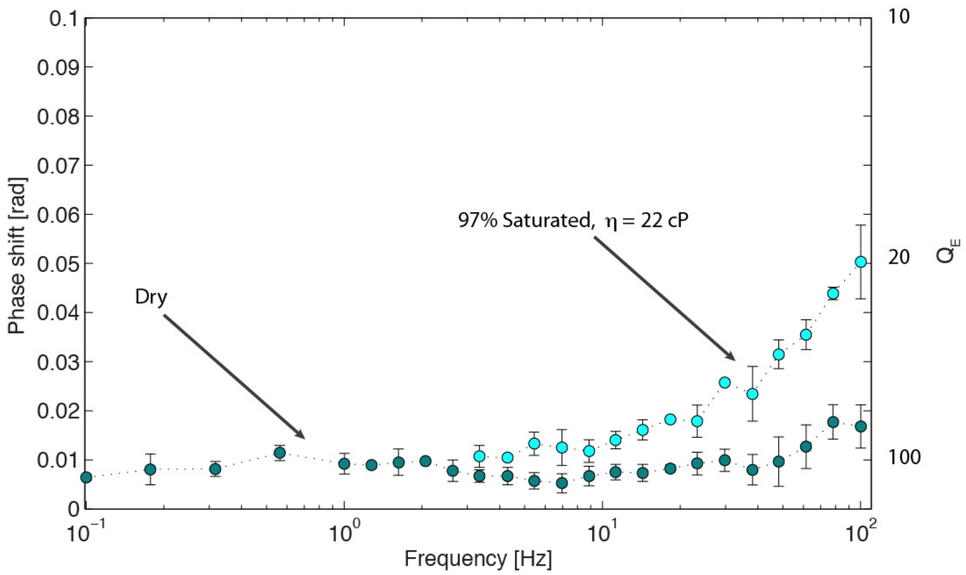

Figure 1. Phase shift and quality factor (Q_E) for dry and glycerin-water solution saturated Berea sandstone.

P 6.10

Application the similarity attributes and the fault enhancement for 3D seismic data from the Kerkennah islands (Tunisia).

Mastouri[1] Raja, Marchant[2] Robin, Marillier[3] François, Jaboyedoff[1] Michel, And Bouaziz[4] Samir

[1] *Institute of Geomatics and Risk Analysis, University of Lausanne, Switzerland,*
[2] *Cantonal Museum of Geology, UNIL- Anthropole, 1015 Lausanne – Switzerland,*
[3] *Engineering School of Sfax, R. L. "Water- Energy- Environment: AD-10-02", University of Sfax, Tunisia,*
[4] *Institute of Geophysics, University of Lausanne, Switzerland.*

The 3D seismic, a relatively recent technique that provides a powerful tool for detailed investigation of the often complex geometry of sediment basin (Nalpas, 1996) is now widely used in areas of intensive oil exploration. Modern visualization and image processing techniques are revolutionizing the art of seismic interpretation. The seismic attributes have been used for many years to improve the structural and stratigraphic interpretation of seismic data and the advent of 3D seismic technology and powerful workstation computers has made it possible to extract as much information as possible from the character of seismic waveform for the generation of several attributes. Hydrocarbon exploration in geologically complex and technologically challenging environment is feasibly the driving force for the use of these attributes for seismic data interpretation in order to minimize the exploration risks of drilling very expensive wells.

The hydrocarbon migration is often associated with fault intersection or splinter faults related to shear along the fault; we use here multiple seismic attributes for highlighting faults. This report describes two concepts; firstly we give an introduction in seismic attributes for faults detection to set the context to understand imaging of faults. Secondly, we discuss the application of post attribute filters to demonstrate how the attribute image can be enhanced by improving the completeness, resolution, and contrast of the similarity attribute.

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P 6.11

Mountains – Up and Down: the Role of Groundwater Pressure

Preisig Giona[1] & Perrochet Pierre[1]

[1] *Centre for Hydrogeology and Geothermics, University of Neuchâtel, Emile-Argand 11, CH-2000 Neuchâtel (giona.preisig@unine.ch)*

In fractured and granular porous aquifers a change in groundwater pressure results in a modification of the effective stress state. Decreasing groundwater pressures can result in a consolidation of the porous media, increasing groundwater pressures in an expansion. This coupled hydromechanical process named fluid-to-solid, i.e., a change in fluid pressure results in a change of the porous volume, has been observed also in the crystalline fractured rock of the Gotthard Massif (Hansmann et al, 2012). Increasing/decreasing water pressures during groundwater recharge/discharge periods lead to cyclical expansions/compressions of the fractured rock mass resulting in a subtle mountain "up and down" (Figure 1). Hansmann et al. (2012) detected these reversible deformations by means of high precision leveling surveys in the framework of the Gotthard Alp transit Base Tunnel Project.

A recent modelling approach specific for fluid-to-solid coupled hydromechanical processes in fractured aquifers has been proposed by Preisig et al. (2012). This method allows the simulation of groundwater flow in the deformable fractures of the aquifer. The deformation of fractures and the associated change of hydrogeological parameters, i.e., porosity, hydraulic conductivity and specific storage, are based on Hooke's law of elasticity. The integration of all fractures deformations under increasing/decreasing water pressures result in the fractured aquifer expansion/compression.

This work presents the modelling of the process detected by Hansmann et al. (2012) using the approach proposed by Preisig et al. (2012). The model is calibrated using the measured deformations data of Hansmann et al. (2012), by varying hydrogeological parameters. Calibrated parameters are compared with measured values.

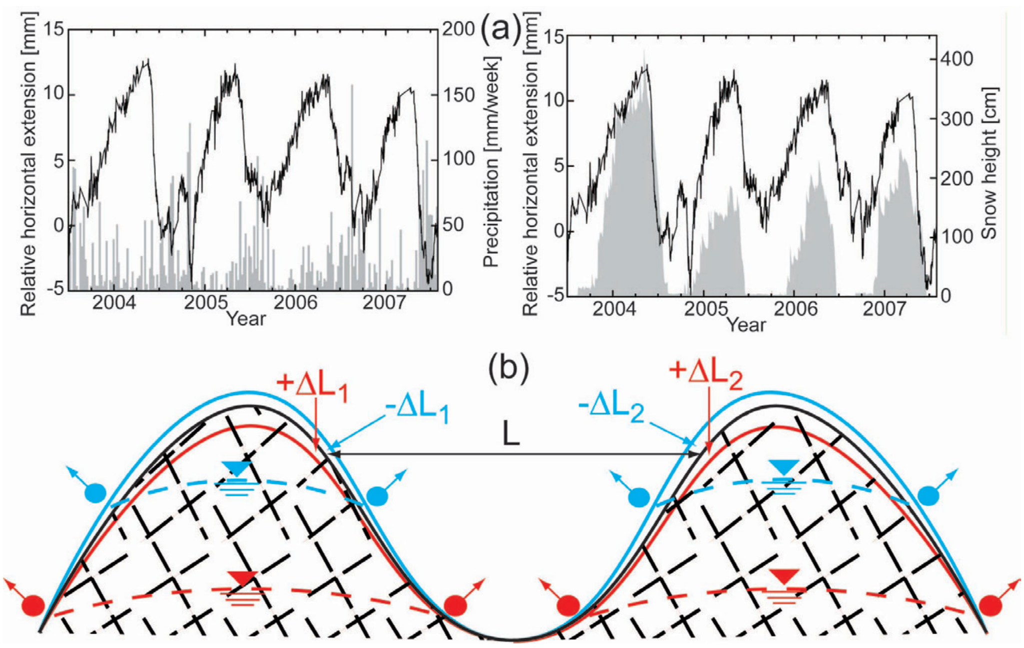

Figure 1. (a) Relative horizontal extension between two reflectors located on slopes of the Santa Maria Valley (solid black line), precipitation and snow height (in gray) as a function of time (Hansmann et al., 2012). (b) Conceptual model illustrating the fractured rock mass expansion (blue line) / compression (red line) under seasonal variations in water table levels, leading to a shortening/extension of the distance L orthogonal to the valley (modified from Hansmann et al., 2012).

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P 6.12

Measuring local seismic anisotropy using ambient noise: a three-component array study

Riahi Nima[1], Saenger Erik H.[1]

[1] *ETH Zurich, CH-8092 Zürich (nima.riahi@erdw.ethz.ch)*

We study seismic noise in the frequency range 0.1 to 1.1 Hz using data from a temporary three-component seismic array in Central France that was deployed in April 2010 during four days. Fourier domain beam-forming is applied simultaneously on all components to jointly estimate back azimuth, apparent phase velocity as well as polarization features as a function of frequency (Esmersoy et al., 1985). This allows us to investigate azimuthal velocity anisotropy of Love and Rayleigh waves, separately. We observe a fast direction at the measurement site that is consistent with the preferred direction of a local fault system. Furthermore, the magnitude of azimuthal anisotropy is larger for Love waves compared to Rayleigh waves. We discuss the potential of such three-component seismic array studies for other applications (Moschetti et al., 2010).

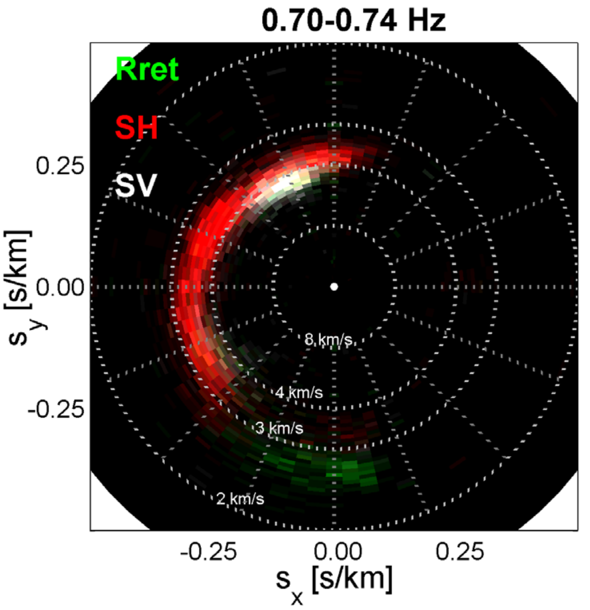

Figure 1. Measured slowness spectrum at 0.72 Hz, based on 65 hours of data (back azimuths are used). Colours identify wave polarization. Strong azimuthal anisotropy in Love wave phase velocity is observed.

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P 6.13

Numerical support of laboratory experiments: Attenuation and velocity estimations

Saenger Erik H.[1], Madonna Claudio[1], Frehner Marcel[1], Almquist Bjarne S. G.[1]

[1] *ETH Zurich, Geological Institute, Sonneggstrasse 5, CH-8092 Zurich (erik.saenger@erdw.ethz.ch)*

We show that numerical support of laboratory experiments can significantly increase the understanding and interpretation of the obtained results. First we perform simulations of the Seismic Wave Attenuation Module (Figure 1) to measure seismic attenuation of reservoir rocks. Our findings confirm the accuracy of this system. However, precision can be improved by optimizing the sensor positions (Figure 2). Second we model wave propagation for an ultrasonic pulse transmission experiment that is used to determine pressure- and temperature-dependent seismic velocities in the rock. Multiple waves are identified in our computer experiment, including bar waves. The metal jacket that houses the sample assembly needs to be taken into account for a proper estimation of the ultrasonic velocities (Figure 3). This influence is frequency-dependent.

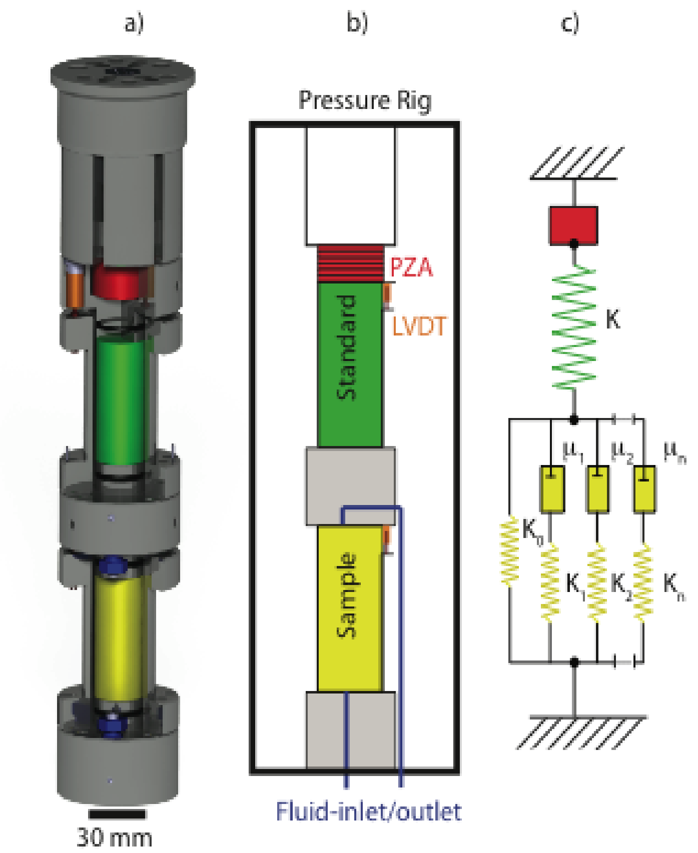

Figure 1. Schematic cross-section of the ETH-developed SWAM (Madonna et al. 2011). a) CAD drawing, b) Sketched construction, c) Physical model.

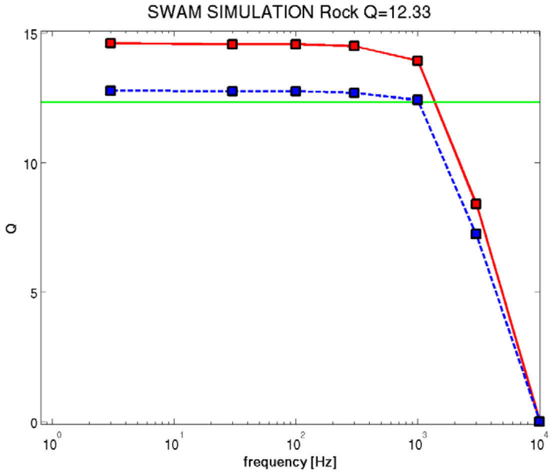

Figure 2. Results of the SWAM computer experiments for a Rock sample with an attenuation of Q=12.33 (green line) for a range of applied excitation frequencies. Q_{real} (red solid line) can be compared with the real experimental setup. An optimized sensor positioning allow for more accurate measurements of Q (Q_{opt}; dashed blue line).

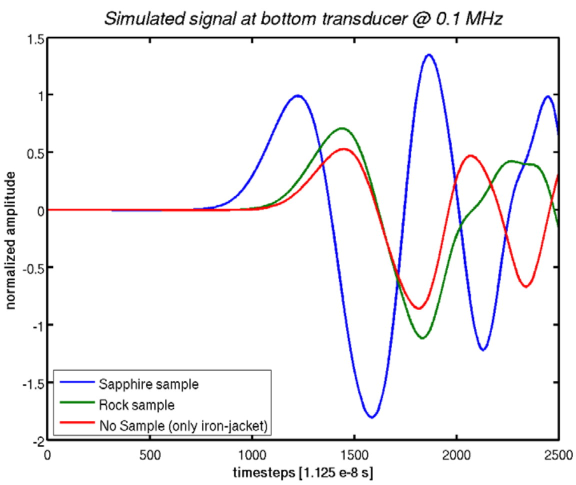

Figure 3. Simulated vertical displacement at bottom transducer of the sample assembly for ultrasonic velocity measurements in the Paterson gas-medium apparatus (Burlini et al., 2005). The reference signal (blue line) using a Sapphire sample arrives first. The time delay of the signal for the rock sample (green line) is normally used to estimate the velocity of the rock. However, the signal with no sample (red line; wave propagation through the iron jacket only) may disturb the signal for the rock.

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P 6.14

Simulating the in situ physical properties of the upper Muschelkalk aquifer, northern Switzerland

Shih Pei-Ju[1,2] Almqvist Bjarne S.G. [2], Zappone Alba [1,3], Tisato Nicola[2], Maurer Hansruedi[1]

[1] *ETH Zurich, Institute of Geophysics, Sonneggstrasse 5, CH-8092 Zurich (shihp@student.ethz.ch)*
[2] *ETH Zurich, Institute of Geological Sciences, Sonneggstrasse 5, CH-8092 Zurich (bjarne.almqvist@erdw.ethz.ch)*
[3] *ETH Zurich, Insitute of Process Engineering, Sonneggstrasse 3, CH-8092 Zurich*

Anthropogenic emission of carbon dioxide (CO_2) is widely believed to contribute to climate change and global warming. Hence, it has been recognized that there is a need for the reduction of carbon dioxide emissions. Recent technologies for carbon capture and storage (CCS), have therefore been developed. Geological CO_2 sequestration is one of the most thoroughly investigated CCS technologies, and its potential for use in Switzerland is currently under investigation (Chevallier et al., 2010).

In this study, the aim is the characterization of one potential storage aquifer and seal pair, in order to gain a better idea of where to geologically store CO_2 in Switzerland. The potential seal and aquifer Formations investigated are the Gipskeuper and upper Muschelkalk, respectively. The stratigraphically underlying aquifer is divided into the Trigodonusdolomit and Hauptmuschelkalk units.

A series of laboratory measurement techniques were employed to characterize the physical properties of core samples of dolomite, recovered from drill core. These measurements consist of density, porosity, permeability and ultrasonic wave velocities. Specifically, the permeability and ultrasonic velocity measurements were performed at conditions similar to reservoir conditions, with elevated pressure, spanning near surface conditions to >3 km depth.

The laboratory measurements were compared with well logging data (courtesy of the National Cooperative for the Disposal of Radioactive Waste, Nagra), from the Benken and Weiach drill sites (northern Switzerland) where the core was recovered. Of particular interest is to understand and quantify the distribution of the physical properties, with the aim to better understand the geophysical signature of the Muschelkalk aquifer (in terms of borehole properties, and seismic surveys). In addition, the laboratory permeability is one of the key parameters in this project since the well logging data can only extract a very rough permeability and hydraulic conductivity data by injection pump tests.

The study found that, in general, the measured velocities show a positive correlation with density and an inverse correlation with porosity. It was also found that higher porosity tends to reduce the ultrasonic velocity, but positively correlates with permeability.

A simple but effective model is created to predict the seismic reflection coefficient (R) in the Trigodonusdolomit, with porosity varying from 0 to 50 %. At low porosity, the reflection expected at lithological boundaries is weak, but with increasing porosity in Trigodonusdolomit, the amount of reflected energy increases. At the Gipskeuper to Trigodonusdolomit horizon the reflection coefficient is negative. In contrast R is positive at the Trigodonusdolomit to Hauptmuschelkalk horizon.

The empirical model agree qualitatively well with the reflection coefficient observed in seismic surveys at the Benken and Weiach drill sites (Nagra, 1989; 2001). Differences in the absolute values of the reflection coefficient are expected, likely related to the scale differences in laboratory and borehole logging results, compared to seismic surveys. In addition, although the volume of pores is the main contributing factor to reduction in seismic velocity, other factors need to be taken into consideration, especially the pore structure resulting from diagenetic alteration.

This model indeed provides a preliminary tool to understand how porosity influences the seismic reflection at the seal/aquifer boundary. The empirical model can be complimented by further laboratory measurements at temperatures suitable for the upper crust, and by employing a fluid substitution model (e.g., Gassmann relations) to account for brine saturation in the carbonates.

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P 6.15

Phase velocity dispersion and attenuation of seismic waves due to trapped fluids in residual-saturated porous media

Holger Steeb[1], Patrick Kurzeja[1], Marcel Frehner[2] and Stefan M. Schmalholz[3]

[1] *Institute of Mechanics, Ruhr-University Bochum, Germany*
[2] *Geological Institute, ETH Zurich, Switzerland (marcel.frehner@erdw.ethz.ch)*
[3] *Institute of Geology and Palaeontology, University of Lausanne, Switzerland*

Propagation of seismic waves in partially saturated porous media depends on various material properties, e.g. saturation, porosity, elastic properties of the skeleton, viscous properties of the pore fluids and, additionally, capillary pressure and effective permeability. If the wetting fluid is in a discontinuous state, i.e. residual saturated configuration, phase velocities and frequency-dependent attenuation additionally depend on microscopical (pore-scale) properties such as droplet and/or ganglia size. To model wave propagation in residual saturated porous media, we (Steeb et al., 2012) developed a three-phase model based on an enriched continuum mixture theory capturing the strong coupling between the micro- and the macroscale.

The three-phase model considers a continuous and a discontinuous part (Figure 1). The continuous part, consisting of the porous solid skeleton and the continuous non-wetting fluid, exhibits similar behavior as the poroelastic model introduced by Biot (Biot, 1956). The discontinuous part describes the movement of blobs/clusters of the wetting fluid and is based on an oscillator rheology (Figure 1; Frehner et al., 2009, 2010; Steeb et al., 2012). In comparison with other three-phase models, the presented one (Steeb et al., 2012) accounts for the heterogeneity of the discontinuous fluid clusters by use of their statistically distributed inertia, eigenfrequency and damping effects. The heterogeneous and discontinuous distribution of the wetting fluid in form of individual blobs or fluid clusters is represented by a model-embedded distribution function of the cluster sizes. We define a dimensionless parameter, D, that determines if the overall motion of the residual fluid is dominated by oscillations (underdamped, resonance) or not (overdamped).

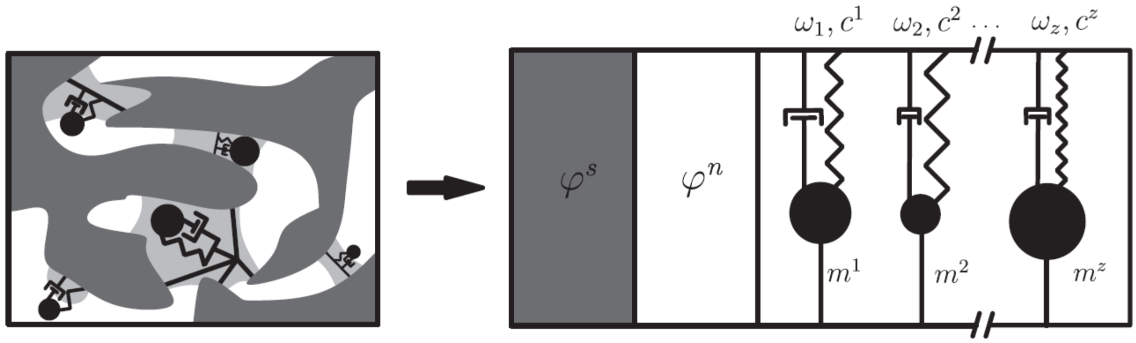

Figure 1. Upscaling from the heterogeneous pore-scale to an oscillatoric behavior of the wetting blobs with different eigenfrequencies and damping mechanisms at the macroscale (REV). The extended poroelastic model with the continuous solid skeleton φ^s, the continuous non-wetting phase φ^n and the discontinuous oscillators representing the wetting phase φ^w is depicted.

In the case of only a single fluid blob size (Figure 2), our results show that the residual fluid has a significant impact on the velocity dispersion and attenuation, no matter if it oscillates or not. For small damping parameters (underdamped oscillations), a dispersion anomaly and a strong attenuation peak occurs around the resonance frequency. For large damping parameters (overdamped oscillations), the dispersion and attenuation curves are equal to the ones of the Biot's-theory, but shifted to higher frequencies. In the case of distributed fluid blob sizes (Figure 3), the same observation can be made comparing very narrow with wide size distributions. In Steeb et al. (2012), we show under which conditions and how the classical biphasic models can be used to approximate the dynamic behavior of residual saturated porous media.

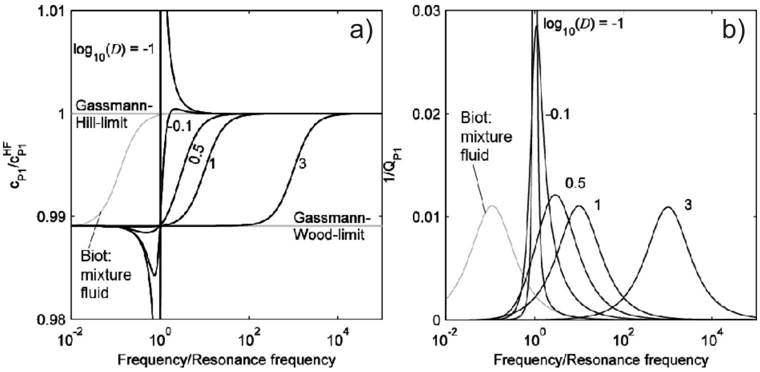

Figure 2. Frequency dependent phase velocity C_{P1} (a) and inverse quality factor $1/Q_{P1}$ (b) of the fast P-wave for different characteristic damping parameters *D* of the wetting fluid. The porous skeleton is a typical reservoir rock saturated with a continuous gas phase. The eigenfrequency of the blob is f_0=100 Hz.

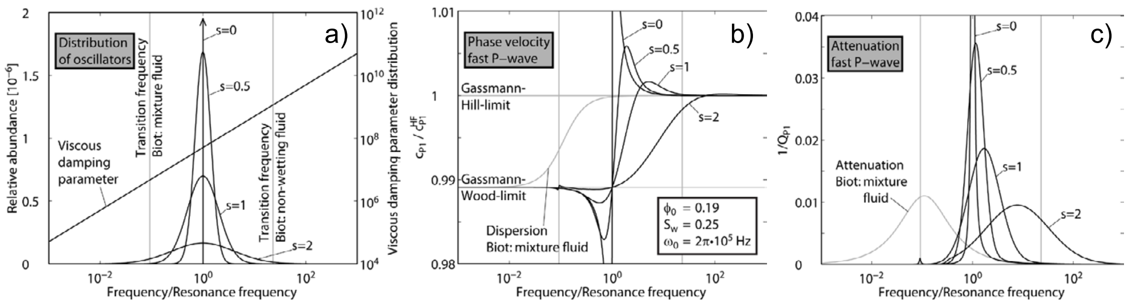

Figure 3. Frequency dependent phase velocity C_{P1} (b) and inverse quality factor $1/Q_p$ (c) of the fast P-wave for different distributions of fluid blob sizes c(ω) and damping coefficients α(ω) shown in a).

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P 6.16

Measuring and simulating transient pore pressure as a consequence of seismic waves

Tisato Nicola, and Quintal Beatriz

ETH Zurich, Soneggstrasse 5, 8092 Zurich, Switzerland (nicola.tisato@erdw.ethz.ch)

It has been demonstrated that seismic wave attenuation (Q^{-1}) in the bandwidth 1-100 Hz can arise from stress induced fluid flow (White, 1975; Mavko and Jizba, 1991; Pride et al., 2004). Flow of fluid within the pores of a saturated rock is driven by pressure gradients. Therefore the measure of pressure transients while the rock is stressed can be crucial to better understand the attenuation mechanism. Understanding attenuation in fluid-saturated rocks is of enormous importance because attenuation can provide information about saturation of crustal and reservoir rocks (e.g. Chapman et al., 2006).

Among other authors, Quintal et al. (2011) have numerically modeled wave-induced fluid flow in the mesoscopic scale. Experimental studies, such as the studies performed by Spencer (1981), Batzle et al. (2006), Tisato and Madonna (2012), show that rock samples dissipate more seismic energy when saturated with fluids and that in those cases attenuation is strongly frequency dependent. However, the scientific community still needs to better understand the mechanisms for fluid-related seismic attenuation in partially saturated rocks.

In this contribution we describe in detail a new experimental technique to measure the stress-induced transient fluid pressure at different positions in a partially fluid-saturated rock sample (Tisato et al., 2011). The laboratory data are compared with results from a numerically modelled creep test on a poroelastic analog rock sample (see Figure 1). The numerical results can explain the laboratory data, providing the first step towards understanding the ongoing physical processes of energy loss in a fluid-saturated porous medium.

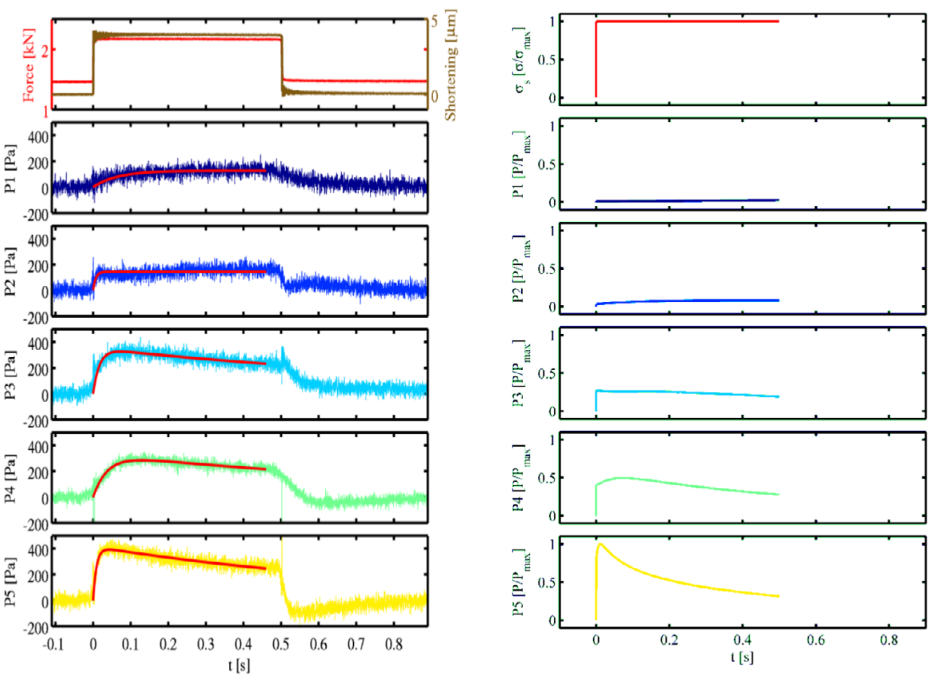

Figure 1. Measured (left) and numerically calculated (right) pore pressure evolutions as a functions of a step stress applied on the top of the sample. The pressure is measured/calculated on five points along a 250 mm long Berea sandstone sample 85% water saturated (15% consists of air).

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Inferring earthquake source properties from dynamic rupture models by means of non-linear kinematic source inversion

Youbing Zhang[1], Seok Goo Song[1], Luis Angel Dalguer[1], & John Clinton[1]

[1] Institute of Geophysics, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich (youbing.zhang@sed.ethz.ch)

An essential element of understanding earthquake source processes is obtaining a reliable source model via geophysical data inversion. Spontaneous dynamic rupture modeling, that incorporates conservation laws of continuum mechanics and constitutive behavior of rocks under frictional sliding, is capable of producing physically self-consistent kinematic descriptions of earthquake faulting and its associated seismic wave propagation, resulting in ground motions on the surface. Therefore, testing kinematic source inversion techniques by inverting synthetic ground motions obtained from dynamic rupture simulations is a solid step to explore the reliability of source inversion techniques to explore the physics of real earthquake source.

We use 24 models of Mw 6.5~7.0 from a large spontaneous dynamic source models database. This set of models is characterized with stochastic initial stress distribution for three classes of faulting (thrust, normal and strike slip) with buried and surface rupturing faults. The state of initial stress and frictional strength are parameterized using two different cases of normal stress: depth-dependent, and depth-independent (Dalguer and Mai, 2011). Compsyn code (Spudich and Xu, 2002) was deployed to generate forward synthetic waveforms, and an Evolutionary Algorithm was used to search for the source parameters: peak slip velocity, rupture time, rise time, and rake angle at low frequency (up to 1Hz). As a first attempt, the regularized Yoffe function is applied as a single window slip velocity function, which is a flexible slip velocity function defined by three independent parameters: the final slip, the slip duration and the duration of the positive slip acceleration, Tacc (Tinti, et al. 2005).

Our preliminary results show that we can obtain better solutions with the regularized Yoffe function, consistent with the overall properties of dynamic rupture models, and the inversion models could capture large slip patches of the dynamic models with better velocity waveform fitting than the wildly used boxcar and triangular functions. However, details of slip velocity complexities resulted from the dynamic rupture models are not well captured by the inversion procedure. Besides, the model spaces could be significantly perturbed, depending on data and modeling schemes used in the inversion. In the next step, we will try to examine how the station geometries effects the source inversion result, and more geodetic data such as high-rate GNSS data will be included to source inversion research.