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“From Fracturing to Friction”

Cataclastic bands and fracture propagation in porous sandstone

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Cataclastic bands that include both compaction and grain crushing form in porous sandstone as a result of deformation. They are a common type of deformation bands that substantially impact petrophysical properties of sandstone reservoirs and therefore have implications for fluid flow in the reservoirs. They affect Ultrasonic velocities and therefore are expected to have different elastic properties than their host rocks. Our study shows that cataclastic bands introduce anisotropy to elastic moduli of reservoir rocks. These bands are known to form and develop as a product of strain hardening during shear loading of rocks. However, changing the deformation behavior from strain hardening to strain softening may locally occur during the development of a cataclastic band, which may result in fracture propagation along deformation bands. We have studied different scenarios for strain hardening and softening within cataclastic bands and further investigated the competition between different modes of fractures during strain softening phase of deformation within a cataclastic band.

Distributed damage, friction and wear

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Distributed damage, friction and wear

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Brittle rock deformation is associated with fracture and friction processes. Fracture is dominant in deformation of rock without a pre-existing macroscopic failure zone, while friction is dominant in situations with existing sliding surfaces. A rheological model of the faulting process should include both processes. The model should address evolving rock properties associated with subcritical crack growth at very early stages of loading and degradation due to increasing crack concentration; crack localization into narrow zones leading to macroscopic brittle failure; post failure deformation and frictional sliding; generation of wear products such as gouge layers and cataclasite zones. Suitable variables should be defined to characterize the deformational aspects of the damaged rocks and granular material in a framework compatible with continuum mechanics and thermodynamics.

Recently developed continuum-based theoretical damage-breakage faulting model [Lyakhovsky and Ben-Zion, 2013, 2014] describes brittle instability and localization of deformation into a narrow slip zone as a phase transition between damaged solid and granular material. The formulation is based on irreversible thermodynamics of damage and breakage processes, each associated with a single key state variable, and corresponding energy functions for the damaged solid and granular material. Dynamic instability is associated with a critical level of damage in the solid, leading to loss of convexity of the solid energy function and transition to a granular phase associated with lower energy level. The developed model provides a new approach for analyzing in a unified way various aspects of brittle failure and localization of deformation, with evolving elastic moduli, evolving slip rates and evolving material phases. A non-local formulation provides an intrinsic length scale associated with the internal damage structure, which leads to a finite length scale for damage localization and eliminates the unrealistic singular localization of local models. Shear heating during deformation can lead to secondary internal (finite-width) localization. The formulation provides a framework for studying multiple aspects of brittle deformation, including potential feedback mechanisms between evolving elastic and related properties of the slip localization zone and subsequent rupture behavior. The model provides a more general description of the transition from slow deformation to dynamic rupture than that associated with frictional sliding on a single interface, and gives time and length scales for the onset of the dynamic fracturing process. Several features of the model including the existence of finite localization width and transition from slow to rapid dynamic slip are illustrated using numerical simulations. A model configuration having an existing narrow slip zone with localized damage produces for appropriate loading conditions an overall cyclic stick?slip motion. The simulated frictional response includes transitions from friction coefficient of ~0.7 at low slip velocity to dynamic friction below 0.4 at slip rates above ~0.1 m/s, followed by rapidly increasing friction for slip rates above ~1 m/s, consistent with laboratory observations. The derivations for steady-state conditions lead to a scaling relation for the damage front velocity considered as the wear-rate. The model predicts that the wear-rate is a function of the shear-stress and may vanish when the shear-stress drops below the micro-fracturing strength of the fault host rock. The simulated results successfully fit the measured friction and wear during shear experiments along faults made of carbonate and tonalite. The presented formulation indicates that wear dynamics in brittle materials in general and in natural faults in particular can be understood by the concept of a «propagating damage front» and the evolution of a third-body layer. The model is also valid for relatively large confining pressures, small damage-induced change of the bulk modulus and significant degradation of the shear modulus, which are assumed for seismogenic zones of earthquake's faults. Numerical simulations indicate that the key parameters governing the evolution from a slow failure process to dynamic slip, and the related transition from damaged solid to granular material, can be constrained by laboratory and seismological observations.

References

Lyakhovsky V. and Ben-Zion Y., 2013. Damage-Breakage rheology model and solid-granular transition near brittle instability. J. Mech. Phys. Solids. 10.1016/j.jmps.2013.11.007

Lyakhovsky V. and Ben-Zion Y., 2014 (in press). A continuum damage-breakage faulting model and solid-granular transitions. Pure Appl. Geoph.

Implications of fracture-toughness anisotropy for crack-growth geometry in the Mancos shale.

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The usage of hydraulic fracturing to recover shale-gas has drawn attention to the fundamental fracture properties of gas-bearing shales. Shales are strongly anisotropic, but there is a general paucity of available experimental data on their anisotropic mechanical properties. However, fracture propagation trajectories in these materials depend on a combination of both the anisotropic mechanical properties of the shale and the anisotropic in-situ stress field.
The mode-I stress intensity factor, KI, quantifies the concentration of stress at crack tips. The fracture toughness of a linear elastic material is then defined as the critical value of this stress intensity factor; KIc, beyond which rapid, catastrophic crack growth occurs. However, shales deviate significantly from linearity, and exhibit marked hysteresis during cyclic loading and unloading. Helpfully, this hysteresis allows for the calculation of a ductility coefficient using the residual displacement after each successive loading/unloading cycle. This coefficient can then be used to calculate a ductility-corrected Fracture Toughness value, KcIc. In the Mancos Shale this ductility correction can be as large as 60%.
Tensile strength and mode-I fracture toughness have been experimentally determined for the Mancos Shale using the Brazil Disk and Short-Rod methodologies, respectively. Measurements were made in all three of the principal fracture orientations; Arrester, Divider and Short-Transverse. Significant anisotropy is observed in the tensile strength, with the Arrester value being 1.5 times higher than the Short-Transverse value. Even larger anisotropy is observed in the fracture toughness, with KcIc in the Divider and Arrester orientations being around 1.8 times that in the Short-Transverse orientation. For both tensile strength and fracture toughness, the Short-Transverse orientation, where the fracture propagates in the bedding plane in a direction parallel to the bedding, is found to have significantly lower values than the other two orientations. Fracture Toughness measurements conducted at elevated temperature demonstrate that preferentially oriented thermal microcracking causes the anisotropy to increase even further; with KcIc in the Arrester orientations being 4 times that in the Short-Transverse orientation at 150oC.
This anisotropy and variability in fracture properties is seen to cause deviation of the fracture direction during experiments on Arrester and Short-Transverse oriented samples, and can therefore be expected to influence the trajectory of propagating fractures. A comparison between the anisotropic tensile strength of the material and the crack-tip stress field for a transversely isotropic material has been used to develop a crack-tip deflection criterion in terms of the elasticity theory of cracks. This criterion suggests that even a small perturbation in the incident angle of a mode-I crack propagating perpendicular to the bedding plane is likely to lead to a substantial deflection towards bedding-parallel (Short-Transverse) propagation. This is significant because it suggests the deflection of vertical hydraulic fractures towards the horizontal direction,
Further experimental work is currently underway on anisotropic fracture toughness measurements at elevated pressures, simulating conditions in shale-gas reservoirs at depths to around 4km.

Breadth of failure mode in volcanic rocks.

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Style, intensity, and duration of volcanic eruptions are intrinsically coupled with the efficiency of volatile degassing from the magma prior to and during these events. Effective degassing of magma tends to manifest in effusive eruptions, whereas inefficient degassing can result in violent explosive episodes, with implications for hazard mitigation and disaster management. Degassing is partially governed by the state and evolution of edifice permeability, however few quantitative data exist regarding the deformation and failure modes of volcanic rocks. In order to assess the mechanical response of volcanic materials with regards to the physical properties defined by their constituent geochemistry, a suite of compressive and permeability experiments were performed on andesite samples from Volcán de Colima, Mexico. The porosities of the samples used herein ranged from 8 to 24%, and were compositionally identical (59.9 ± 1.0% SiO2). Water permeabilities ranged from ~ 10-13 to 10-17 m2; in all samples gas permeability was greater than water permeability by approximately one or two orders of magnitude. Compressive strength tests under effective confining pressures (Peff) from 0 (uniaxial) to 70 MPa were performed with a constant strain rate of 10-5s-1. In volcanic systems, edifice material is unlikely to be above its glass transition temperature; all experiments were accordingly carried out below this threshold. Depending on experimental conditions and the initial rock properties, either dilatant or compactive failure modes were discernible. Low Peff fostered brittle failure, embodied by axial splitting or shear faulting. Thin-section analysis of these samples indicated coalescence of vesicle-emanated microcracks forming macroscopic faults. Shear-enhanced compaction was favoured at higher Peff: deformation in this regime was manifested in features resembling compaction bands described in deformed sedimentary samples. These bands were oriented sub-perpendicular to the maximum principal stress, and their formation was associated with bursts of AE activity. So as to study the evolution of these features at high effective pressures, targeted experiments were carried out under the same conditions, to strains of 1.5, 3, and 6%. Microstructural analysis yielded evidence for pore collapse in and proximal to the bands. Samples of higher porosity required less effective pressure to facilitate this switch between dilatant and compactive regimes: samples of 24 and 19% porosity switched between 10 and 50 MPa effective pressure; 11% porosity samples transitioned between 50 and 70 MPa. The equivalent depth range of the switch in failure modes is on the order of one kilometre, meaning that this transition can be expected within many silicic-to-intermediate volcanic edifices. The mode of deformation and failure drastically alter the evolution of host rock properties, especially permeability; previous studies on sedimentary rocks have shown that compaction features can reduce permeability by three orders of magnitude. Patently, a decrease in permeability reduces magma degassing, increasing the potential explosivity of an eruption as well as fostering pressure build-up within the edifice. Contrastingly, shear faults can serve to increase edifice permeability and hence lessen explosiveness and mechanical instability. Further study of the evolution of permeability during and after this transition is critical, in order to fully determine the influence of failure mode on volcanic eruption dynamics and structural edifice stability.

Radon emanation from mechanical and thermal fracturing in granites: Direct evidence of transient signals under tri-axial stress

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Radon-222, a radioactive gas (half-life 3.8 days) naturally produced in the Earth's crust, gives precious information about the subsurface and is sometimes considered as a potential earthquake precursor. Here, experiments are performed on various granites representative of the upper crust. First, thermal cracking shows that heating at 850°C irreversibly decreases emanation by 60?95 % due to amorphization of minerals hosting radon sources. Second, on-line daily radon measurements performed under tri-axial stress and pore fluid pressure show that mechanical damage resulting from cycles of differential stress intensifies radon release up to a factor of 3 when the sample ruptures. This radon peak is transient and results from isolated microporosity being newly connected to the permeable network rather than new crack surface creation per se. Finally, a new procedure involving on-line continuous radon measurements under tri-axial stress and pore fluid pressure arouses particular interest. Radon release shows large sensitivity to various parameter changes: isotropic conditions, pore fluid pressure, differential stress, etc. Significant transient signal is observed at the macroscopic rupture of the sample. This study and the developed procedures open perspectives in the understanding of the relation between radon emanation of crustal rocks, deformation and P-T conditions.

Krauklis wave initiation in fluid-filled fractures by a passing body wave: Finite-element modeling and application to earthquake-induced mudvolcanic tremor

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Krauklis waves are a special seismic wave mode that is bound to and propagates along fluid-filled fractures (Ferrazzini and Aki, 1987; Korneev, 2008). They can repeatedly propagate back and forth along a fracture and eventually fall into resonance emitting a seismic signal with a dominant characteristic frequency. They are of great interest because this resonant behavior can lead to strongly frequency-dependent propagation effects for seismic body waves and may explain seismic tremor generation in volcanic areas (Chouet, 1988; Chouet, 1996) or affect micro-seismic signals in fractured fluid reservoirs. It has been demonstrated that Krauklis waves can be initiated by a seismic source inside the fracture (Frehner and Schmalholz, 2010), for example by hydrofracturing (Ferrazzini et al., 1990) or when a fracture intersects a borehole (Ionov, 2007). However, it remains unstudied whether Krauklis waves can be initiated by body waves, and therefore be really relevant for active seismic surveys in fractured reservoir situations or for seismic earthquake signals traveling through fractured rocks.
In the first part of the study, Krauklis wave initiation by an incident plane P- or S-wave is studied using numerical finite-element simulations (Frehner, 2013; Frehner, 2014). It is found that both seismic body waves are reflected and scattered at the fracture, but also, that two Krauklis waves are initiated with significant amplitude, one at each fracture tip (i.e., at the diffraction-points of the fracture). Generally, incident S-waves initiate larger-amplitude Krauklis waves compared to an incident P-wave. For both incident wave modes, the initiation of Krauklis waves strongly depends on the fracture orientation. In the case of an incident P-wave, large-amplitude Krauklis waves are initiated at moderate (12°?40°) and high (>65°) inclination angles of the fracture with a distinct gap at approximately 50°. In the case of an incident S-wave, the dependency of Krauklis wave initiation on fracture orientation is almost inversed and the largest-amplitude Krauklis waves are initiated at an S-wave incidence angle of approximately 50°. Knowing that both P- and S-waves are able to initiate large-amplitude Krauklis waves has some severe implications as they should lead to strongly frequency-dependent and anisotropic propagation behavior for body waves in situations where seismic body waves propagate through fluid-filled fractured rocks.
Once Krauklis waves are initiated, either by body waves or by a seismic source inside the fracture, they propagate along the fracture. Yet, their signal cannot be detected at a relatively short distance from the fracture because their amplitude spatially decays exponentially away from the fracture (Ferrazzini and Aki, 1987). However, Frehner and Schmalholz (2010) demonstrated that Krauklis waves both reflect and diffract at fracture tips and at intersection points between two fractures. The diffraction of Krauklis waves emits body waves into the surrounding rock, which then propagate away from the fracture. Therefore, it can be assumed that Krauklis wave-related signals can also be recorded further away from the fracture, for example at seismic stations at the Earth's surface.
The second part of the study is a direct application of the conclusion of the first part, that Krauklis waves can be initiated by passing body waves. Seismic tremor signals around the Salse di Nirano mudvolcano in northern Italy are analyzed assuming that Krauklis wave-related signals are present in the recorded seismograms. Immediately after an earthquake, the seismic tremor increased and its frequency content was much more narrow-banded than before the earthquake with a frequency-peak at around 2 Hz. Apparently, the seismic body waves from the earthquake excited a resonant behavior of the mudvolcano system, and it is assumed that this resonant behavior is due to Krauklis waves being initiated by the passing body waves. Based on these assumptions, the analytical solution for the Krauklis wave phase velocity (Korneev, 2008) is used to estimate the maximum fracture length in the mudvolcano system. This analytical solution relates the frequency-dependent phase velocity with the fracture thickness and the petrophysical parameters of the mudvolcano system. The latter can be taken from the literature. As a result, the geometrical parameters of the fractures (thickness and length) can be related to the observed dominant tremor frequency. To visualize this relationship, a kind of phase diagram is created,

which makes it easy to read the geometrical parameters of the fracture. In the studied mudvolcano system, the maximum fracture length is found to be in the order of few 100 m.

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References

Chouet B., 1988: Resonance of a fluid-driven crack: Radiation properties and implications for the source of long-period events and harmonic tremor, Journal of Geophysical Research 93, 4375?4400, doi:10.1029/JB093iB05p04375.
Chouet B., 1996: Long-period volcano seismicity: Its source and use in eruption forecasting, Nature 380, 309?316, doi:10.1038/380309a0.
Ferrazzini V. and Aki K., 1987: Slow waves trapped in a fluid-filled infinite crack: Implication for volcanic tremor, Journal of Geophysical Research 92, 9215?9223, doi:10.1029/JB092iB09p09215.
Ferrazzini V. Chouet B., Fehler M. and Aki K., 1990: Quantitative-analysis of long-period events recorded during hydrofracture experiments at Fenton Hill, New Mexico, Journal of Geophysical Research 95, 21871?21884, doi:10.1029/JB095iB13p21871.
Frehner M., 2013: Krauklis wave initiation in fluid-filled fractures by a passing body wave, in Poromechanics V: Proceedings of the fifth Biot Conference on Poromechanics (eds: C. Hellmich, B.B. Pichler and D. Adam), American Society of Civil Engineers, 92?100.
Frehner M., 2014: Krauklis wave initiation in fluid-filled fractures by seismic body waves, in press for Geophysics 79, doi:10.1190/GEO2013-0093.1.
Frehner M. and Schmalholz S.M., 2010: Finite-element simulations of Stoneley guided-wave reflection and scattering at the tips of fluid-filled fractures, Geophysics 75, T23?T36, doi:10.1190/1.3340361.
Ionov A.M., 2007: Stoneley wave generation by an incident P-wave propagating in the surrounding formation across a horizontal fluid-filled fracture, Geophysical Prospecting 55, 71?82, doi:10.1111/j.1365-2478.2006.00577.x.
Korneev V., 2008: Slow waves in fractures filled with viscous fluid, Geophysics 73, N1?N7, doi:10.1190/1.2802174.

Experimental and Microstructural Investigations into the Spectrum of Slip Behaviors of Carbonate-bearing Faults

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The combination of high-resolution seismology, seismic reflection profiles, and subsurface geology has led to the identification of the carbonate lithologies where earthquakes throughout Italy nucleate and propagate. To better understand the complex slip behaviors observed on faults cutting these lithologies, we combine field and microstructural studies of carbonate bearing faults, exhumed from the seismogenic crust, with experimental determinations of the mechanical, hydrologic, and elastic behaviors of these rocks. For some carbonate fault zones; field observations of sharp principal slip zones composed of ultra cataclasites combined with microstructural observations of relict calcite and clay, numerous vesicles, poorly crystalline/ amorphous phases, and newly formed calcite skeletal crystals indicate that seismic mechanisms are associated with thermally activated processes (i.e. dehydration and decarbonation). In other carbonate fault zones; the distribution of deformation over of wide zones combined with microstructural observations of frictional sliding along phyllosilicate foliations and pressure solution indicate a slow and aseismic slip behavior. Our mechanical data show that fault areas characterized by sharp slipping zones would exhibit high friction, velocity-weakening frictional behavior, and significant restrengthening post slip. Additionally, in such areas of the fault, decarbonation of gouge material would alter fault behavior during slip, via increases in pore pressure, and post slip, through the formation of portlandite. Our mechanical data also show that regions of the fault characterized by foliated fault rocks would exhibit low friction, velocity-strengthening frictional behavior, and no post slip restrengthening. Our combination of microstructural observations and mechanical data has revealed a broad spectrum of fault slip behaviors and the processes and structures that are likely responsible for such behavior.

The evolution of fault surface topography in direct shear experiments

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We present here experimental results of the evolution of fault surface topography with slip distance. Faults in the upper crust contain discrete slip surfaces which have absorbed a significant part of the shear displacement along them. Field measurements demonstrate that these surfaces are rough at all measurable scales and indicate that surfaces of relatively large-slip faults are statistically smoother than those of small-slip faults, when comparing geometrical sections at the same wavelength along the slip orientation. However, post faulting and surface erosion process which might affect the geometry of outcrops cannot be discounted in such measurements.
In order to isolate the effect of shear distance on surface roughness, a single prismatic fine grain limestone block is first fractured in tension mode, using the three-point bending testing methodology and then the fracture surface topography is scanned using a laser profilometer. We then shear the obtained tensile fracture surfaces in direct shear, ensuring the original fracture surfaces are in a perfectly matching configuration at the beginning of the shear test. Shearing is conducted to distances varying from 5 to 15 mm under constant normal stress of 2Mpa and a constant displacement rate of 0.05 mm/s using two closed-loop servo controlled hydraulic pistons. In the tested configuration peak shear stress is typically attained after a shear displacement of ~ 2-3 mm, beyond which lower shear stress is required to continue shearing at the preset displacement rate of 0.05 mm/s as is typical for rough joints. Following some initial compression the interface begins to dilate and continues to do so until the end of the test. Following the shearing the fracture surface is scanned again and the geometrical evolution, in term of RMS roughness and power spectral density (PSD) is analyzed.
We show that shearing smooth the surface along all our measurements scales. Roughness ratio, measured by initial PSD / final PSD, for each wavelength, increases as a function of the slip amount. However, for every given test, the ratio increases with increasing wavelength up to a few millimeters, whereas from a few millimeters to a few centimeters the ratio remains constant. At this region, the roughness measured after slip can be fitted by a power-law similar to that of the initial tensile surface. Therefore, if an initial fault surface roughness is characterized by a power-law as function of the length, then our results imply that the power will remain constant after a slip but that the coefficient will decrease with increasing distance of the slip. However, when the fault surfaces are not perfectly matched due to either previous shearing cycles, dilation, or wear layer generation within the fault aperture, the small scale asperities might be less affected by interlocking deformation, and therefore smoothing is expected to be less efficient at scales smaller than the total shear displacement. We interpret this geometrical evolution by deformation of interlocked asperities along with shear induced dilation.

Tensile fracturing and dyking in volcano-tectonic settings, a laboratory approach.

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It is well known that magma ascends trough the crust by the process of dyking. To enable dyke emplacement, basement rocks typically fail in a mode 1 fracture, which acts as conduits for magma transport. An overpressure of the ascending magma will further open the fracture, permitting the dyke to propagate in a process that remains poorly understood in volcanic systems. In order to explore the emplacement and arrest of dykes in the subsurface, analogue and numerical studies have been conducted (Gudmundsson, 2011). However, a number of assumptions regarding rock mechanical behaviour, specifically tensile strength, are frequently made as such data are difficult to directly measure at the pressure/temperature conditions of interest: high temperatures at relatively shallow depths. Such data are key to simulating the magma intrusion dynamics through the lithologies that underlie the volcanic edifice.

Tensile strength is typically determined using the indirect «Brazilian disc» setup. This method however, gives a large scatter in the results, tends to overestimate the tensile strength when compared with numerical models, and is hard to implement in combination with appropriate temperature and pressure conditions. Here we present a new laboratory setup, which allows us to investigate the tensile fracturing properties under both temperature and confining pressure.

We have modified a traditional Paterson type triaxial test assembly setup to accept a new high temperature deformation assembly. Sample setup consists of a cylindrical rock sample of 40mm length and 22mm diameter with a 8mm conduit drilled axially that is then filled with a material chosen such that it is in a liquid state at the conditions of interest. The top and lower parts of the rock sample are fitted with plugs sealing in the «melt». The assembly is then placed between ceramic pistons to ensure there are no thermal gradients across the sample and jacketed to ensure the confining medium (Ar) cannot enter the assembly. Around the top piston a filler material is placed to prevent jacket rupture (Fig. 1). When the assembly is brought to the desired PT conditions, a piston is driven up which pressurizes the conduit and the filler material. The filler material is «squeezed out» and thus transfers little to no axial stress on to the sample, but sufficiently pressurizing the molten material in the middle.

As a starting point, we are now testing an analogue material to replace the magma to avoid such high temperatures, relying of maintaining similar temperature/viscosity ratios between magma/ country rock in the laboratory and the field. We chose PMMA (commonly known as plexiglass) for this task as it displays a large range in viscosities (log(visc)range = 10?1) with temperatures between 100 and 300 ?C, making it an excellent analogue material. In addition PMMA solidifies after the sample cools to permit post-test analysis of the pseudo dyke.

With the inner melt / PMMA conduit pressurized, a sufficient pressure difference between the inner and outer surfaces eventually causes the sample to deform and fail in the tensile regime. Tensile fracture occurs when the hoop stress exerted on the outer shell exceeds its tensile strength. The melt / PMMA is then likely to flow into the newly formed fracture, depending on its viscosity and the fracture dimensions, allowing comparisons to be made between the temperature and intrusions dynamics of the simulated dyke process.

Here, we present new data linking conduit pressure to the failure of the country rock in the tensile regime, allowing tensile strength of the specimen to be calculated via a treatment that uses the conduit and sample geometry and measure axial force. Additionally, we present an analysis of the ensuing fracture patters both via traditional SEM and optical methods and via 3D X-ray tomography. These analyses confirm that the fractures nucleate without any preferential location, and are not influenced by embedded crystals. We also show data that suggest the formation of microcrack linkage plays a significant role in the development of these (rapid) tensile fracturing events, well-known from classical Griffith theory.

Ultimately this method will be extended to higher temperatures using NIST standard glasses and collected volcanic glasses for comparison to the analogue setup.

The lock-up angle for brittle activation of a phyllosilicate-rich mylonitic fabric: implications for rock strength and failure modes

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A plausible mechanism for explaining the nucleation and propagation of weak faults showing a non-Andersonian attitude is provided by the mechanical anisotropy of phyllosilicate-rich strongly-foliated (e.g. mylonitic) rocks. Here we report on an experimental study of nucleation and propagation of mechanical damage in foliated rocks of the Grandes Rousse Massif (French Alps).
The variable orientation of foliation with respect to principal stress axes results in different fracture modes in the field. End-members are represented by (i) the case in which foliation controls the deformation with no additional fracturing, or (ii) classical Andersonian failure mode. The deformation and failure mode can be investigated through rock deformation laboratory experiments, that allow us to quantify the mechanical anisotropy and the absolute strength of rocks.
The Grandes Rousses Massif is one of the external crystalline massifs in the Helvetic/Dauphinois Domain of the French Alps. In the Lac Blanc and Lac Bramant area the chlorite- and mica-schists of the Grandes Rousses massif are affected by an Alpine brittle deformation developing on an Hercynian mylonitic SCC' fabric: it is identifiable both with widespread brittle reactivation of the mylonitic fabric (fig 1b) and with rarer Andersonian conjugate shear fractures (fig 1a). This different behavior is related to the geometrical relationships between foliation and dip angle of the mylonitic fabric.
To better understand the relationships between reactivation and dip of the mylonitic fabric, we have reconstructed the paleostress field. The analysis yields a wrench tectonics regime, with ?2 almost vertical, ?1 horizontal WNW-ESE, and ?3 horizontal NNE-SSW, suggesting a strike slip behavior according to classical Andersonian conjugated fractures.
The average orientation for the two conjugated families is of 88/229 and 87/166 and is associated to areas with a foliation inclination of about 65°. When the average foliation inclination increases to about 75°, we observed the brittle activation of foliation with the development of cataclastic seams along S, C and C' surfaces. Tensional joints, filled with quartz and chlorite fibers, are present in both domains and are consistent with the paleostress reconstruction.
Assuming an homogeneous paleostress field, we believe that the different brittle deformation mechanisms can be related to the different dip angle, which implies a different angle between the mylonitic foliation and ?1 of about 65° where we observe Andersonian fractures, while at ca. 55° we observe brittle deformation along foliation planes. We propose that the lock-up angle for reactivation of the Grandes Rousses schists mylonitic foliation falls between these two values, at about 60°. This angle marks the boundary between a domain where the reactivation of preexisting anisotropies is still possible and another one where reactivation is not possible and Andersonian fractures develop.
In order to investigate these different failure modes, physical and mechanical properties of representative samples from the Grandes Rousses Massif, collected in undisturbed areas out of the Lac Blanc and Lac Bramant deformation zone, have been tested at the Rock Physics Laboratory of the British Geological Survey, UK. Here we report preliminary results, in terms of physical (density and porosity) and mechanical (point load, uniaxial compressive strength - UCS and elastic moduli) properties. The tests have been performed on samples cored along two different orientations, i.e. perpendicular and parallel with respect to the foliation planes. UCS and point load tests carried out on samples with foliation planes perpendicular to the load show higher strength and a failure mode characterized by an irregular geometry with a sequence of millimetric segments composed of low-angle steps developed along foliation planes connected by high-angle segments with an Andersonian orientation (fig 1a). USC and point load tests on samples with foliation parallel to the loading show a lower strength with a failure mode controlled by the formation of main fractures along the foliation, originating axial splitting (fig 1b), typical

outcome of uniaxial tests.

Field observations and preliminary results of laboratory experiments are in agreement and highlight the role of preexisting anisotropy in controlling the mechanical behavior of foliated rocks which is characterized by the interplay of the Andersonian failure mode and the role of foliation planes.

Numerical modeling and laboratory measurements of seismic properties in fractured fluid reservoirs

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Understanding fluid-saturated reservoir rocks is essential for the applications of, for example, CO2-sequestration, hydrocarbon exploration, or underground nuclear waste disposal. Seismic waves are influenced by the fluids in reservoir rocks, leading to dispersion and frequency-dependent attenuation (Biot, 1962). A reliable rock characterization can be obtained if the effects of fluids filling the pore and fracture space on the seismic response are well understood.
The Krauklis wave is a unique seismic waveform, which is bound to fluid-filled fractures and propagates along such fractures. It is highly dispersive with low phase velocity at low frequency (Korneev, 2008). It can resonate and emit seismic signals with a signature frequency. This resonant behavior should lead to strong frequency dependence for seismic body waves, enabling the identification of Krauklis wave-related signals in the coda of recorded seismograms (Korneev, 2008). Aki et al. (1977) and Chouet (1996) used this resonance behavior in interpreting volcanic tremor to show the potential of volcanic eruption forecasting. Identifying the characteristics of Krauklis waves in recorded seismograms might be one of the keys to reveal fracture-related petrophysical parameters of reservoirs.
Several theoretical studies have demonstrated analytically the dispersion behavior of Krauklis waves in infinitely long and straight fractures (e.g., Korneev, 2008). However, purely analytical methods cannot reveal the realistic fracture geometries or finite-length fractures. Therefore, we combine numerical modeling results with laboratory experiments to study and visualize fracture-related effects on seismic wave propagation in reservoir rocks. Frehner and Schmalholz (2010) demonstrated that the Krauklis wave can be detected as a converted body wave as a result of scattering and diffraction at the fracture tip. The study also shows that the reflection behavior of the Krauklis wave depends significantly on different fracture geometries and different fluids in the fracture. For laboratory studies, we simulate similar conditions for a homogenous medium (i.e., plexiglas) as in the numerical experiments. The cylindrical sample has a length of 120 mm and a diameter of 25 mm. A 0.1 mm thick fracture is created by cutting the sample at 45°, milling on one side a 0.1 mm deep, 25x15 mm elliptical hole, and gluing the sample back together with chloroform (Fig. 1). We record the signals obtained from propagating ultrasonic waves along samples with and without a fracture. The design of the experimental setup thus allows observing and comparing the effects of fractures.The preliminary experimental results indicate that the fracture leads to frequency-dependent attenuation and a slight frequency shift of the peak seismic amplitude. By comparing numerical modeling (Frehner and Schmalholz, 2010; Frehner, 2014) and experimental results we hope to be able to extract information about the fractures from the recorded seismic signals.

REFERENCES

Aki K., Fehler M. and Das S., 1977: Source mechanism of volcanic tremor: Fluid-driven crack models and their application to the 1963 Kilauea eruption, Journal of Volcanology and Geothermal Research 2, 259?287.
Biot, M.A. 1962: Mechanics of deformation and acoustic propagation in porous media, Journal of Applied Physics 33, 1482?1498.
Chouet B.A., 1996: Long-period volcano seismicity: Its source and use in eruption forecasting, Nature 380, 309?316.
Frehner M., 2014: Krauklis wave initiation in fluid-filled fractures by seismic body waves, Geophysics 79, in press, doi:10.1190/GEO2013-0093.1.
Frehner M. and Schmalholz S.M., 2010: Finite-element simulations of Stoneley guided-wave reflection and scattering at the tips of fluid-filled fractures, Geophysics 75, T23?T36.
Korneev V., 2008: Slow waves in fractures filled with viscous fluid, Geophysics 73, N1?N7.

An integrated approach for monitoring slow deformations preceding dynamic failure in rockfalls

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Rock slope monitoring is a major aim in territorial risk assessment and mitigation. The high velocity that usually characterizes the failure phase of rock instabilities makes the traditional instruments based on slope deformation measurements not applicable for early warning systems. We analyse an unstable patch of the Madonna del Sasso, Verbania, Italy rock mass, prone to the development of rock falls and repeated failure episodes, preceded by neat and long lasting episodes of slow deformation.We first carried out geomechanical and geophysical tests to preliminary better understand the instability mechanism and to design the monitoring systems. The geomechanical study in terms of stability analysis showed that the stability of the slope is due to rock bridges. Their failure progress can results in a global slope failure. The geophysical characterisation (both in-hole and surface seismic geophysical tests have been undertaken) allowed to establish the best nodes position and internal characteristics of the monitored rock mass, providing fundamental parameters for a correct definition of the velocity field of the rock mass.In order to identify the characteristic signs of impending failure, we developed a «site specific» microseismic monitoring system to detect frequency microseismic events which reflect the subtle changes of the mechanical properties of the medium, made of 4 triaxial piezoelectric accelerometers operating at frequencies up to 23 KHz with a conventional monitoring for seismic detection (4.5 Hz seismometers) provided by the University of Turin that were deployed in October 2013 and that will be implemented in spring/summer 2014 with high-frequency equipment provided by SEIS-UK (Fig. 1). The high-frequency equipment will allow us to develop a network capable of recording events with Mw

Predicting the failure of two phase viscoelastic suspensions

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Material failure laws are apt to describe the stress at failure for porous rocks and the analogous two phase viscoelastic suspensions. However, there is much debate about the applicability of predicition tools such as the Failure Forecast Method (FFM). We use synthetic standard glass powders and sinter them for different times (0-32 hours) at high temperature (575-650 C) to achieve a sample suite with porosities in the range 0-40%. Consequently, the samples have a range of microstructures because the viscous sintering process promotes a fining of pores and a coarsening of grains. This sample suite was then subjected to mechanical tests at constant strain rates with a dual acoustic emission rig to test the effect of varying porosity and deformation rate on the success of both the material failure laws and the FFM. The constant strain rate tests were performed at temperatures in the region of the material glass transition, yielding a strain-rate dependent viscous component to deformation. The pore-emanated crack micromechanical model describes the peak stress at failure in the elastic regime for our materials. With prior knowledge of the exact sample failure time we can apply the FFM to both the energy release rate and the event rate recorded by the acoustic emission system. We demonstrate that the FFM predicts failure within 1-5% error at porosities >0.05. However, when porosities are

A damage model for volcanic eruptions

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Volcanic eruptions are due to the increase of magma pressure into magma reservoirs that may be imbedded in the volcanic edifice and/or in the crust and upper mantle. Pressure increases up to reach the confined rock strength near the top of the reservoir, reservoir ruptures and magma transfers from the reservoir to the surface. The complete process can have various dynamics depending on magma viscosity and gas content. Our aim is first to understand the deformation process around the magma reservoir up to strain localization (e.g., a dyke eventually reaching the surface in a basaltic volcano when tension occurs). The classical view of the deformation process around the pressurized reservoir is a purely linear elastic one, so that variation of the pressure in the magma reservoir may be directly inferred from the linear elastic inversion of surface displacement. In this work we will concentrate on understanding the rock deformation during the inter-eruptive phase, up to the initiation of the rapid magma transfer, taking into account the anelastic deformation of the rock under stress by a progressive damage approach. Microearthquake occurrence shows that damage occurs into the edifice around the magma reservoir. In this frame we consider a non-linear elastic relation between pressure in the magma reservoir and surface deformation by using effective elastic moduli depending on a damage variable instead of the usual constant elastic moduli. We use the crack density parameter as a damage variable and consider crack interaction using the cumulative seismicity rate in our damage model. Using GPS surface displacements and seismicity rates as data, we perform a least square inversion for estimating the model parameters. Average constant structural parameters are first computed. Crack density parameter is then computed as a function of time, featuring the progressive damage history. Finally other important physical parameters, especially the effective shear modulus, reservoir pressure variation and magma inflow are deduced and compared with the purely elastic solution. Results show that relatively constant magma inflow may occur with limited reservoir pressure increase, reproducing the observed surface displacement if damage occurs around the reservoir.

Mechanical properties of lava dome products: from endogenous dome building to effusion at Santiaguito volcano, Guatemala

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The ongoing eruption at Santiaguito is characterised by the continuous effusion of lava punctuated by cyclic explosions over timescales of minutes to days. Over the last 90 years Santiaguito volcano has undergone cycles of eruptive activity variable over months to years creating distinctive facies over four vents. Eruptive style at Santiaguito can be correlated with discharge rate and the pre-eruptive properties of magma and dome material. The rheology of magma within the conduit and the internal strength of dome and wall rock may constrain the dominant behaviour. Here, we present an experimental and analytical description of magma/rock properties in order to constrain the conditions that lead to changes in eruptive behaviour.
We apply experimental and analytical methods to characterise properties of dome rock, spine rock and lava from Santiaguito volcano. Dome eruptions at Santiguito have produced andesitic to dacitic rock with 28±10 vol.% crystals, 3-12 vol.% porosity and ss a anmsteadily decreasing in SiO2 over time, from 66% SiO2 in 1922 to 62% in the present day (Scott et al. 2013, Avard & Whittington 2012). The rheology of magma associated with effusion of lava domes and flows and their transition to spine growth or explosive events have been assessed via uniaxial compression deformation tests conducted at a range of temperatures (above and below the glass transition temperature) and strain rates (10-5 to 10-1 s-1). At high temperatures, magma deformation is mostly viscous (with some plasticity) at low strain rates, but brittle as strain rate approaches the rheological limit of the liquid structure. Frictional processes - which characterised the extrusion of spines as well as cycles of uplift/collapse of the dome (at rates of 1 - 2 m.s-1, Johnson et al., 2008) during gas-and-ash venting activity - have been studied using a high-velocity rotary shear apparatus. Friction experiments under applied axial stresses (0.7 ? 5 MPa) and applied rates (0.4 ? 1.5 m.s-1) rates show the highly variable frictional behaviour of magmas. While gouge on the slip surface may induce a lubricating effect, the sudden formation of melt by flash heating can drastically increase resistance to slip applying a viscous brake. Rate and state friction laws are modified by melt production and the resultant viscous component of deformation within the slip plane.
Variation within the three lava dome products in frictional behaviour, porosity and internal strength are compared with interpretations of emplacement processes and facies characterisation from field mapping and correlated with new descriptions of historic extrusion rates and behaviour at Santiaguito volcano. These data are used to describe a model linking the material properties and rate of volcanic processes at Santiaguito volcano to the dominant eruptive styles and resulting volcanic facies.
Avard, G., & Whittington, A. G. (2012). Rheology of arc dacite lavas: experimental determination at low strain rates. Bulletin of Volcanology, 74(5), 1039?1056. doi:10.1007/s00445-012-0584-2
Johnson, J. B., Lees, J. M., Gerst, A., Sahagian, D., & Varley, N. (2008). Long-period earthquakes and co-eruptive dome inflation seen with particle image velocimetry. Nature, 456(7220), 377?81. doi:10.1038/nature07429
Scott, J. a. J., Pyle, D. M., Mather, T. a., & Rose, W. I. (2013). Geochemistry and evolution of the Santiaguito volcanic dome complex, Guatemala. Journal of Volcanology and Geothermal Research, 252, 92?107. doi:10.1016/j.jvolgeores.2012.11.011

Failure and friction in volcanic rocks

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Volcanic landscapes are amongst the most dynamic on earth and, as such, are particularly susceptible to strain localisation, failure and frictional processes. Damage accumulation is frequently accompanied by the release of seismic energy, which has been shown to accelerate in the approach to failure on both a field and laboratory scale. The stress at which failure occurs is highly dependent upon strain-rate, which also dictates the slip-zone properties that pertain beyond failure. Movement along slip surfaces generates fault rocks, including gouge, cataclasite and pseudotachylyte that have been observed in many composite volcanoes, including Mount Unzen (Japan), Mount St. Helens (USA) and Soufrière Hills (Montserrat). This mode of eruptive behaviour is often accompanied by characteristic repetitive seismic signatures generated by non-destructive source mechanisms, arguably stick-slip motion.

Conduit margins, especially in these dome-building volcanoes, may be considered akin to large-scale faults in the sense that slip zones host sustained movement, and thus a picture emerges in which the control of magma transport passes from buoyant forces at depth to a frictional control during ascent. Mechanical work driving friction induces both mechanical comminution of asperities as well as heat.

Comminution produces ash gouge, and high-velocity rotary shear (HVR) experiments demonstrate that gouge behaves according to Byerlee's rule at low slip velocities, irrespective of glass content. A non-linear reduction of the friction coefficient with slip velocity is observed, while textural analysis reveals that strain localisation and development of shear bands are more prominent at higher slip velocities (>10 mm/s). Heating, if sufficient, may induce melting and generation of pseudotachylyte. It is generally inferred that the viscosity of the silicate melt so generated controls the subsequent resistance to slip along the fault plane. Silicate melts are viscoelastic bodies whose rheology envelops the glass transition. This thermo-kinetic transition bestows melt with the ability to either flow or fracture: with potentially drastic consequences for frictional slip dynamics. Silicate melt reveals a strong velocity-dependence and yields a tendency for extremely unstable slip, indicating that it may be the cause and consequence of stick-slip extrusion and drumbeat seismicity during viscous magma ascent. In this scenario, the repetitive nature of drumbeats is easily accounted for by the arrival of fresh magma at a mechanical transition zone. These processes highlight the important role that fracture and friction play in volcanic eruptions.

Premonitory activity, Stress drop, Rupture velocity and Energy budget during stick-slip experiment in Westerly granite

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Since the proposal by Brace and Byerlee [1966] that the mechanism of stick-slip is similar to earthquakes mechanics, many experimental studies have been conducted in order to improve the understanding of earthquakes. Here we report macroscopic stick-slip events in saw-cut Westerly granite samples deformed under controlled upper crustal stress conditions in the laboratory. Experiments were conducted under triaxial loading (?1>?2=?3) at confining pressures (?3) ranging from 10 to 100 MPa. The angle between the fault plane and the maximum stress (?1) was imposed to be equal to 30°. Usual a dual gain system, a high frequency acoustic monitoring array recorded particles acceleration during macroscopic stick-slip events and premonitory background microseismicity.
Here, we show that the macroscopic friction coefficient of the fault plane continuously increases with normal stress. At low friction (µ0.7). In addition, by using external shortening measurement, we show that the macroscopic friction and the foreshocks activity are highly dependent of the coupling along the fault surface, i.e. the ratio between the seismic and the aseismic slip. These results suggest that the macroscopic friction also controls the intensity of the premonitory activity in our experiments.
For the first time, we also record the stress drop dynamically, and show that the dynamic stress drop, measured locally close to the fault plane, is almost total µ0.4 takes a few tens of microseconds only. Our measurements are consistent with flash heating, while stress drops measured at higher normal stress generally reveal a second frictionnal drop, consistent with the onset of melting, which was confirmed by our post-mortem microstructural analysis. Relationships between initial friction, rupture velocities, high frequency radiation and stress drop suggest that at high normal stress (i.e. at supershear velocities), the rupture processes become more dispersive. This result seems in agreement with seismological observations.

Changes of pore fluid thermodynamic conditions and compressibility in active fault core: implications for acoustic waves velocities and fault stability

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Since the beginning of the seventies[i], many observations of variation of wave propagation velocities have been reported in fault cores and zones around active faults before the coseismic period, allowing the scientific community to consider them as possible reliable precursors of earthquakes[ii],[iii]. This hope was unfortunately not confirmed in other observations. The effects of pore fluids, their pressure variation and the role of gas are still being debated (Miller[iv], Fitzenz[v], Hartman 2005[vi], King 2006[vii], Géli[viii], Maury[ix]).

We recently developped a poro-mechanical fault model based upon a Cam-Clay like interface constitutive law which enables to account either for the contractant or dilatant mode, or deformation of fault cores and then get an evaluation of the fault core pore pressure evolution during dilatant preseismic or coseismic periods in drained or undrained regime (Piau, publication in preparation, brief summary in Ref9). The model shows that significant pore pressure drops of several MPa may arise during dilatant preseismic periods in undrained conditions. However in its current state the model assumes a constant fluid compressibility without taking into account its own implication on possible deep modifications of the thermodynamic state and compressibility of the fault core fluid induced by pore pressure variation.

Then the first objective of this paper, at the junction between seismology and the thermodynamics of geofluids, is to have a deeper insight into the variations with pressure of the physical properties of fault core fluids. More precisely we focus on the changes with pressure of fluid state in PVT diagram (liquid, liquid+gas, gas) and the correlated changes of compressibility, considering both the isothermal and adiabatic cases.

Then we discuss the implications of such changes upon the compressibility of porous rocks and upon the velocity of primary waves . Numerical applications taking the case of H20 and CO2 fluids and considering the pore pressure changes from our fault model make it possible to compare the expected changes with those observed by geophysicists in the vicinity of active fault cores.

Finally coming back to our fault model, we discuss the possible implication of fluid compressibility increase upon the (in)stability itself of active faults and the triggering of seismic events. Indeed the model shows that this parameter also plays a significant and direct role on the unstable effective stress domain of geological faults.

The outline of the paper is as follows:

- brief presentation of the fault model developped by Piau summarized in ref9.
- implications in terms of pore pressure variation in the vicinity of dilatant active faults, assuming a fault core in undrained regime
- effect of pore pressure decrease upon the thermodynamic state of geofluids, in terms of phase composition (liquid, liquid+vap, gas) and changes of isothermal and adiabatic compressibilities,

noticeably around the bubble point; orders of magnitude for water and CO_2 (Nichita et al.[x], NIST[xi])
- effect of fluid compressibilities on the global rock compressibilities, as a function of the mode and rate of deformation
- discussion about the effective compressibility to consider (adiabatic or isothermal ?) for the evaluation of (Broseta et al.[xii])
- order of magnitude of variation in DVp, DVs resulting either directly from dilatancy or from the change in fluid state and compressibility
- comparison with seismological observations (and also with well known cases of oil production hydrocarbons reservoirs passing below the bubble point due to depletion)
- conclusions in the seismogenic context on the inter-relation between (i) stress path and induced deformation at the end of the preseismic period, (ii) "fluid-phase path» in the PVT diagram and consequences (iii) on variation of primary wave velocity and (iv) the triggering of fault instabilities.

[i] Dobrovolsky I.P.et ass , Estimation of the size of earthquake preparation zones, pure and applied geophysics 1979, Volume 117, Issue 5, pp 1025-1044
[ii] Lucente et ass., Temporal variation of seismic velocity and anisotropy before the 2009 MW 6.3 L'Aquila earthquake, Italy, Geology First published online October 12, 2010, doi: 10.1130/G31463.1 v. 38 no. 11 p. 1015-1018
[iii] Li Yong-Gang et ass., Seismic velocity variations on the San Andreas fault caused by the 2004 M6 Parkfield Earthquake and their implications, Earth Planets Space, 59, 21?31, 2007
[iv] Miller S.A. "Properties of large ruptures and the dynamical influence of fluids on earthquakes and faulting", JGR, Vol. 107, N° B9, 2182, [doi : 10.1029/2000JB000032] 2002
[v] Fitzenz D. D. and Miller S. A. "Fault compaction and overpressured faults : results from a 3-D model of a ductile zone" Geophys. Int. J. (2003) 155, pp 111-125
[vi] Hartmann, J, Levy, J.K. Hydrogeological and gasgeochemical earthquake precursors - A review for application NAT HAZARDS 34 (3): 279-304 MAR 2005
[vii] King, CY, Zhang, W, Zhang, ZC Earthquake-induced groundwater and gas changes
PaGeo 163 (4): 633-645 APR 2006
[viii] Géli L. et ass Gas emissions and active tectonics within the submerged section of the North Anatolian Fault zone in the Sea of Marmara, Earth and Planetary Science Letters 274 (2008) 34?39
[ix] Maury, V, Piau, J.-M. Fitzenz D., Mechanical effect of the presence of gas on faults modeled as a sandwiched Cam-Clay material,Proc. XIIth Intern. Cong. Rock Mechanics, Beijing (2011)
[x] Nichita D., P Khalid, D Broseta (2009). Calculation of isentropic compressibility and sound velocity in two-phase fluids, Fluid Phase Equilibria, Vol. 291, 95-102.
[xi] NIST WebBook of Chemistry
[xii] Broseta D., Khalid P, Nichita D., Galliéro G, N. Favretto-Cristini N. and Blanco J. A New Look at Seismic Properties of Low Gas-saturated Reservoirs Event name: 71st EAGE Conference & Exhibition
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Modelling large-scale hydraulic properties of a seismogenic fault at 10 km depth (Gole Larghe Fault Zone, Italian Southern Alps)

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The definition of hydraulic properties of fault zones is a major issue in structural geology, seismology, and in several applications (hydrocarbons, hydrogeology, CO2 sequestration, etc.). The permeability of fault rocks can be measured in laboratory experiments, but its upscaling to large scale structures is not straightforward. For instance, typical permeability of fine-grained fault rock samples is in the 10-18 - 10-20 m2 range, but, according to seismological estimates, the large-scale permeability of active fault zones can be as high as 10-10 m2. Solving this issue is difficult because in-situ measurements of large-scale permeability have been carried out just at relatively shallow depths - mainly in oil wells and exceptionally in active tectonic settings (e. g. SAFOD at 3 km), whilst deeper experiments have been performed only in the stable continental crust (e.g. KTB at 9 km). In this study we combine field and microstructural observations with fracture-network modelling techniques developed in the oil industry, in order to model the hydraulic structure of the Gole Larghe Fault Zone (GLFZ, Italian Southern Alps). This fault, now exposed in world-class glacier-polished outcrops, has been exhumed from ca. 8 km, where it was characterized by a well-documented seismic activity, but also by hydrous fluid flow resulting in alteration halos and precipitation of hydrothermal minerals in veins and along cataclasites. The strategy of our study consists of: (1) quantitative field characterization of the large- and meso-scale 1D fracture density based on continuous DGPS scanlines across all the fault zone; (2) evaluation of the 2D fracture-network scaling laws based on image analysis on 3D digital outcrop models; (3) evaluation of the aperture of fractures based on microstructural and mechanical considerations; (4) reconstruction of realistic Discrete Fracture Network (DFN) 3D models; (5) output in terms of upscaled hydraulic parameters; (6) calibration based on the observed large scale fluid-rock interaction pattern. In this contribution we present some results of this study, which show that the GLFZ was characterised by a composite, heterogeneous, and highly anisotropic hydraulic structure.

Experimental investigations on the brittleness and slowness of shear rupture propagation in porous saturated rocks

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Pore fluid pressure and shear rupture are long known to be interwoven: an increase in pore fluid pressure can unclamp the fault by reducing the effective normal stress and thus cause the fault to slip at lower shear stress. This mechanism is well illustrated by induced seismicity near fluid injection. More recently, several lines of evidence suggest that pore fluid pressure play a significant role in slow slip phenomena, which include non-volcanic tremor, low to very low frequency earthquakes, episodic tremor and slip. However, the differences in seismic signals between the induced but regular seismicity and the slow slips indicate different rupture processes which question our understanding of the source processes. How different slip instabilities results from pore pressure? Are specific environmental conditions required to condition the occurrence of slow rather than regular earthquakes? Is elevated pore pressure necessary to produce slow slip or is it only the effective stress variation which allows such slip behaviors?

In this study, we designed loading configurations and conducted triaxial deformation experiments to investigate how the reduction of effective normal stress affects slip instability and fracture propagation. Water saturated porous sedimentary rocks were deformed at constant strain rates and under fully drained conditions. Using the existing theoretical framework (bifurcation model, slip weakening model), we provide quantitative measure of the differences between slow and regular slip behaviors. In the brittle faulting regime, generally considered to allow the dynamic propagation of a shear fracture which produces regular earthquakes, excess pore pressure does not induce any change in slip behavior but enhanced seismic slip by lowering the shear strength which can explain the increased seismicity associated with elevated pore pressure near reservoirs. In the transitional regime where aseismic creep takes place instead, failure process should lead to a diffused, velocity strengthening aseismic fault. However, in these conditions, excess pore pressure enables slip to occur with quantifiable differences from that in brittle regime, showing a slower slip rate and smaller stress drop. A decrease of normal stress only produces similar rupture characteristics than observed in the brittle faulting regime. Microstructural observations highlight that increasing pore pressure allows overcoming the dilatancy strengthening. Moreover, our data show that if a rock already ruptures in a slow manner in the brittle regime, increasing pore pressure allows sustaining a more brittle slip behavior. Further observations even suggest that there may exist a continuous spectrum of slip rate and energy budget between ordinary earthquake (rapid slip) and slow slip phenomena.

True triaxial testing reveals the effect of s2 on all aspects of failure in rocks from granite to sandstone

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True triaxial testing facilitates the direct observation of the intermediate principal stress (s2) role in rock failure level and type, as well as in failure-plane angle, a role hitherto generally unrecognized. For a given s3, the threshold of strain localization and the magnitude of s1 at which rock fails (s1,peak) rise monotonically with s2 beyond their base values under conventional triaxial testing axisymmetric compression (AC), when s2 = s3. An inflection point is reached at some level of s2 that defines its maximum s1,peak for the given level of s3. Further rise in s2 leads to a gradually lower s1,peak, such that when s2 approaches s1,peak, strength is nearly the same as at s2 = s3. Similarly, fault angle for a given s3 in the brittle regime increases with the rise in s2, at least until the maximum s1,peak is reached. The effect of s2 on failure and fault angle are totally neglected by the commonly accepted Mohr-Coulomb theory, which assumes that faulting is a function of only the two extreme principal stresses, and considers fault angle a unique material property.

Experiments in two crystalline rocks, Westerly granite (Haimson and Chang, IJRMMS, 2000) and KTB amphibolite (Chang and Haimson, JGR, 2000), exhibited a remarkable s2 effect: At low s3, higher s2 increased failure stress s1,peak by up to 50% over its s2 = s3 level. As s3 was raised, the increase in s1,peak dropped steadily, but even at s3 = 100 MPa maximum s1,peak in both rocks increased by 20% or higher over the base level. Fault angle also increased with the rise in s2, by up to 20° as s2 rose above s3.

A milder effect of s2 on failure level and fault angle was observed in a low porosity (f = 7%) siltstone, extracted from the TCDP, Taiwan test hole (Oku, et al, GRL, 2007). At low s3 (25 MPa), the maximum s1,peak was about 30% larger than the AC level. At higher s3 (100 MPa), the maximum s1,peak, reached at s2 = 300 MPa, was only 12.5% higher than the strength at s2 = s3. Fault angle increase with s2 for the same s3 was limited to less than 10°, irrespective of s3 level. In Coconino sandstone (f = 17%), an even smaller s2 effect was observed. s1,peak as a function of s2 regardless of s3 level, reached a maximum of about 10% higher than under AC. Fault angle rise with s2 for the same s3, was less than 10°, independent of s3 level. The smallest s2 effect on rock failure and fault angle was found in the high porosity (f = 25%) Bentheim sandstone. In this rock s1,peak reached a maximum of less than 10% over its AC magnitude at all levels of s3. Average fault angle decreased from about 80° at s3 = 0 MPa, to 48° at s3 = 80 MPa, to about 0° at s3 = 150 MPa (compaction band). In the brittle regime (s3 = 0 - 80MPa), fault angle rise was limited to less than 10°.

The effect of s2 on failure mode was observed, for example, in Coconino sandstone, where at s3 = 100 MPa, the characteristics of brittle-ductile transition (multiple conjugate and parallel shear bands) observed at s2=s3 were gradually reversed as s2 is raised. Stress-strain plots also revealed a gradual change from contraction to dilatancy as s2 rose above s3.

Fluid Injection Processes (Fracking, CO2 Sequestration, ...)

Proppant-Induced Opening of Hydraulically Created Fractures

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Despite its controversy, hydraulic fracturing (also referred to in the vernacular by the vulgar term «fracking») is the only energy efficient procedure that can improve the extraction of energy from a resource bearing formation. Hydraulic fracturing procedures have been proposed for enhancing the productivity of gas bearing shales, enhanced oil recovery and the recovery of geothermal energy. The objective of hydraulic fracturing is to create controlled fracturing the extent of which is largely determined by the in situ stress state and at shallow depths, also by the fracture toughness of the resource bearing formation. If the fracturing pressures are relieved, this will cause the closure of the fracture, which would defeat the purpose of hydraulic fracturing. The increase in the energy extraction efficiency is governed by the extent to which the fracture can be maintained in an open condition. This is generally achieved by introducing a granular material with the fracturing fluid that can introduce a restraint to closure of the fracture faces by the geostatic stress state. The interaction between the resource bearing formation and the proppant is a complex problem in mechanics that should address the poromechanical behaviour of the resource bearing formation and the mechanics of the particulate proppant. To date there are no advanced developments of this kind that have been proposed in the literature. Some progress can be made by considering the proppant region as a non-deformable inclusion region between the fracture surfaces and to establish the extent of the open region of the fractured surfaces, which ultimately controls the effective permeability of the aperture [1-5]. The resource bearing formation is treated as an elastic medium and the conditions related to the end of hydraulic fracturing and long term configuration of the opened fracture can be gleaned by assigning either undrained or fully drained elasticity parameters for the skeletal response of the resource bearing formation. This paper presents certain theoretical developments that could be used to estimate the geometry of the zone of separation at a fracture kept open by the proppant occupying an arbitrary zone.

[1] Selvadurai APS (1994) A contact problem for a smooth rigid inclusion in a penny-shaped crack, Journal of Applied Mathematics and Physics (ZAMP), Vol. 45, pp. 166-173.
[2] Selvadurai APS (1994) Separation at a pre-fractured bi-material geological interface, Mechanics Research Communications, Vol. 21, pp. 83-88.
[3] Selvadurai APS (1994) A unilateral contact problem for a rigid disc inclusion embedded between two dissimilar elastic half spaces, Quarterly Journal of Mechanics and Applied Mathematics, Vol. 47, pp. 493-510.
[3] Selvadurai APS and Mahyari AT (1997) Some moving boundary problems associated with poroelastic media, in Moving Boundaries IV (R van Keer and CA Brebbia Eds.) 251-261, Comp Mech Publ, Southampton.
[4] Selvadurai APS (2003) On an invariance principle for unilateral contact at a bi-material elastic interface, International Journal of Engineering Science, Vol. 41, pp. 721-739.

Poro-elastic damage modeling applied to wellbore hydraulic stimulation

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During hydraulic stimulations, a complex interaction is observed between the injected flux and pressure, number and magnitude of induced seismic events, and changes in seismic velocities. Our modeling of the formation and propagation of damage zones and seismicity patterns induced by wellbore fluid injection include the coupling of poro-elastic deformation and groundwater flow with damage evolution (weakening and healing) and its effect on the elastic and hydrologic parameters of crystalline rocks. Numerical modeling demonstrates that damage originates around the injection well and thereafter propagates away accompanied by seismic activity. The direction of the elongated damage zone is close to the main principal stress orientation. The process occurring during constant fluid injection can be divided into three stages. The duration of each stage depends on the hydrological and mechanical parameters. Initially, fluid flows into the rock with no seismic events. At this stage, damage increases up to failure conditions. Thereafter, the occurrence of seismic events and faulting begins and accelerates. The velocity of the advancing damage is limited only by the rock parameters controlling damage evolution. At the third stage, the damage decelerates because fluid transport becomes a limiting factor as the damage zones are too long to efficiently transfer the pressure from the well to the tip of the damage zones. The time and distance of propagation depend on the damage-permeability coupling and the remote shear stress. Higher remote shear stress causes shorter initial periods of no seismicity; strong damage-permeability coupling causes longer acceleration stages. Typically, after a flux increase, the wellbore pressure also rises to satisfy the flux conditions. Thereafter, the elevated pore pressure triggers damage accumulation and seismic activity that is accompanied by permeability increase. As a result, wellbore pressure decreases retaining the target injected flux.

?Dry-out' phenomena on initial experimental study of microscale supercritical CO2 displacement

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As a continuous stream of CO2 is injected into a saline aquifer, the water is continuously extracted from the brine and evaporated into CO2. Previous researches of this dry-out phenomena presented simulations to illustrate, but laboratory experimental description of pore-scale is rarely reported. Up-to-date, a series of pore-scale visualization of the CO2-water displacement experiments were conducted in a near?homogeneous water-wet micromodel with precisely micro-fabricated pore structures. A high-pressure micromodel experimental system was modified to allow the entire system to be pressure and temperature controlled to make CO2 into supercritical state. The CO2 displacement processes in the micromodel under 1305 psi and different conditions, including different temperatures (from 40 to 80 °C) and different flow rates (from 10 to 5000?L/h), were investigated by using fluorescent microscopy. As a result, when injecting pure CO2 (which is called ?dry-CO2') into water on micromodel which is initially saturated with water, under a low injection rate (e.g., 10 ?L/h), then dry-CO2 entered the pore network in the form of wide forward and lateral flowpaths with clusters of entrapped water, which indicates capillary fingering, and finally obtain a high CO2 saturation. However, when injecting CO2 dissolving water into saturated (which is called ?wet-CO2') under the same scenario, then wet-CO2 front entered the pore network in the form of two narrow forward progressing flowpaths, which can only obtain a much lower CO2 saturation. But under a high injection rate (e.g., 5000?L/h), both of ?dry-CO2' and ?wet-CO2' displacements are controlled by the viscous force of the CO2, and the CO2 entered the pore network at several locations in the form of narrow flowpaths distributed over the entire width of the micromodel, indicating viscous fingering and at last obtain almost the same displacement efficiency. This paper analyzes that injection of pure CO2 into aqua-solution (e.g., saline) can cause dry-out effect when CO2 dissolving and migrating water at the interface between CO2 and water, which is capable of dramatically increasing CO2 saturation and CO2 sweep efficiency. Furthermore, the experimental study in this paper is the first focusing on the dry-out effect by CO2 displacing water at pore scale.

Dissolution and compaction instabilities in geomaterials: theory and experiments

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Compaction bands play an important role in reservoir engineering and geological storage. Furthermore, their presence in geological formations may provide useful information on various geological processes. Various mechanisms can be involved at different scales and may be responsible for compaction band instabilities [1,2]. Mechanical and chemical degradation of the grain skeleton and grain crushing are some factors that might lead to compaction band triggering. The purpose of the present study is twofold. On one hand it focuses on the mathematical modeling of chemically induced compaction band instabilities in porous rocks and on the other hand it explores the conditions for compaction band instabilities experimentally.
From the mathematical point of view, the study of compaction bands is a challenging topic. Compaction bands can be seen as an instability of the governing mathematical system leading to localization of deformation [3,4,5]. In a saturated porous rock, the progressive mechanical damage of the solid skeleton during compaction results in the increase of the interface area of the reactants and consequently in the acceleration of the dissolution rate of the solid phase [5]. Thus, the solid skeleton is degraded more rapidly (mass removal because of dissolution), the overall mechanical properties of the system diminish (contraction of the elastic domain ? chemical softening), deformations increase and the solid skeleton is further damaged (intergranular fractures, debonding, breakage of the porous network etc.). By accounting for (a) the mass diffusion of the system, (b) a macroscopic failure criterion with dissolution softening and (c) the reaction kinetics at the micro level, a micromechanical model is proposed. The conditions for compaction band instabilities are investigated (a) theoretically by considering the strong chemo-poro-mechanical coupling due to chemical dissolution [6,7,8,9] and (b) through experiments on an analogous material under oedometric conditions and reactive fluid flow.

References

[1] P. Baud, V. Vajdova, and T. Wong (2006), Shear-enhanced compaction and strain localization: Inelastic deformation and constitutive modeling of four porous sandstones, J. Geophys. Res., 111(B12), 1?17.
[2] P. Baud, S. Vinciguerra, C. David, A. Cavallo, E. Walker, and T. Reuschlé (2009), Compaction and Failure in High Porosity Carbonates: Mechanical Data and Microstructural Observations, Pure Appl. Geophys., 166(5-7), 869?898.
[3] J.W. Rudnicki, and J.R. Rice. «Conditions for the Localization of Deformation in Pressure-sensitive Dilatant Materials.» Journal of the Mechanics and Physics of Solids 23.6 (1975): 371?394.
[4] I. Vardoulakis and J. Sulem: Bifurcation analysis in geomechanics. Blackie. 1995.
[5] J.W. Rudnicki, «Conditions for Compaction and Shear Bands in a Transversely Isotropic Material.» International Journal of Solids and Structures 39.13-14 (2002): 3741?3756.
[6] Rimstidt, J.D., and H.L. Barnes. «The Kinetics of Silica-water Reactions.» Geochimica et Cosmochimica Acta 44.11 (1980): 1683?1699.
[7] I. Stefanou and J. Sulem. «Chemical degradation and compaction instabilities in geomaterials ». In 5th BIOT Conference on Poromechanics (Vol. 33). Vienne. 2013.
[8] L.-B. Hu and T. Hueckel. «Coupled Chemo-mechanics of Intergranular Contact: Toward a Three-scale Model.» Computers and Geotechnics 34.4 (2007): 306?327.
R. Nova, R. Castellanza and C. Tamagnini. «A Constitutive Model for Bonded Geomaterials Subject to Mechanical And/or Chemical Degradation.» International Journal for Numerical and Analytical Methods in Geomechanics 27.9 (2003): 705?732.

Experimental evidence for calcite dissolution and subsequent precipitation in a carbonate rock in presence of supercritical CO2

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Carbon dioxide (CO2) is a greenhouse gas which emission into the atmosphere largely increased throughout the past century. One solution to limit anthropic CO2 concentration in the atmosphere is via sequestration inside natural geological formations. Four possible trapping mechanisms have been identified for gaseous or supercritical CO2 (Izgec et al., 2008). They are ranked by increasing long-term trapping stability:
Stratigraphic trapping: intact CO2 plume underlying a sealing formation; Residual trapping: bi-phasic fluid (CO2 and formation water) in the pore network; Dissolution: CO2 dissolution in the formation water; and Chemical trapping: mineral precipitation.
CO2 is also used for Enhanced Oil Recovery (EOR) because of its affinity with hydrocarbons and because it is commonly produced during oil pumping. The best-case scenario would be combining CO2 EOR and storage. The most appealing CO2 storage mechanism involves mineral precipitation that could improve the mechanical strength of the reservoir. The most appealing CO2 injection scenario for EOR would involve improving oil recovery without affecting the reservoir mechanical resistance and permeability. Under most deep reservoir conditions, the CO2 is in a supercritical phase (e.g. Hangx et al., 2010), with properties somehow between a gas and a liquid.
The present study aims at investigating the role of SuperCritical CO2 (SCCO2) on the integrity and rock physics response of a carbonate rock under controlled laboratory conditions that mimic subsurface scenario. To this end, the petrophysical properties of a natural carbonate rock, the Savonnieres limestone, are characterized prior and after SCCO2 residence. The Savonnieres is a relatively homogeneous clean biogenic limestone (~100% calcite) made up of calcite oolites embedded in a fine-grained, micro-porous, calcite cement. Its over all porosity is f ~ 25 % and its permeability is k ~ 100 mD.
The experimental protocol consists of injecting and maintaining SCCO2 in a brine-saturated specimen for 2 hours (wet2h) or 4 hours (wet4h), under a confining of Pc ~ 15 MPa, and a pore pressure of Pp ~ 12.5 MPa, at T ~ 50°C. Under these conditions, CO2 is in a supercritical state. During the injection phase at one end of the specimen, the sample is imaged using a medical X-ray CT scanner to monitor the fluid distribution in the pore space and the potential textural changes of the solid matrix (resolution ~ 1 mm). At the opposite end of each specimen (wet2h or wet4h), a small amount of pore fluid is sampled prior to SCCO2 injection, and after SCCO2 injection and residence (2h or 4h). The chemical compositions of the produced fluids were analysed to track and quantify the concentration in calcium cations. In addition, to characterise the changes in the specimens' properties, a set of physical measurements were carried out under ambient temperature prior and after SCCO2 residence: (i) pressure dependency of helium porosity and permeability under dry conditions; (ii) pressure dependency of P- and S-wave velocities (Vp and Vs) under dry and brine-saturated conditions; and (iii) pressure dependency electric resistivity (Rt) under dry and brine-saturated conditions.
A (transversal) slice of the sample is chosen far from the injection side for CT monitoring of the injection process. As shown in Figure 1, the evolution in fluids distributions in the sample saturations is reported in terms of (i) mean CT numbers of the rock slice at each time step (i.e. green, blue and orange symbols); and (ii) an imaging software to highlight the densities differences in the slices for the most important steps. The dissolution of SCCO2 in the pore brine can be visualised through the X-ray CT dataset and is related to the expected increase in the pore fluid acidity.

A significant increase in the concentrations of Ca2+ ions were observed in the pore fluid of the specimen wet2h after two hours of SCCO2 residence. Furthermore, the measured physical properties show: (i) decrease in Vp, Vs and Rt at no confining, and increase in their pressure dependency; and (ii) porosity and permeability increase. All measurements thus add up to suggest calcite dissolution from wet2h, i.e., matrix toward the pore fluid.

An even larger increase in the concentrations of Ca2+ ions is observed in the pore fluid of the specimen wet4h after four hours of SCCO2 residence. However, measured Vp, Vs and Rt increase, and porosity and permeability decrease. This suggests that even though dissolution is enhanced in wet4h, an opposite effect from dissolution is also observed from the change in physical properties. It is concluded that the large increase in Ca2+ ions in the pore water lowers the thermodynamic threshold for calcite precipitation in the sample.

Multidisciplinary Shale Gas Research at University College London

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Currently it is estimated that there are about 190 trillion cubic metres of shale gas reserves worldwide (1). Since the 1940s, hydraulic fracturing has been used in the United States to extract this gas and now the same methods are being implemented by countries that also have economically extractable reserves. At University College London five different groups are actively investigating different aspects of shale gas energy, forming the UCL Shale Gas Hub. These different groups approach the issue of shale gas from the following perspectives:

Fracture propagation in shales: To improve the efficiency and safety of shale gas extraction, the factors controlling the extent and geometry of induced fractures must be understood. Fracture toughness is a key control on fracture propagation and is being investigated using both laboratory experiments and associated numerical modelling. This research is being sponsored by ExxonMobil and undertaken by Mike Chandler, Philip Meredith and Nicolas Brantut.

Shale gas production: To reduce the impact of shale gas operations on local communities, research is being undertaken to understand the factors controlling shale deposition, its mechanical properties and gas generation. This research is a collaboration between the Institute of Sustainable Resources (Jabraan Ahmed), the Department of Earth Sciences (Juergen Thurow and Philip Meredith), the London School of Nanotechnology (Neal Skipper) and the UCL Institute of Risk Disaster Reduction (Joanna Faure-Walker).

Gas geochemistry: New approaches using the compositions of carbon, nitrogen and noble gases within shales are being implemented to determine the volumes of extractable gas from free pore space, compared to structurally bound gas in minerals. This research, undertaken by Sudeshna Basu and Adrian Jones and funded by the BG Group, is working towards earlier identification of shale with high gas retention.

Chemical engineering: Within the department of Chemical Engineering at UCL (Alberto Striolo and Tuan Ho), research is focussing on the sustainability and efficiency of gas extraction using hydraulic fracturing. This involves analysing the chemical properties of water, salt and hydrocarbons confined to pore space within shale formations.

Policy for exploiting shale gas: At the International Energy Policy Institute, research is being undertaken to understand how shale gas is currently managed in the United States, where hydraulic fracturing is currently in operation. This information is then being used to create policies to advise countries, such as Australia, on exploiting shale gas reserves. This research is being undertaken by Stefaan Simons and Navinda De Silva at UCL Australia.

Although the individual groups are investigating different aspects of shale gas as an energy source, they combine within the UCL Shale Gas Hub to address the key issues related to the safe and efficient extraction of shale gas. These range from the fundamentals of how shales fracture, through engineering the extraction of gas, to creating policies for countries planning to exploit their own shale gas reserves.

1. Shale gas extraction in the UK: a review of hydraulic fracturing. June 2012. The Royal Society and Royal Academy of Engineering.

What can we learn from ultrasonic velocities monitoring during hydraulic fracturing of tight shale ?

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Methods of predicting crack dimension during hydraulic fracturing of rocks are essential for a proper design of a well stimulation in a field. Several fracture-propagation models have been developed. However, there are only few practical methods of evaluating theoretical work and mostly they have been limited to indirect field measurements. Elastic wave monitoring may be a useful tool. Indeed, the elastic wave velocity of a medium containing a fracture will be sensitive to the fracture geometry and its content: dry or water saturated.
In this paper, we focus on ultrasonic velocities monitoring during hydraulic fracturing of tight shale. The hydraulic fracturing experiment was carried out on Niobrara shale outcrop blocks of 279*279*381 mm in dimensions from Colorado, USA, [Stanchits et al. 2012]. In this experiment, the block was loaded in a polyaxial loading frame made by TerraTek, a Schlumberger Company. Stresses were applied to the rock blocks independently in three directions using flat jacks. Then fluid was injected through a borehole at a constant flow rate. 20 PZT sensors were embedded into pockets drilled in the rock. They were used for the registration of Acoustic Emission (AE) signals and periodical ultrasonic P-wave velocities in different directions.
Our results show that ultrasonic measurements can be useful for understanding the mechanics of the crack growth. More precisely, from the evolution of the P-velocities and their amplitude during the loading, we are able (i) to estimate the velocity of the hydraulic fracture, which was found to be 0.15 mm/s (a result close to the fracture velocity inferred from the AE evolution in space); (ii) in addition, the evolution of the P-velocities during the loading shows that a liquid-free crack always precedes the liquid front. In our experiment, the lag is estimated to be 15 mm. (iii) Finally, at fixed distances from the borehole, we could predict the aperture of the hydraulic fracture, and its evolution during the loading. For example, at 10 cm from the borehole, the aperture reaches a value of 1 mm at the moment of borehole pressure breakdown and decreases slightly to 0.9 mm during fluid pressure drop.
These results shows that ultrasonic velocities monitoring can yield direct measurements of fracture width, length and propagation. These inferred properties of the hydraulic fracture can also provide critical tests of the various theories of fracture propagation.
Reference : S. Stanchits, A. Surdi and R. Suarez-Rivera. Monitoring hydraulic fracturing of tight shale by acoustic emission and ultrasonic transmission techniques. Extended abstract of the 74th EAGE conference, Copenhagen. , Denmark, 4-7 June 2012.

Hydraulic fracturing experiments in large low-permeability rock samples under confining pressure

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Enhanced Geothermal Systems (EGS) still raise great expectations for large-scale geothermal energy conversion. In deep and dense formations the controlled siting and creation of a fracture system still needs to be developed to the point where the engineered fracture system is designed as to serve the purpose of an efficient heat exchanger between the hot dry rock and the steam power plant driving water cycle. We currently develop a fracture propagation code based on the Extended Finite Element Method which we verify against large-scale hydraulic fracturing experiments in the laboratory. Future plans envisage verification of the code in the field and its coupling with an existing heat and mass transport code on the reservoir scale to give a lay-out design tool for deep geothermal fracture systems.
The project, financed by the Federal Ministry for Environment, Nature Conservation and Nuclear Safety, is led by the Institute of Applied Geophysics and Geothermal Energy. The testing facility was planned and constructed by the Chair of Geotechnical Engineering, which is also running the current tests in its laboratories. This contribution presents the current stage of the project's experimental part.
The new testing device enables the initiation of hydraulic fractures in rock samples of size 300 x 300 x 450 mm. Prior to the injection procedure the desired primary stress state has to be set up. Therefore outer pressures up to 30 MPa in vertical and up to 15 MPa in the horizontal directions are applied to the specimen. Afterwards fluid is injected into a centric open-hole by a high pressure syringe pump to initiate a fracture. To reach a stable propagation of the fracture specific injection procedures are run. Stable and slow fracture propagation is of great importance for our purpose to verify the numerical simulations. During the test different measurements are conducted to monitor the fracture propagation. Acoustic emissions are recorded to analyze the fracture growth. Therefore, up to 32 transducers are mounted on the specimen surfaces. For the documentation of the created fractures, the block is split into parts and recorded by a 3D scanning machine.
The conference contribution will present the status of the project with respect to the experimental point of view. Our testing device and its capabilities will be introduced. The main results of our tests will be presented and discussed.

Swelling of coals due to CO2/CH4 adsorption: experimental and modeling investigations

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The purpose of this work is to achieve a better understanding of the coupling between adsorption and swelling in microporous materials. This is typically of utmost importance in the enhancement of non-conventional reservoirs or in the valorization of CO2 geological storage. Indeed, in situ adsorption-induced coal swelling has been identified as the principal factor leading to a rapid decrease of CO2 injectivity during enhanced coal bed methane production by CO2 injection. The coal swelling may close the cleat system and reduce the global permeability. We consider here the case of fully saturated porous solids with pores down to the nanometer size (? 2nm). Hardened cement paste, tight rocks, activated carbon or coal are among those materials.
Experimentally, different authors tried to combine gas adsorption results and volumetric swelling data, especially for bituminous coal. However, most results in the literature are not complete in a sense that the adsorption experiments and the swelling experiments were not performed on the exact same coal sample [1]. Other authors present simultaneous in-situ adsorption and swelling results but the volumetric strain is extrapolated from a local measurement on the surface sample or by monitoring the two-dimensional silhouette expansion [2]. Only elastic and reversible swellings are reported in the literature.
Theoretically, most continuum approaches to swelling upon adsorption of gas rely on a coupling between the adsorption isotherms and the mechanical deformation. A new poromechanical framework [3] has been recently proposed to express the swelling increment as a function of the increment of bulk pressure with constant porosity. However, this framework has to be extended to take into account the porosity evolution upon swelling.
This paper aims at presenting a new experimental set-up where both adsorption and strain are measured in-situ and simultaneously and where the full-field swelling is monitored by digital image correlation. Experiments have been performed on activated carbon fully saturated with CH4 and CO2 at 30°C and up to 120 and 50 bars respectively. Permanent strain and damage are observed.
On the other hand, we present an extended poromechanical framework where the porosity is variable upon swelling. A new incremental nonlinear scheme is proposed where the poromechanical properties are updated at each incremental pressure step, depending on the porosity changes. Interactions between swelling and the adsorption isotherms are examined and a correction to the classical Gibbs formalism is proposed. Predicted swellings are compared with results from the literature and with our own experimental database.

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References

[1] Ottiger et al., 2008, Adsorption, 14 (4): 539-556.
[2] Day et al., 2008, Int J Coal Geol, 74 (1): 41-52.
[3] Vermorel et al., 2013, In: Damage Mechanics of Cementitious Materials and Structures: 19-50.

Effects of fluid injection on a poorly consolidated sandstone ? Part II: acoustic monitoring

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We studied the effect of fluid injection on the mechanical behaviour of a poorly consolidated and layered sandstone, under varying stresses, with micro-seismic (MS) monitoring. In order to highlight possible weakening effects, water and inert oil have been injected into companion samples to assess their effect on strength and elastic properties on critically-loaded samples and to derive the acoustic signature of the saturation front for each fluid. The mechanical data are reported in a companion abstract, the focus of the present abstract is on active and passive acoustic monitoring.

The specimens were instrumented with (i) three contactless axial displacement transducers; (ii) a two-point radial displacement half-ring; and (iii) 16 ultrasonic P-wave transducers (fcentral = 0.5 MHz) directly attached to its cylindrical surface through a Viton sleeve (Sarout et al., 2010). The evolution of P-wave velocity along multiple ray paths, and MS activity were monitored during the whole fluid injection and loading process.

After an over-consolidation hydrostatic loading in dry conditions up to Pc = 25 MPa, the specimen was unloaded and stabilised at Pc = 5 MPa. Two distinct fluid injection experiments were carried out: (i) fluid injection at Pc = 5 MPa (so-called «calibration» test); and (ii) fluid injection under critically loaded triaxial conditions. For both protocols, the specimen was first vacuumed from its top end for about an hour and fluid was injected at its bottom end at a low target fluid pressure of 0.5 MPa. The fluid injection was stopped for an injected volume corresponding to at least one pore volume.
For the calibration test, fluid was injected at Pc = 5 MPa confining pressure. After the injection phase, confining and pore pressures were increased simultaneously to 7 and 2 MPa, respectively, in order to close all potential residual trapped gas bubbles within the saturating fluid. Then, the sample was axially loaded up to failure. This test allowed us to calibrate the end-member properties of the Sherwood sandstone in terms of strength, elastic properties and micro-seismic response. For the second set of experiments, the sample was critically loaded up to 16 MPa differential stress (80% of the dry peak stress) prior to fluid injection.

Water invasion in the pore space induces a significant decrease of the P-wave velocity, whereas oil invasion shows a velocity increase. In the latter case, the observed increase in P-wave velocity is well captured by Biot-Gassman predictions. The velocity decrease associated to water injection is analysed in terms of attenuation mechanisms and associated critical frequencies (Mavko et al., 2003). It is shown that in the 0.5 MHz frequency range, both squirt-flow and patchy saturation are the most likely mechanisms inducing wave attenuation.

For the calibration triaxial test in fully saturated conditions, MS events were spatially located using a homogeneous and transversely isotropic velocity model defined from multiple ray path P-waves measurements (Nadri et al., 2012). MSE hypocenters showed the nucleation of a brittle failure, as previously observed by Stanchits et al. (2011). Post-mortem visual inspection of the damaged samples revealed a good agreement with MS events location.

Under critically stressed conditions, water injection led to a large amount of MS events associated with sample creep and subsequent failure before the specimen was fully saturated. In contrast, oil injection led to very small amount of creep and no significant MS activity.

The recorded MS events were also relocated using the velocity surveys performed along the experiment. However, the spatial location of MS events resulting from fluid injection required a more velocity model more complex than homogeneous transversely isotropic. A Tian ray-tracing method (Tian and Chen, 2005) was used to take into account the velocity heterogeneity due to the fluid front displacement along the sample length. This layered velocity model is updated with time, and the time intervals constrained by the location of the fluid front as inferred from the monitored volume of fluid injected. The model has been calibrated using the velocity measurements obtained during the calibration tests (fluid-saturated end-member). To assess the reliability of the spatial location algorithm, the velocity surveys were used to locate the active sources of known position (ultrasonic transducers). The velocity model has then been applied to locate actual MS with more confidence.

Sarout J., Ougier-Simonin A., Guéguen Y., and A. Schubnel, Active and passive seismic monitoring of shales under triaxial stress conditions in the laboratory, EAGE Shale Workshop, 2010.

Mavko G., Mukerji T. and J. Dvorkin, The Rock Physics Handbook. Cambridge University Press, 2003.

Nadri D., Sarout J., Bona A. and Dresen G., Estimation of the anisotropy parameters of transversely isotropic shales with tilted symmetry axis. Geophys. J. Int., vol. 90, 1197-1203, 2012.

Stanchits S., Mayr S., Shapiro S. and Dresen G., Fracturing of porous rock induced by fluid injection. Tectonophysics, vol. 503, 129-145, 2011.

Tian, Y. and X.F. Chuen, A rapid and accurate two-point ray tracing method in horizontally layered velocity model. Acta Seismologica Sinica, vol. 18, 151-164, 2005.

Geomechanical aspects of tensile stimulation treatment in a EGS Geothermal reservoir

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Enhanced Geothermal System (EGS) are characterized by low natural permeability that must be enhanced to enable commercial flow rates, which are high enough to achieve the target set for heat extraction and/or power production. In this study the focus is on the evaluation of poroelastic response of the rock mass due to a tensile fracture generated by injection of cold fluid at a pressure high enough to overcome minimum in-situ stress and tensile strength of the rock. Numerical investigation has been performed to understand treatment data recorded on the field with respect to seismicity and to water level change in a nearby well.
Correctly forecasting the rock mechanical response due to the stimulation treatment in terms of local stress and pore pressure change allows to design effective treatment while mitigating unwanted seismicity.
A relevant role in evaluating the effectiveness of the stimulation is played by the "cloud" of microseismic events recorded during the stimulation treatment. More than 10'000 microseismic events have been recorded for a single multi-day stimulation treatment in natural fractured rocks at different sides worldwide. Maximum magnitude recorded for events triggered by geothermal stimulation treatment ranged from -3 up to 3, from purely instrumental to human felt seismicity. Investigation of seismic response to the treatment is therefore a powerful tool to understand the correct development of the operations and at the same time to reduce a potential harm to the project. Understanding why this response shows distinct temporal and spatial patterns, requires to investigate the complex rock-fluid interaction taking place.
SOME OBSERVATIONS FROM GROß SCHÖNEBECK RESEARCH WELL
In August 2007, Groß Schönebeck well was stimulated with a waterfrac treatment lasting five days. Injection of fluid cycled between low and high rate, up to 150 L/s, for a total fluid injected volume of 13'170 m^3, with recorded wellhead pressure up to 58.6 MPa.
Two faults are located respectively to the east and to the west side of the new generated fracture. Both of them were expected to show microseismic activity during the treatment, being favourably oriented to accommodate shearing in the tectonic stress regime of the target reservoir and surrounding rock. However, the eastern one did not show any micro-seismic signals in response to the treatment, while the western fault showed very low micro-seismic activity: about 50 events were recorded but only 30 could be located. Average and maximum moment magnitude for the located events is -1.3 and -1, respectively. The silent fault is located between the stimulated well and a nearby well. This well was equipped with a three component seismometer and a water level recording unity for the complete duration of the stimulation treatment. The measured water level reflects the pressure in the target reservoir.
Sudden increase of water level associated with increase in injection rate have been observed in the monitoring well, suggesting the presence of a geological feature hydraulically connecting the two wells, possibly being the aforementioned silent fault. However, successive tests failed to show communication between the wells, raising questions about hydraulic behaviour of the fault.
A coupled hydro-mechanical model is proposed to discuss the presence of geological features hydraulically and mechanically connecting the two wells.

Effects of fluid injection on a poorly consolidated sandstone ? Part I: mechanical weakening

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We studied the effect of fluid injection on the mechanical behaviour of a poorly consolidated and layered sandstone, under varying stresses, with micro-seismic (MS) monitoring. In order to highlight possible weakening effects, water and inert oil have been injected into companion samples to assess their effect on strength and elastic properties on critically-loaded samples and to derive the acoustic signature of the saturation front for each fluid. The acoustic monitoring data are reported in a companion abstract, the focus of the present abstract is on the mechanical tests and the weakening effect of water.

In order to assess water weakening effects in reservoir rocks, previous studies have focused on changes in the failure envelopes derived from triaxial tests conducted with rocks saturated either with water or with inert fluid or gas (Baud et al., 2000). As little attention has been paid so far on the mechanical behaviour of stressed rocks during water injection, we propose a different protocol for studying the water weakening effect in water injection tests (Stanchits et al., 2011). The selected rock for this study was the Sherwood sandstone, a weakly consolidated sandstone sampled on an outcrop at Ladram Bay in UK. This sandstone is actually the reservoir host rock for the Wytch Farm Oil Field operated by Perenco.

In a first stage we studied the kinetics of water front propagation in capillary imbibition tests at room conditions with acoustic velocity monitoring and X-ray CT scan techniques, in order to get knowledge on (i) the imbibition kinetics, (ii) the geometry of the water front and (iii) the evolution of P wave velocity when water is rising into the rock sample.

In a second stage a triaxial test was conducted on a dry sample at low confining pressure (5 MPa) after a consolidation cycle up to 25 MPa (below the effective critical pressure P*=39 MPa). The objective of this test was to get the compressive strength of the dry Sherwood sandstone (20 MPa). Another triaxial test on a water saturated sample under the same conditions showed that the mechanical strength is significantly lower (14 MPa) and thus water weakening effects are important in the Sherwood sandstone.

In a third stage creep tests were conducted on dry samples loaded at the same confining pressure (5 MPa) and an axial load corresponding to 80% of the compressive strength. While these conditions are kept constant, the specimen was first vacuumed from its top end for about an hour. Then a fluid is injected at the bottom end of the sample with a low back pressure (0.5 MPa) to minimize effective pressure variations during the test. This was done firstly using water as the pore fluid, secondly using fluorinert, an inert oil. During these experiments the specimens were instrumented with (i) three contactless axial displacement transducers; (ii) a two-point radial displacement half-ring; and (iii) 16 ultrasonic P-wave transducers (fcentral = 0.5 MHz) directly attached to its cylindrical surface through a Viton sleeve (Sarout et al., 2010). The evolution of P-wave velocity along multiple ray paths, and MS activity were monitored during the whole fluid injection and loading process.

As soon as fluids start to propagate into the samples, creep is taking place with a much higher strain rate for water injection compared to oil injection. A transition from secondary creep to tertiary creep is observed in the water injection test when a volume corresponding to only 18% of the pore volume has been injected. In the oil injection test no significant creep acceleration is observed after one pore volume of oil was injected. The most remarkable difference is that water invasion in the pore space induces failure, whereas oil invasion does not. This was confirmed by the analysis of acoustic emissions activity and post-mortem sample imaging using CT scan. Contrasting evolutions of the P wave velocity during the fluid front propagation were also observed in both experiments.

Baud, P., Zhu, W. and Wong, T.f., Failure mode and weakening effect of water on sandstone, J. Geophys. Res., 105, 16371-16389, 2000.

Sarout J., Ougier-Simonin A., Guéguen Y., and A. Schubnel, Active and passive seismic monitoring of shales under triaxial stress conditions in the laboratory, EAGE Shale Workshop,

2010.
Stanchits S., Mayr S., Shapiro S. and Dresen G., Fracturing of porous rock induced by fluid injection. Tectonophysics, vol. 503, 129-145, 2011.

Hydraulic fracturing DEM model

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A fully coupled hydro-mechanical 3D discrete elements model (YADE DEM open source software, https://yade-dem.org/doc/) able to deal with the progression of cracks within the rock matrix in presence of a discrete fracture network has been adapted and used to study the hydraulic fracturing in rock for shale gas production or geothermal energy. The objective here is to grasp the role of the rock-bridges failure on the propagation of the main fluid driven fracture under different stress fields and pre-existing fracture orientations.
The intact rock is modeled by a discrete element method (DEM) able to reproduce fracture initiation and propagation, rock brittleness, texture effect and macroscopic non-linear failure envelopes [Scholtès & Donzé 2013]. The pre-existing fractures are explicitly modeled as a discrete fracture network (DFN) plugin and their response is fully coupled with the DEM model [Scholtès & Donzé 2012; Harthong et al. 2012]. Finally, the fluid and it's interaction with the intact and fractured rock is modeled by means of a Pore-scale Finite Volume (PFV) scheme [Catalano et al. 2013] specially enhanced for fractured rock modeling.
A series of hydraulic fracturing simulations were performed on a stress loaded medium. The proposed method provides a spatio-temporal distribution of the induced events which can be recorded during the simulations, making possible the identification of the local mechanisms controlling the resulting stimulated volume.

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References:
- Scholtès L., Donzé F.V. (2013). A DEM model for soft and hard rocks: role of grain interlocking on strength. Journal of the Mechanics and Physics of Solids (61), pages 352?369.
- Scholtès L., Donzé F.V. (2012). Modelling progressive failure in fractured rock masses using a 3d discrete element method. International Journal of Rock Mechanics and Mining Sciences (52), pages 18?30.
- Harthong B., Scholtès L., Donzé F.-V. (2012). Strength characterization of rock masses, using a coupled DEM-DFN model. Geophysical Journal International (191), pages 467-480.
- Catalano E., Chareyre B., Barthélémy E. (2013). Pore-scale modeling of fluid-particles interaction and emerging poromechanical effects, International Journal for Numerical and Analytical Methods in Geomechanics (in press).

Hydro-mechanical properties of chemically altered limestones using 2D and 3D Full-Field multi-scale investigations

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Geological storage of CO_2 by injection within deep saline aquifers is one of the solutions for the reduction of the greenhouse effect related to human activity. These reservoirs present a huge storage capacity, because they are several hundreds of meters thick and widely spread, such as the Dogger formation. The constitutive carbonate rocks are quite porous (10-30%) and characterized by high permeability, which is a necessary parameter for reliable injection. However, the long term hydro-mechanical behavior of the carbonaceous rocks subjected to the presence of aggressive fluids (CO_2 saturated brine) is still unclear. Therefore, in order to ensure the long term integrity of such reservoirs, studies of the effect of chemical alteration on the hydro-mechanical properties of carbonates are needed. This is the purpose of the present work, with specific focus on the relatively homogeneous Lavoux carbonates.
The rocks were subjected to a complex protocol alternating retarded acid treatments and brine flushing, in order to allow homogeneous alteration. The flow characteristics of the intact and altered rocks were combined with microstructural investigations. Post mortem SEM imaging evidenced the dissolution processes. The understanding of the nontrivial relationships between monotonous porosity increase with alteration cycles and fluctuating permeability was allowed by contrast absorption X-ray tomography (MCT) and image processing techniques. We clearly observed the in-situ presence of fine mobile particles, which may cluster and restrict pore throat access. Those particles were also filtered out from the flushing effluents.
The evolution of the mechanical behavior of the altered rocks was studied by 1) classical macroscopic triaxial tests, 2) multi-scale uniaxial tests combined with either optical or SEM observations and consecutive digital image correlation (2D-DIC), and 3) triaxial tests combined with in-situ MCT and digital volume correlation (3D-DVC). The latter tests were performed with a specifically designed miniature triaxial cell (5-10 MPa confinement), fitting within a microtompgraph.
The alteration leads progressively to decaying shear moduli and to the transition from brittle to ductile type of failure. The DIC and DVC analysis allowed characterizing the full strain fields all along the loading history, to focus on the localization areas and to identify the deformation/ damage modes. For example, at increasing alteration levels we could observe the transition from fragile shear fractures to sharp and ultimately to wide compaction shear bands.

Modelling hydraulic fracturing in shale ? from the lab to the reservoir scale

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Pressure-driven fracturing, also known as hydraulic fracturing, is a process widely used for developing geothermal resources, extracting hydrocarbons from unconventional reservoirs such as tight sandstone and shale formations, as well as for preconditioning the rock-mass during deep mining operations. While the overall process of pressure-driven fracturing is well understood, a quantitative description of the process is difficult due to both geologic and mechanistic uncertainties. Among them, the simulation of fractures growing in a complex heterogeneous medium is associated with computational difficulties. Experimental evidence based on micro-seismic monitoring clearly demonstrates the important influence of rock mass fabric on hydraulic fracture development, and the interaction between fluid-driven fractures and pre-existing discontinuities. However, these components are not well accounted for by standard numerical approaches. Thus, the design of hydraulic fracturing operations continues to be based on simplified models whereby the rock mass is treated as a homogeneous continuum. The purpose of this paper is to present the preliminary results obtained using the combined finite-discrete element (FDEM) technology to study the interaction between fluid driven fractures and natural rock mass discontinuities. The numerical models have been calibrated against hydraulic fracturing laboratory observations, which include the spatial material heterogeneity, the evolution with time of the geometry of the cracks, as well as the microseismicity associated with the cracking. The lab scale calibrated numerical models have been then extended to wellbore scale simulations and the influence of pre-existing discontinuities and bedding planes has been numerically assessed and successfully compared to available field data.

Stress field variations obtained from focal mechanisms of induced seismicity at The Geysers geothermal field: Geomechanical implications

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Studying spatio-temporal variations of the stress field orientation caused by massive fluid injection is relevant towards an improved understanding of geomechanical processes in different types of geo-reservoirs. However, a reliable determination of rotated principal stress axes based on inversion of focal mechanisms of induced seismicity requires dense local seismic networks with good azimuthal coverage and low magnitude-detection threshold.
In this study, we aim to determine potential spatial and temporal variations of the local stress field orientation at The Geysers geothermal field using fault plane solutions of local seismic events located by the Northern California Earthquake Data Center. To determine the deviatoric stress tensor and the relative stress magnitude we apply a linear stress inversion scheme involving a complete uncertainty assessment at 95% confidence by using bootstrap resampling of the original input focal mechanisms. The software package is essentially an updated version of the SATSI stress inversion algorithm (Hardebeck and Michael, 2006) that includes several additional features and that is freely available (MSATSI package, Martinez-Garzon et al., subm.).
We investigate the stress field orientation at different depth levels using high quality focal mechanisms of induced seismicity distributed over the whole reservoir. The results indicate a clear change in the stress field regime at reservoir depth (normal faulting regime) with respect to above and below (strike-slip regime). These observations are interpreted to represent the reduction of horizontal stresses due to the long-term depletion of hydrocarbon and geothermal reservoirs (Segall and Fitzgerald, 1998). This is also supported by the relative changes of the principal stress magnitudes (R value).

We also study potential temporal variations of the stress orientation related to flow rates during reservoir stimulation analyzing data from a prominent seismicity cluster associated with an Enhanced Geothermal System within the reservoir. The results show a clear correlation between significant changes in the stress field orientation and peak-flow rates of fluid injected into the reservoir (Martínez-Garzón et al., 2013) (Fig. 1). These observations are interpreted to either reflect the reactivation of pre-existing NE-trending cracks or the opening of new fractures through hydro and/or thermal fracturing processes. A geomechanical explanation of the stress rotation based on the increase in the horizontal stresses due to the fluid injection is provided.

In this study we discuss potential mechanisms responsible for the induced seismicity at The Geysers Geothermal Field assuming that the crust is critically stressed and close to failure. Seismicity may be connected with the thermal fracturing of the reservoir rock associated to cooling from fluid injection, or to pore pressure increase due to the injection of fluid. We assume that increases in the pore pressure result in the increase in the magnitude of horizontal stresses, as pointed out by Segall and Fitzgerald (1998).

References:

Hardebeck, J. L., and A. J. Michael (2006). Damped regional-scale stress inversions: Methodology and examples for southern California and the Coalinga aftershock sequence, J. Geophys. Res. Solid Earth 111, no. B11, B11310, doi 10.1029/2005JB004144.
Martínez-Garzón, P., M. Bohnhoff, G. Kwiatek, and G. Dresen (2013). Stress tensor changes related to fluid injection at The Geysers Geothermal Field, California, Geophys. Res. Lett. 2596-2601, doi 10.1002/grl.50438.
Martínez-Garzón, P., G. Kwiatek, M . Ickrath and M. Bohnhoff . MSATSI: A MATLAB© package

for stress inversion combining solid classic methodology, a new simplified user-handling and a visualization tool (submitted to Seism. Res. Lett.).
Segall, P., and S. D. Fitzgerald (1998). A note on induced stress changes in hydrocarbon and geothermal reservoirs, Tectonophysics 289, no. 1?3, 117?128, doi 10.1016/S0040-1951(97)00311-9.

Fluid Extraction Processes (Petroleum Engineering, Gas/Shale, ...)

A more robust experimental determination of Thomsen's anisotropy parameters ? The ? parameter

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Shales are extremely variable in terms of physical, mechanical and chemical properties. The relationships between these properties and the petrophysical measurements performed downhole and/or in the laboratory are generally not straightforward. The current understanding of the elastic properties and associated anisotropy of shales is particularly insufficient in view of the need for such information in field applications like 4D seismic monitoring or exploration. This is due to a combination of several factors including: (i) availability of a limited number of measurements caused partly by the time-consuming nature of laboratory testing which results from shales' extremely low permeability (nanoDarcy range) and partly by the lack of well-preserved samples; and (ii) the fact that among the scarce amount of laboratory data available in the literature, only few experiments were performed under realistic in-situ conditions, especially in terms of specimen's preservation, pore fluid saturation, and pore pressure control. The core of this paper relies on a comprehensive laboratory investigation of the elastic anisotropy aspect of shales. In particular, we will focus on ultrasonic data acquired in the laboratory using an array of ultrasonic transducers attached to the shale specimen. These data are interpreted in terms of Thomsen's anisotropy parameters (Thomsen, 1986) using a novel inversion algorithm published recently by Nadri et al. (2012). Particular emphasis is put on the ? parameter that controls the geometry of the propagating wave front, and plays a crucial role in field applications such as amplitude versus offset (AVO), vertical seismic profile (VSP), seismic tomography or ray tracing (Brevik et al., 2007).

The novel aspect of this experiment and associated interpretation method as compared to similar work published in the literature (Podio et al., 1968; Jones and Wang, 1981; Lo et al., 1986; Vernik and Nur, 1992; Hornby, 1998; Wang, 2002; Dewhurst and Siggins, 2006, Sarout and Gueguen, 2008, Delle Piane et al., 2011) is the fact that the determination of two Thomsen's anisotropy parameters, namely ? and ?, is now based on an over-determined number of independent P-wave velocity measurements along numerous ray paths on the same shale specimen, rather than on only three P-wave velocities including a single off-bedding propagation path. This is particularly crucial for the accurate and reliable assessment of the ? parameter which in the past was determined through the measurement of a single P-wave velocity propagating at 45° off the shale bedding plane. The use of a single off-bedding velocity to determine ? (see Fig. 1) raises the question of whether this determination is accurate enough for comparison with field data. While in the field, P-wave velocities can be estimated along many different ray paths, in the laboratory, only a single off-bedding velocity is usually reported. The claimed large difference in the magnitude of Thomsen's ? parameter determined in the laboratory and observed in the field (Leany, 1994; Brevik et al., 2007) triggered this need for a better assessment of this specific anisotropy parameter at the laboratory scale.

To this end, two similar cylindrical shale specimens are sampled perpendicular to the bedding plane from preserved parent cores. Typical sample size is: length L ~ 80 mm; diameter D = 38 mm. Each specimen is subjected to a given stress state following a re-saturation stage. Both specimens are instrumented with ultrasonic transducers directly attached to its surface. Specimen # 1 is equipped with 16 P-wave transducers, whereas Specimen #2 is fitted with the classical array configuration often reported in the literature and involving 6 P-wave transducers and 4 S-wave transducers, with a single ray path off-bedding (see Fig. 1). The estimation of Thomsen parameters from the data for specimen #2 is straightforward (e.g., Dewhurst and Siggins, 2006). For specimen #1, an inversion procedure is required as detailed in Nadri et al., 2012. The results of these two experiments are reported in Table 1. They show a good agreement in terms of P-wave velocity perpendicular to the bedding, ?, and in temrs of P-wave anisotropy, ?; however, a large discrepancy is observed for the ? parameter. This difference is attributed to the over-determined nature of the P-wave velocity measurements available for specimen #1, and as such, it is believed that the ? value found for this specimen is a closer representation of the actual shale property.

A new model to predict intrinsic and apparent permeabilities from pore size distribution in porous materials

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The purpose of this work is to achieve a better understanding of the relationship between damage, failure and the transport properties of porous materials. This is typically of utmost importance in the enhancement of non-conventional reservoirs or in the long-term assessment of the tightness of CO2 geological storage, vessels or containment facilities.
Many authors have looked for predictive models of porous media permeability. Pioneering work by Kozeny [1] related the permeability to the porosity, the tortuosity and an average pore size. Later on, Katz and Thompson [2] predicted the permeability from the electrical conductivity of the porous material through a critical pores radius. There are also several more recent studies in which the pore size distribution (PSD) was modeled, e.g. with a bimodal or multimodal distribution, and then entered into some capillary bundle model.
Usually, analyses are restricted to intrinsic permeability of the material and the evolution of the apparent permeability, with respect to the pressure gradient and to the nature of the fluid considered are left aside. This paper aims at presenting a new model capable to provide estimates of the apparent permeability directly from the PSD measurements and from the properties of the fluid to be considered. The intrinsic permeability and the evolution of the apparent permeability with mean pressure are provided by combining Darcy [3], Poiseuille [4] and Knudsen [5] laws, which represent respectively the macroscale flow, the microscale viscous flaw and the microscale diffusion flow in the porous media.
In order to achieve a porous network in the material, which is consistent with a mercury intrusion technique, random generation of pores is implemented. The technique yields a hierarchical porous network, which mimics the porous space measured experimentally.
Comparisons with experimental data acquired on mortar specimens show that the model is able to reproduce both the intrinsic and the apparent permeabilities and their evolution when the material is subjected to mechanical damage, provided the PSD are available. Test data with several types of gases compare quite well with the model.
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References
[1] Kozeny. 1927. Über kapillare Leitung des Wassers im Boden. Wien, Akad. Wiss, 136 (2a): 271.
[2] Katz and Thompson. 1986. Quantitative prediction of permeability in porous rock. Phys Rev, 34 (11): 8179-8181.
[3] Darcy. 1856. Les fontaines publiques de la ville de Dijon. Paris: Dalmont.
[4] Poiseuille. 1840. Recherches expérimentales sur le mouvement des liquides dans les tubes de très petits diamètres. C. r. hebd. séances Acad. sci., T11 (1): 1041-1048.
[5] Steckelmacher. 1986. Knudsen flow 75 years on: the current state of the art for flow of rarefied gases in tubes and systems. Rep Prog Phys, 49 (10): 1083.

Seismic attenuation at low frequencies in partially saturated rocks: what we have learnt, and new prospective

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Low frequency wave attenuation (1/Q at f In the last five years, employing the Broad Band Attenuation Vessel (BBAV), we have investigated the attenuation related to the frame and the saturating fluids in Berea sandstone. We have also studied the fluid pressure transient caused by a sudden increase of stress (1 in Fig 1a; Tisato and Madonna, 2012; Tisato et al., 2013; Tisato and Quintal, 2013). In particular, we have better understood the relationships between 1/Q and i) saturation, ii) confining pressure, and iii) strain. Especially, combining laboratory and numerical results, we have demonstrated that wave induced fluid flow (WIFF) on the mesoscopic scale is responsible for the large, and frequency dependent attenuation observed in the laboratory measurements of a partially saturated sandstone (Fig 1b).
However, the behavior of attenuation as a function of distribution of fluids in the pore space still needs further study. In particular, the imaging of the i) internal structure of the rock and the ii) distribution of the fluids in the pore space, combined with the laboratory measurements, could strongly aid the understanding of wave induced fluid flow mechanisms.
This contribution summarizes the main results obtained in the last five years at ETH Zurich employing the BBAV and their relevance in geophysics. In particular, for Berea sandstone, we show that:
1) 1/Q becomes frequency dependent and high as 0.08, in the bandwidth 1-100 Hz, if the rock is partially saturated;
2) 1/Q varies with confining pressure (Pc) and becomes very low and frequency independent after a certain Pc threshold;
3) for a strain ranging between 0.7 and 20×10-6 the frame related 1/Q is strain sensitive while the fluid related 1/Q can be considered strain insensitive;
4) the results have been modeled and explained with theoretical models.
Finally, we present and discuss how the use of X-Ray computed tomography (CT), combined with a newly designed high pressure vessel (2 in Fig. 1a), will allow measuring 1/Q and complex elastic moduli simultaneously with the imaging of the internal structure of the rock (Fig. 1a). The vessel is X-Ray transparent and can fit into a CT scanner installed at the University of Toronto (3 in Fig. 1a). This technological development, together with the results already obtained, enriches the knowledge of seismic wave attenuation mechanisms for partially saturated rocks.

References

Mavko, G. (2009), The rock physics handbook: tools for seismic analysis of porous media, 2nd ed., Cambridge University Press.

Spencer, J., Jr. (2013), Viscoelasticity of Ells River bitumen sand and 4D monitoring of thermal enhanced oil recovery processes. Geophysics, 78(6), D419?D428. doi: 10.1190/geo2012-0535.1

Tisato, N., and C. Madonna (2012), Attenuation at low seismic frequencies in partially saturated rocks: Measurements and description of a new apparatus, Journal of Applied Geophysics, 86, 44?53, doi:10.1016/j.jappgeo.2012.07.008.

Tisato, N., C. Madonna, and E. Saenger (2013), Seismic wave attenuation for partially saturated sandstone as a function of confining pressure, SEG Technical Program Expanded Abstracts 2013: pp. 2626-2631, doi: 10.1190/segam2013-0301.1

Tisato, N., and B. Quintal (2013), Measurements of seismic attenuation and transient fluid pressure in partially saturated Berea sandstone: evidence of fluid flow on the mesoscopic scale, Geophysical Journal International, 195(1), 342?351, doi:10.1093/gji/ggt259.

Seismic wave attenuation caused by gas dissolution: A new mechanism

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Wave induced fluid flow (WIFF) can cause large attenuation and is governed by the diffusion of fluids into a porous media. Regardless the scale at which the diffusion occurs, the fluid flow is a function of diffusivity [m2/s] and a pressure gradient [Pa/m]. Pressure gradient is caused by the propagation of the seismic wave, and it is responsible for the fluid flow which subtracts energy from the seismic wave (e.g White, 1975). However, some published and recently acquired data-set regarding fully saturated sandstones are difficult to be explained with WIFF theories (e.g. Tisato, 2013).
On the other hand, micro bubbles containing gas might be present in the pore space of rock even when the saturation is considered very close to 100% (e.g. 0.1% of the pore space occupied by gas; Madonna et al., 2013). In an almost fully saturated porous media the strain caused by a seismic wave increases the fluid pressure (Tisato and Quintal, 2013) and preferentially deform these bubbles. Assuming equilibrium between gas and liquid phase prior to the seismic wave propagation, an increase and a decrease of fluid pressure will cause gas dissolution and exsolution, respectively (Cussler, 1997).
Utilizing a kinetic model of spherical gas bubble dissolution, we are able to explain attenuation measurements at tele-seismic to seismic frequencies which cannot be explained with wave induced fluid flow theories (i.e. squirt flow or patchy saturation) (Figure 1; Tisato, 2013).
We believe that the present contribution is of major impact for geophysics because it reports a new attenuation mechanism for saturated rocks operating at seismic and tele-seismic frequencies (Figure 2).

References

Cussler, E. L. (1997), Diffusion: mass transfer in fluid systems, 2nd ed., Cambridge University Press, New York.
Mavko, G. (2009), The rock physics handbook: tools for seismic analysis of porous media, 2nd ed., Cambridge University Press, Cambridge, UK?; New York.
Madonna, C., B. Quintal, M. Frehner, B. S. G. Almqvist, N. Tisato, M. Pistone, F. Marone, and E. H. Saenger 2013: Synchrotron-based X-ray tomographic microscopy for rock physics investigations, Geophysics, 78(1), D53?D64, doi:10.1190/geo2012-0113.1.
Tisato, N. 2013: Experimental characterization of reservoir rocks and geotechnical materials. Low frequency attenuation, ultrasonic velocities and local pore pressure effects, PhD Thesis (Diss. Nr. 21106) ETH Zurich, Switzerland.
Tisato, N., and B. Quintal (2013), Measurements of seismic attenuation and transient fluid pressure in partially saturated Berea sandstone: evidence of fluid flow on the mesoscopic scale, Geophysical Journal International, 195(1), 342?351, doi:10.1093/gji/ggt259.

Quantitative estimation of the effect of clay distribution on the elastic properties of shales

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Clay-rocks are rarely pure clayey materials. They contain in addition to interstitial water, a significant amount of «accessory» minerals (up to 50 wt%), such as quartz and carbonates, which affect their mechanical properties: the content of carbonates and their spatial organization directly are known to impact the failure strength as well as the elastic behaviour of clay-rocks.
In this work, our objective is to study the effects of the clay distribution on the macroscopic-mechanical (elastic) behavior of clay-rock. The approach is based on: (a) mineral maps which are obtained from chemical elements maps acquired by SEM-microscopy coupled with an electron probe microanalyzer and (b) the theoretical works of Hilfer (i.e., Local Porosity Theory-LPT) which allow to infer macroscopic physical properties from a statistical description of the pore-space geometry. Here, LPT is revisited to consider clay-rock as a two-phase mixture consisting of clay matrix and non-clay grains.
Following the ideas of Hilfer, it is assumed that the microstructure and more precisely the spatial clay distribution in clay-rock can be captured by two sets of empirical probability densities: (a) the local shaliness distributions which provides information about shaliness (spatial) fluctuations and (b) the local percolation probabilities which describes clay connectivity fluctuations. Both probability densities and histograms are obtained from a parameter called the «local shaliness » defined as the volume fraction of clay in a square cell (in a 2D sample) of side-length L which is a subset of the total sample. In a practical point of view, these various empirical probability densities are directly calculated from a square lattice (with a lattice constant equal to L) which is obtained by spatial discretization of mineral maps. Moreover, these probability densities can be easily included in effective medium theories.
Consequently, this approach offers two advantages: (1) it introduces geometric observables such as clay fraction and clay connectivity which are easy to measure from mineral maps or images and (2) it can be conveniently used for effective medium calculations of elastic properties of clay-rock.
After a brief description of this new approach, this communication focuses on: (a) a sensitivity analysis on the empirical probability densities and (b) numerical applications performed with a real mineral map obtained from the Callovo-Oxfordian argillites extensively studied for potential repository site of radioactive waste.

What controls the strength and brittleness of shale rocks?

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With respect to the productivity of gas shales, in petroleum science the mechanical behavior of shales is often classified into rock types of high and low ?brittleness', sometimes also referred to as ?fraccability'. The term brittleness is not well defined and different definitions exist, associated with elastic properties (Poisson's ratio, Young's modulus), with strength parameters (compressive and tensile strength), frictional properties (cohesion, friction coefficient), hardness (indentation), or with the strain or energy budget (ratio of reversible to the total strain or energy, respectively). Shales containing a high amount of clay and organic matter are usually considered as less brittle. Similarly, the strength of shales is usually assumed to be low if they contain a high fraction of weak phases.

We performed mechanical tests on a series of shales with different mineralogical compositions, varying porosity, and low to high maturity. Using cylindrical samples, we determined the uniaxial and triaxial compressive strength, static Young's modulus, the tensile strength, and Mode I fracture toughness.

The results show that in general the uniaxial compressive strength (UCS) linearly increases with increasing Young's modulus (E) and both parameters increase with decreasing porosity. However, the strength and elastic modulus is not uniquely correlated with the mineral content. For shales with a relatively low quartz and high carbonate content, UCS and E increase with increasing quartz content, whereas for shales with a relatively low amount for carbonates, but high quartz content, both parameters increase with decreasing fraction of the weak phases (clays, kerogen). In contrast, the average tensile strength of all shale-types appears to increase with increasing quartz fraction. The internal friction coefficient of all investigated shales decreases with increasing pressure and may approach rather high values (up to ? 1). Therefore, the mechanical strength and elasticity of shales is not simply related to the total clay and kerogen content, but depends mainly on porosity and composition, including mechanically strong (quartz, pyrite), intermediate (calcite) and weak (clay, organics) minerals.

The investigated shales show typical semibrittle behaviour with increasing ductility with increasing pressure and temperature and decreasing strain rate. Under similar conditions, the mechanical behavior is mainly controlled by porosity and ? within the investigated range of pressure and temperature - relatively unaffected by mineral content. We conclude that the correlation between brittle strength and mineralogy is strongly formation depended, but high porosity generally promotes ductile creep at lower strength. Complete shale constitutive laws are required to allow extrapolation of the test results to the production timespan of unconventional reservoirs.

Thermal and Geothermal Processes

Experimental measurements of dilatancy and permeability evolution during triaxial compression of micro-gabbro and implications for hydrothermal circulation at the mid ocean ridge.

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The brittle to ductile transition in rocks may strongly influence their transport properties (i.e. permeability, porosity, topology...) and the maximum depth and temperature where hydrothermal fluids may circulate. To examine this transition in the context of Icelandic crust, we conducted deformation experiments on a micro-gabbro (initial porosity

Advanced THM Testing of Rocks Related to Canadian Used Nuclear Fuel Management

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Thermo-hydro-mechanical (THM) processes in rocks are increasingly important research topics, mainly due to the demands for the design, construction, and performance of underground repositories for radioactive waste, and other civil engineering works such as underground storage caverns and geothermal energy extraction. The Canadian used nuclear fuel management organization (NWMO) is considering siting a Deep Geological Repository (DGR) for the long-term containment and isolation of used nuclear fuel in a suitable rock formation of either in sedimentary or crystalline rock at a depth of approximately 500 meters. This paper presents briefly the current state of the used nuclear fuel management in Canada. Details are then given of advanced coupled hydro-mechanical and thermo-hydro-mechanical experiments on Lindsay limestone, which is a common sedimentary rock type in Southern Ontario, Canada.

The coupled THM experiments were performed within a loading cell, which was geophysically instrumented, under hydrostatic and deviatoric stresses. In addition, the test specimens were subjected to temperatures at ambient and elevated temperatures up to 150ºC. During the experiment, under the coupled thermo-mechanical loading, seismic wave velocities were measured. In the paper, variations and differences in the evolution of these velocities, during various stages of the experiment, are discussed. It is shown that these correspond to the heterogeneous and anisotropic nature of the specimens. The velocities were observed to be influenced by microcracks caused by the heating. This damage was in addition to the progressive fracture growth during the deviatoric loading stage, which subsequently led to the failure of the specimens. The measurement of the elastic wave velocities is a way to observe the effect of dilatancy earlier compared to what is interpreted from the evolution of the volumetric strain calculated from the strain measurements. Permeability of the specimens was measured using a pulse decay method. Permeability was observed to decrease during the heating stage. As the test continued, with mechanical loading, the permeability increased beyond compaction and even more after the emergence of axial cracking.

The results from these experiments show the dependency of the mechanical and transport properties of the Lindsay limestone to the applied temperature and stresses. There is a self-consistent behaviour among the evolution of seismic wave velocities with the hydrostatic stresses, heating, mechanical loading, and transport properties of the rock. These experiments are crucial to model the various stages of hydro-mechanical and thermo-hydro-mechanical conditions in order to understand the relationship between types of stresses in relation to the deformational responses of sedimentary rocks.

Effective Pressure Dependence of Fracture Permeability

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The efficiency of geothermal energy provision predominantly relies on the hydraulic performance of cracks and fractures preexisting or artificially created within the reservoir. During fluid production, effective pressure on fracture planes increases. In turn, so induced rock elastic responses should decrease fracture permeability and thus well productivity.

For quantifying this effect and concurrent transient phenomena a series of mechanical experiments was conducted in a conventional triaxial deformation apparatus under hydrostatic loading conditions. Three types of reservoir analog rocks, one sandstone (Flechtinger, Rotliegend) and two carbonate rocks (Neuburger Bankkalke [I] and Treuchtlinger Marmor [II], both Malm), were prepared in cylindrical shape and were then either saw-cut or split along the main axis in a Brazilian test to create an artificial fracture. Sample porosity was determined by weighing the dry and wet sample mass and by He-pycnometry before each test. Matrix water permeability was measured as a function of effective pressure before cutting or fracturing. Fracture width was measured optically both before and after testing. The mechanical tests were conducted at room temperature by cycling effective pressure between 2 and 40 MPa several times and measuring sample water permeability in defined pressure intervals. The applied flow rates between 0.25 and 10 ml/min were chosen in accordance with individual fracture conductivities yielding a certain pressure gradient across the sample.

For all rock types permeability decreased with increasing effective pressure. For the Flechtinger sandstone, initially, fracturing yielded a permeability enhancement by a factor of approximately 3 (from 0.2 mD to 0.6 mD). However, the fracture became healed after the first pressure cycle and permeability then was dependent on the poroelastic properties of the rock matrix only with no further transient effects. This behavior, qualitatively, was similar for the saw-cut carbonate sample (type [I]). Permeability was increased from 1 mD to 3 mD by cutting and decreased again to 1 mD after the first pressure cycle. In contrast, the fractured carbonate specimen (type [II]) experienced a significant permeability enhancement by more than five orders of magnitude from 10-3 mD to 500 mD. After the first pressure cycle, permeability was approximately one order of magnitude lower but stabilized at that level with only minor transient effects at subsequent pressure cycles. Fracture permeability, then, changed reversibly from approximately 60 mD at 2 MPa effective pressure to 8 mD at 40 MPa. Variations in flow rate did not alter measured permeabilities.

Characteristic unconfined fracture width before pressure cycling was 50 µm for the sandstone and 200 µm for the carbonate specimen, respectively. Although optical measurements of fracture widths were conducted at ambient pressure observations are in qualitative agreement with the outcome of permeability measurements. For the Flechtinger sandstone the artificial fracture was only hardly visible after the test. For the fractured carbonate specimen (type [II]) fracture width was measured to have decreased after the test by a factor of 2 to 4. Here, along the fracture plane bridging solid contacts can be observed suggesting some degree of slip induced during the Brazilian test itself or at a later stage during pressure cycling. This feature was not observed for the sandstone sample.

In conclusion, the transient response of fracture permeability to changes in effective pressure not only depends on rock type, lithology and fracture geometry but even more on shear on the fracture plane and the inherent mechanical properties of the rock matrix within the pressure limits applied. In turn, small shear offsets on fracture planes can yield positive and sustainable permeability improvements without additional propping agents.

Hydrodynamic characterization of a fractured aquifer using seismic refraction: A case study done on San Cristobal and Santa Cruz islands (Galapagos archipelago)

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Santa Cruz and San Cristobal Islands are the most inhabited of the Galapagos archipelago, Ecuador. They face important water resource problems which might lead to a major impact on their unique and pristine ecosystem. The scarcity of geological and hydrological data combined with the difficulty of access for field measurements lead to a poor understanding of the islands hydrogeology. The Islands are formed by series of thick fractured basaltic lava flows dissected by faults. The low-lying, extensive "basal" aquifer is the unique groundwater body clearly identified on the islands. This basal aquifer is subjected to sea-water intrusion, which has been mapped from electrical resistivity imaging with an airborne electromagnetic SkyTEM survey (D'Ozouville et al. 2008, Pyret et al. 2012).
In order to better understand the hydrodynamic properties of the basal aquifer, we acquired, in 2011 and 2013, geophysical data based on seismic refraction. The experiment was conducted on three study sites on Santa Cruz (P wave) and six sites (P and S waves) on San Cristobal, located at different altitudes above the see level. The P-wave refraction data were obtained using 24 geophones (1 component) and an acquisition system Daklink. A hammer was used as an energy source. This source was the most environmentally friendly source that could be obtained and used in the Galapagos Island. Geophone spacing for the spreads was 2- meters.
From our geophysical data, we could identify the different geological layers that constitute this basal aquifer and to estimate the thickness of these layers. We could as well clearly see the water level in the aquifer. More interesting on the islands, we found a P-wave velocity of ~1600 m/s in the dry fractured basalt lava flow, and a P-wave velocity of ~2700 m/s in the water saturated fractured basalt lava flow. The same velocity values were obtained in the different sites. This tends to show that the elastic properties of the aquifer are homogeneous and isotropic (at the scale of the seismic refraction experiment ~100m). In order to interpret the value of the P-wave velocities, we measured in the laboratory the ultrasonic velocities on non-fractured blocks from the field. By, comparing the ultrasonic and the seismic velocities and using an effective medium model, we are able to 1) estimate the porosity of the aquifer and 2) inferred a mean in situ crack density. Using a cracks/fractures geometry model, we are able to estimate the permeability of the basal aquifer.

Static and dynamic elastic moduli of Malm carbonate rock

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Static elastic moduli were derived from the slope of stress-strain curves in rock mechanical test and dynamic elastic moduli were derived from velocity measurements. A simultaneous measurement of dynamic and elastic moduli was performed in a conventional triaxial set up (see attached figure). The setup was equipped with piezoelectric transducers to measure the acoustic wave velocities. The triaxial setup allows applying a maximum confining pressure of 140 MPa and a maximum temperature of 200 °C. The pore pressure pumps can operate independent of triaxial system. The limestone rock samples, coming from an outcrop analog to a geothermal reservoir in Molasse Basin in South Germany, were used. The confining pressure was cycled between 3 to 80 MPa and temperature increased step wise from 30 to 120 °C. The jacketed and unjacketed experiments were performed and static and dynamic elastic parameters as well as static and dynamic Biot coefficients were measured. The rate of increase in compressional wave velocity with regards to shear wave velocity was higher at unjacketed conditions in comparisons to jacketed conditions. In general the static and dynamic elastic moduli are not equal and the ratio between them is pressure dependent. The dynamic solid bulk modulus was increased linearly with increasing pressure and deceasing temperature.

Thermal microcracking in granite

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The permeability of an efficient geothermal reservoir should be sufficient to permit the circulation of geothermal fluids. Since permeability decreases over the life cycle of the system, it is usually necessary to artificially maintain and enhance the natural permeability of these systems. One of the methods of enhancement ? studied here ? is thermal stimulation (injecting cold water at low pressure). This goal of this method is to encourage thermal cracking within the reservoir host rocks, thereby increasing reservoir permeability. To investigate thermal microcracking in the laboratory we selected two granites: a fine-grained (Garibaldi Grey granite, grain size = 0.5 mm) and a course-grained granite (Lanhelin granite, grain size = 2 mm). Both granites have an initial porosity of about 1 vol.%. Our samples were heated to a range of temperatures (100-1000 °C) and were either cooled slowly (1 °C/min) or shock cooled (100 °C/s). A systematic microstructural (2D crack area density, using standard stereological techniques, and 3D BET specific surface area measurements) and rock physical property (porosity, P-wave velocity, uniaxial compressive strength, and permeability) analysis was undertaken to understand the influence of slow and shock cooling on our reservoir granites. Microstructurally, we observe that the 2D crack surface area per unit volume and the specific surface area increase as a result of thermal stressing, and, for the same maximum temperature, crack surface area is higher in the shock cooled samples. This observation is echoed by our rock physical property measurements: we see greater changes for the shock cooled samples. We can conclude that shock cooling is an extremely efficient method of generating thermal microcracks and modifying rock physical properties. Our study highlights that thermal treatments are likely to be an efficient method for the permeability enhancement of granitic geothermal reservoirs.

Micro-damage of crystalline rocks having subjected to severe thermal and mechanical stress loading

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The investigation of micro-cracks propagation and consecutive damage is one of the most important aspects of rock mechanics and rock engineering studies. Indeed, most of the physical properties of crustal rocks are influenced by cracks whose origin arises from various geological processes; the two main ones being: chemo-thermal processes and tectonic loading (David et al., 1999). The first one is related to variations in temperature, while the second one is associated with stress changes in the rock mass.

Stress damage has been widely investigated over the last few decades and in recent years special attention has been paid to thermal damage in relation to the extraction of geothermal energy or to radioactive waste disposals. Jansen et al. (1993) investigated the development of thermal cracks by continuously monitoring acoustic emissions (AE) generated during thermal cycles in a granite. They showed that these micro-cracks open at temperatures above 80°C, and that micro-cracks can coalesce to form a macroscopic fracture. They concluded that this type of material alteration could have dramatic consequences on the permeability evolution of a nuclear waste disposal repository. Based on laboratory investigations on thermally treated granitic rock, Chaki at al. (2007) showed that thermal damage had a strong influence on porosity, permeability, ultrasonic wave velocity and therefore on rock strength (UCS).

In spite of these broad investigations on the mechanical behavior of thermally and stress damaged rocks, there is still limited research on the mechanisms of damage evolution, especially in thermally treated specimens, where chemical reactions (such as oxidation) and burst of fluid inclusions occur. This might be due to a lack of interdisciplinary research between rock petrology and rock mechanics. Nevertheless, the questions that arise are: What role does the mineralogy of the rock play during progressive damage? What are the chemical processes involved?

In this paper, we focus on laboratory observation of damage induced by ultra-high stress and thermal loading in gabbro specimens. The two types of damage have been analyzed with Optical Miscroscope on thin sections and with X-Ray tomography techniques. All experiments were performed in the labs of the University of Grenoble. The micro-damage mechanisms will be discussed based on an interpretation of the test results. The advantages and disadvantages of both the methods will also be presented and discussed.

Selected References

Chaki S., Takarli M. and Agbodjan, W. P., 2007, Influence of thermal damage on physical properties of a granite rock: Porosity, permeability and ultrasonic wave evolutions, Construction and Building Materials, 22, 1456 - 1461.

Fonseca, J., Bésuelle, P., Viggiani, G., 2013, Micromechanisms of inelastic deformation in sandstones: An insight using x-ray micro-tomography, Geotechnique Letters 3 (April-June), pp. 78-83

Gabet T, Malécot Y, Daudeville L. Triaxial behaviour of concrete under high stresses: Influence of the loading path on compaction and limit states. Cement Concrete Res., 2008; 38: 403 - 412.

Jansen D. P., Hutchins A.D. and Young R.P., 1993, Ultrasonic imaging and acoustic emission monitoring of thermally induced microcracks in Lac du Bonnet granite, Journal of Geophysical Research, 98, 22231 - 22243.

Keshavarz, M., 2009, Contribution to experimental investigations on thermally and mechanically damaged crystalline rocks, PhD Thesis, University Joseph Fourier, Grenoble, France.

Keshavarz M., Pellet F. and Loret B, 2010, Damage and Changes in Mechanical Properties of a Gabbro Thermally Loaded up to 1,000°, Pure and Applied Geophysics, Vol. 167 No. 12, pp: 1511-1523.

Pellet F.L. Keshavarz M., and Amini Hosseini K., 2011, Mechanical damage of a crystalline rock having experienced ultra high deviatoric stress up to 1.7 GPa, Int. J. Rock Mech. Min. Sci., vol. 48, pp 1364?1368.

Pellet F. L., 2013, Thermal and mechanical damage to rocks under different loading conditions and consequences for behavior of underground openings, Scandinavian Rock mechanics meeting, Ed. BeFo, Stockholm, pp 1-13.

Long-term Geological Storage (Nuclear Waste, CO_2, Flowback, ...)

Experimental observations of Crack Propagation in Glass under Creep Condition

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The present work is focused on crack propagation in glass under constant strain rate tests and under creep condition. The aim of our work is to understand the stable brittle creep induced by a sub-critical crack propagation which leads to a progressive failure in tertiary creep.
The experiments are performed in a triaxial cell on thermally cracked boro-silicate glass samples. The initial crack microstructure has been observed with SEM and is well documented. The cell is designed to investigate the mechanical and physical properties of rocks under conditions of effective pressure and deviatoric stress: the confining pressure range is 0 - 100 MPa, and the deviatoric loading is applied through a piston (maximum load of 700 MPa for a sample of 40mm diameter). The effect of the environment can be studied through the pore fluid that can be argon gas, water or other more corrosive fluid. Pore pressure can reach 100 MPa. Temperature is controlled with an accuracy of 0.5°C and can be increased until 100° C. The evolutions of axial and radial strains were measured using strain gages. Elastic wave velocity measurements and acoustic emission were recorded using 16 piezoelectric sensors.
Through constant strain rate tests, we measured i) the maximum mechanical strength and ii) the elastic constants of the cracked glass. Then, the creep experiments are performed at constant confining pressure (15 MPa). The differential stress is increased up to 80% of the maximum strength and is kept constant during 24 hours. Each day, differential stress is increased by 10 MPa steps to reach the failure in a reasonable time. Data are recorded at a frequency of 1 Hz during each of the 24 hours steps at constant stress.
Dilatancy is not observed in constant strain rate experiments but takes place in creep experiments. Dilatancy in brittle creep conditions is a time dependent process. The acoustic emission rate shows that the dilatancy increase is due to stable crack propagation. As a consequence, slow crack growth is evidenced in glass. Failure appears to be a progressive phenomenon in creep condition and post-mortem sample presents a localized failure in a shear plane. This is not observed in constant strain rate experiments.
Increasing temperature increases crack growth rate. The different experiments performed at different temperatures allow determining the activation energy (32 KJ.mol-1). Temperature has also an influence on the sample failure: strain rate increases and the time to rupture decreases. The effect of confining pressure and differential stress is also investigated in order to extrapolate the long time behavior of glass in storage conditions. Finally, the effect of the pore fluid is also determined in order to check the effect of a possible alteration of glass by fluid corrosion.

References:
Mallet C., Fortin, J., Guéguen, Y., Bouyer, F. (2013) Effective elastic properties of cracked solids : an experimental check, International Journal of Fracture, DOI : 10.1007_s10704-013-9855-y
Mallet C., Fortin, J., Guéguen, Y., Bouyer, F. (2013) Brittle Creep and Sub-Critical Crack Propagation in Glass ? Part 1 : Experimental results, JGR (submitted)
Mallet C., Fortin, J., Guéguen, Y., Bouyer, F. (2013) Brittle Creep and Sub-Critical Crack Propagation in Glass ? Part 2 : Theoretical model, JGR (submitted)

Theoretical Model of Crack Propagation in Glass under Creep Conditions

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Crack propagation is an important subject of investigation for geological and geophysical issues such as time dependent deformation of the crust, earthquakes, underground reservoir mechanical stability, etc... The aim of this study is to understand the experiment results obtained in glass under creep conditions. Indeed, it has been shown that under a constant stress state below the critical strength of material, cracks can propagate. Two behaviors are observed: i) first cracks propagate at a constant velocity (secondary creep) ; ii) second, when cracks reach a critical length, crack interactions lead to the failure of the sample in tertiary creep.
We develop a micromechanical model, which describes the brittle creep and the tertiary creep in terms of sub-critical crack propagation. This model relies on two key assumptions that are: (i) an exponential sub-critical crack propagation law, and (ii) a wing-crack geometry. The sub-critical crack growth law presents the advantages to take into account experimental parameters (temperature and pore fluid environment) and to be theoretically justified. Indeed, it considers that crack propagation is a thermally activated process. The wing-crack geometry allows to quantify the stress intensity factor. The stress intensity factor is assumed to result from: (i) a wedging force that comes from applied differential stress, (ii) a remote compressive stress that tends to close the wing crack, and (iii) a crack interaction due to the attractive force between two cracks. At the beginning of creep, a stable behavior is observed: the interaction between two cracks can be neglected. When crack interaction becomes no more negligible, strain rate increases up to failure.
It is possible to describe the crack evolution in the two above different creep stages. When crack interaction becomes non negligible, the time to rupture is obtained. The overall behavior depends on stress, temperature and pore fluid conditions of the experiment on one hand, and on elastic, microstructural and thermal parameters of the material on the other hand.
The application of the model to rock is checked against experimental data. It allows also to explain the important differences between glass and rocks.

References:
Mallet C., Fortin, J., Guéguen, Y., Bouyer, F. (2013) Brittle Creep and Sub-Critical Crack Propagation in Glass ? Part 2 : Theoretical model, JGR (submitted)

General Equation for Mass Exchange in Deformable Porous Media

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The description of processes of mass exchange between fluid and particles material in porous media from various kinds of rocks (primarily, sedimentary rocks) is examined. It is shown that in some important cases there is a storage equation of non-linear diffusion equation type. In addition, process of filtration in un-swelling soils, swelling porous rocks and coupled process of consolidation and chemical interaction between fluid and particles material are considered. In the latter case equations of physical-chemical mechanics of conservation of mass for fluid and particles material are used. As it is well known, the mechanics of porous media is theoretical basis of such branches of science as hydro-geo-mechanics, soil physics and so on. But at the same moment some complex processes in the geo-systems lacks full theoretical description. The example of such processes is metamorphosis of rocks and correspondent variations of stress-strain state. In such processes chemical transformation of solid and fluid components, heat release and absorption, phase transitions, rock destruction occurs. Extensive usage of computational resources in limits of traditional models of the mechanics of porous media cannot guarantee full correctness of obtained models and results. The process of rocks consolidation which happens due to filtration of underground fluids is described from the position of rock mechanics. As an additional impact, let us consider the porous media consolidating under the weight of overlying rock with coupled complex geological processes, as a continuous porous medium of variable mass. Problems of obtaining of correct storage equations for coupled processes of consolidation and mass exchange between underground fluid and skeleton material are often met in catagenesi processes description. The example of such processes is metamorphosis of rocks and correspondent variations of stress-strain state. In such processes chemical transformation of solid and fluid components, heat release and absorption, phase transitions, rock destruction occurs. Extensive usage of computational resources in limits of traditional models of the mechanics of porous media cannot guarantee full correctness of obtained models and results. The present work is dedicated to the retrieval of new ways to formulate and construct such models. It was shown that in some important cases there is a governing equation of non-linear diffusion equation type (well-known Fisher equation). In addition, process of filtration in usual un-swelling soils, swelling porous rocks and coupled process of consolidation and chemical interaction between fluid and skeleton material are considered.

Characterization of CO2 reservoir/seal rock in Switzerland

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Anthropogenic emissions of Carbon Dioxide (CO2) are one of the key drivers regarding global climate change (IPCC, 2007). Carbon Dioxide Capture and Storage (CCS) is one valuable technology to mitigate current climate change with an immediate impact. The IPCC special report on CCS predicted a potential capture range of 4.7 to 37.5 Gt of CO2 by 2050. Among several countries, Switzerland has started to investigate its potential for CO2 storage (Chevalier et al., 2010) and is currently performing research on the characterization of the most promising reservoir/seal rocks for CO2 sequestration. For Switzerland, the most feasible option is to store CO2 in saline aquifers, sealed by impermeable formations.
One aquifer of regional scale in the Swiss Molasse Basin is a carbonate sequence consisting of reworked shallow marine limestones and accumulations of shell fragments. The upper part of the formation presents the most promising permeability values and storage properties. The storage potential has been estimated of 706 Mt of CO2, based on the specific ranking scheme proposed by Chevalier et al. 2010. The sealing formation is a thinly bedded alternation of claystones, anhydrite, gypsum and marls, up to 100 m thick.
In this study, key parameters such as porosity, permeability and acoustic velocities in compressional and shear mode have been measured in laboratory at pressures and temperatures simulating in situ conditions. Both reservoir and seal rock samples have been investigated. Permeability has been estimated before and after CO2 injection in supercritical state. The simulation of typical reservoir conditions allows us to go one step further towards a significant evaluation of the reservoir's true capacities for CO2 sequestration.
The correlation between the permeability and confining pressure, temperature and pore pressure conditions of the sample is a first important result of the study.

Mechanical and petrophysical study of fractured shale materials

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Understanding of the mechanical and physical properties of shales is of major importance in many fields such as faults hydro-mechanical behavior, cap-rock and unconventional reservoir studies or nuclear waste disposal. In particular, relationships between fluid transport properties, applied stress and textural anisotropy are critical both in intact and fractured shales. Therefore, these relations need to be investigated in the laboratory in order to have a better understanding on in-situ mechanisms.
Hence, the mechanical behavior and the petrophysical properties of Toarcian shale of the Tournemire underground laboratory (France) have been investigated. The petrophysical properties have been measured along a 20 meters core drilled through a fault zone from the Tournemire tunnel. Along the core, P and S waves velocity and anisotropy, as well as magnetic susceptibility anisotropy and porosity were measured.
In addition, conventional triaxial tests have been performed in order to determine the elasto-plastic yield envelope on three sets of samples with different orientations relative to bedding (0°, 45°, and 90° to the vertical axe). For each set, six experiments were carried out at increasing confining pressures (2.5, 5, 10, 20, 40, 80MPa). Experiments were performed in dry conditions, at a strain rate of5x10-7 s-1 up to failure. During each experiment, P and S wave elastic velocities were continuously measured along different directions, in order to assess both P wave anisotropy and shear wave splitting and their evolutions with deformation. Our results show that brittle failure is preceded by the development of P wave anisotropy and shear wave splitting, due to crack re-opening and crack growth. However, the orientation of principal stress components relative to the bedding plane plays an important role on both the brittle strength, as well as on the magnitude of shear-enhanced P wave velocity anisotropy and S wave splitting.
Our perspective is now to perform fluid injections, both at the field and laboratory scale and measure the evolution of hydraulic diffusivity by tracking the fluid front by both passive and active seismic measurements.

Acoustic properties of microporous carbonate reservoirs: implication of micrite particle size and morphology. Example of the Late Jurassic limestones of the Paris Basin (France)

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Micritic limestones exhibit large variation of (1) sedimentary texture from mudstone to packstone, (2) facies composition and (3) petrophysical properties (porosity, acoustic velocity). Those heterogeneities imply a complex distribution of fluid flow properties and a complex petrophysical signature. In the Eastern Paris Basin, Late Jurassic micritic carbonate deposits constitute a main aquifer located directly above the Callovian-Oxfordian clay-rich formation studied by the French National Radioactive Waste Management Agency (Andra) as a potential host rock for a deep geological disposal of high level radioactive wastes. A precise understanding of the factors controlling the petrophysical properties within carbonate aquifers is thus essential for rock-typing studies and fluid flow modelling. The first objective of this study is to better characterize the vertical distribution of both petrographical characteristics (texture, facies and composition) and petrophysical properties (porosity, permeability and acoustic velocity) on about 100 plugs sampling along 230 m of cores in well EST205, located at the top of the Underground Research Laboratory at Bure, France. The secondary aim is to better understand the influence of micrite type and grain to grain contact on acoustic velocity-porosity relationships by a rock typing approach.

Microfacies observations reveal 7 facies, which can be grouped into 4 facies associations ranging from upper offshore to supratidal environments. Those facies are stacked into 7 third-order depositional sequences. Most of the samples are (1) oncoid-peloid packstones (45 samples, n=45) and (2) bioclastic wackestones (n=25), both deposited in low energy environmental settings. Oolitic grainstone facies are not well-developed in these limestones (n=14) and macroporosity is absent. SEM observations reveal 3 micrite particle types both in matrix and clasts. (1) Fine (~ 1 µm) rounded micrites with very punctic inter-crystalline contacts, (2) Fine to coarse (1 µm ? 2 µm) subrounded micrite particles with partially coalescent contacts and (3) coarse (> 2 µm) anhedral crystals with sutured contacts (mostly indistinct) forming a dense and fused matrix. Types 1 and 2 are observed in porous levels (15 - 25% porosity) and display low to moderate P-wave velocities (3000 to 4500 m/s) whereas type 3 is observed in very low to non-porous units (

The micritic particle types allow us to define 3 typical class or 3 «acoustic fabrics» on a porosity-velocity diagram, demonstrating a clear influence of micrite size and morphology on acoustic and porosity properties. The origin and development of such micritic matrixes is related to porosity creation by mineralogical stabilisation of carbonates through freshwater-related diagenesis. In the Oxfordian, such a relationship between porous horizons and exposures also exists. Indeed, porous levels are located in inner ramp low energy facies below sequence boundaries, where exposure evidences are abundant and widespread from the Andra laboratory to local outcrop section.

Mechanical behaviour of porous carbonate rocks and the effect of microstructural parameter (Middle Jurassic limestones, Paris Basin, France)

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In recent studies, P-wave velocity measurements performed on samples from the Oolithe Blanche formation (Middle Jurassic Limestone, Paris basin) showed that dynamic moduli of carbonate rocks are largely controlled by microstructural arrangement of both porosity within the grains (uniform versus rimmed microporosity; Type A) and the presence/absence of isopachous cement around the ooids (Type B) (Brigaud et al., 2010; Casteleyn et al., 2010, 2011).
Here, conventional triaxial experiments were performed on Type A and Type B samples to investigate the effect of such microstructural parameter on the mechanical behavior of carbonate rocks. This work is of primary importance since the Oolithe Blanche formation, a deep saline aquifer, is a possible target for CO2 sequestration and geothermal production in the center of the Paris Basin.
Experiments were performed under saturated state with respectively two sets of experimental conditions: (1) a 5 MPa pore pressure and a 28 MPa confining pressure with a temperature of 55°C for Type A carbonates to mimic in-situ conditions in the Center of the Paris Basin; and (2) a 0.5 MPa pore pressure and a 1.5 MPa confining pressure for Type B samples. Sample types have similar facies and composition (oolithic microporous grainstone with a 500µm average grain size), and porosity ranges from 17% to 20%. Permeability values are also very similar and range from 10-2 mD to 10-1 mD.
Different mechanical behaviors were observed: (1) Type A samples with a uniform porosity display a typical behavior of the brittle failure regime with stress-strain curves reaching a peak (138 MPa) beyond which strain softening was recorded, and strain localization on a shear fracture. (2) Type A samples with a rimmed porosity display a ductile behavior with no localization of the deformation.
(1) Type B samples with isopachous cement show a brittle behavior with stress drop (16 MPa to 18 MPa) and localization on a shear fracture. When isopachous cements are absent, a more ductile type of behavior is observed.
Our set of data suggests that the amount of isopachous fibrous cement seems to be a microstructural parameter which has a significant control on the mechanical behavior in carbonate rocks.

References

Brigaud B., Vincent B., Durlet C., Deconinck J.F., Blanc P., Trouiller A., 2010 ? Acoustic properties of ancient shallow-marine carbonates: effects of depositional environments and diagenetic processes (Middle Jurassic, Paris Basin, France)

Casteleyn L., Robion P., Collin P.Y., Menendez B., David C., Desaubliaux G., Fernandes N., Dreux R., Badiner G., Brosse E., Rigollet C., 2010 - Interrelations of the petrophysical, sedimentological and microstructural properties of the Oolithe Blanche Formation (Bathonian, saline aquifer of the Paris Basin). Sedimentary Geology 230 (2010) 123-138.

Casteleyn L., Robion P., David C., Collin P.Y., Menendez B., Fernandes N., Desaubliaux G., Rigollet C., 2011 ? An integrated study of the petrophysical properties of carbonate rocks from the «Oolithe Blanche» formation in the Paris Basin. Tectonophysics 503 (2011) 18-33.

Brittle vs ductile creep in porous limestone

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We performed water-saturated triaxial experiments on a porous oolitic limestone in order to determine the time-dependency of the deformation processes in the brittle regime. For deformation rates of the order of 10^{-5} s^{-1} and effective pressures (Peff) less than 30 MPa, the material is macroscopically brittle. Under creep conditions (i.e., at constant differential stress) at Peff=10 MPa, the material remains brittle and only little inelastic strain can be accommodated before failure. Measurements of P-wave speed during both creep and constant strain rate tests under these conditions indicate only a limited rate-dependency of damage accumulation. By contrast, under creep conditions at Peff=20 MPa, the material can accommodate large amounts of strain provided that the imposed stress is not too close to the short-term strength of the rock. The creep behaviour remains similar to typical brittle creep (as previously observed in other rock types such as sandstones, granite and basalt), but when the creep strain rate decreases below 10^ {-7} s^{-1}, large strains can be accumulated. In addition, we observed enhanced compaction below this strain rate. The rate of decrease of the P-wave speed during deformation decreases with decreasing strain rate, which indicates that less damage is accumulated per unit strain when the strain rate is low. This suggestion is further supported by complementary observations obtained during strain-rate stepping tests on the same material. Microstructral observations show that intragranular plastic deformation is present in the calcite cement of the rock, along with stress induced microcracking. Overall, our observations show that rate-dependent compactant deformation mechanisms compete with dilatant subcritical crack growth during deformation at low strain rates and under low creep stress conditions. In our water-saturated experiments, it is likely that pressure-solution creep is the mechanism responsible for the enhanced compaction and the change in damage accumulation with decreasing strain rates.

EDZ permeability monitoring through barometric pumping : two case studies, in the Opalinus Clay (Mont Terri URL, Swiss Jura) and in gneissic rock (Roselend URL, French Alps).

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Free oscillations of the atmosphere induce variations of the barometric pressure (Lamb, 1911). The barometric signal includes i) short period variations ? diurnal and semi-diurnal variations ? due to daily temperature variations of the atmosphere and tides, ii) medium period due to weather such as cyclonic and anticyclonic phenomenon, iii) and also long period related to seasonal cooling or heating of the atmosphere. Atmospheric or barometric pumping is a piston-like process, cyclic and nearly reversible, responsible of gas motion between subsurface permeable rock mass and the atmosphere (e.g. Nilson et al., 1991). A decrease of atmospheric pressure induces gas carrying out of the permeable rock; an increase of atmospheric pressure pushes the air into the rock subsurface.
Barometric pumping is classically described as a low-cost and passive method used in the extraction of contaminated soil gas in the vadose zone (e.g., Olson et al., 2001 ; Rossabi and Falta, 2002). Barometric signal propagation into the subsurface rocks constitutes also a simple technique to characterize gas permeability of subsurface medium (Nilson et al., 1991 ; Alhers et al., 1999 ; Wassermann et al., 2011 ; Guillon et al., 2013). Indeed the gas diffusivity (a function of the ratio of air-permeability and air-filled porosity) describes the attenuation and time-lag that characterized the propagated barometric signal into the subsurface. A long-term measurement of barometric signals in obturated boreholes and at the surface could constitute, through the deduced time-lag and attenuation, a monitoring of potential gas permeability variations.
In the context of nuclear waste geological disposal, the permeability of the Excavation Damaged Zone (EDZ) is one of the most important parameter that will influence the safety of the confinement of the radio-nuclides by the host rocks. In order to test the reliability of the method in monitoring EDZ permeability variations, we look at pressure monitoring performed during several months in boreholes into two different damaged rocks. Firstly, into an EDZ surrounding a tunnel in a crystalline rock mass (Roselend Underground Rock Laboratory, Roselend URL). Secondly, into the EDZ surrounding gallery excavated in Opalinus Clay of the Mont Terri URL (Swiss Jura).
The Roselend URL occupies a subhorizontal dead-end tunnel drilled by blasting within the Méraillet crystalline massif (French Alps). The Roselend URL tunnel is located near the west bank of the Roselend artificial lake. This nearly straigth excavation about 128 m long crosses fractured micaschists and gneisses successively. The natural fracture pattern is related to the Alpine orogeny and presents an heterogeneous metric fracture density along the tunnel. Water content in the massif and flow rates of percolating waters depend on seasonal precipitation (drought, rain and snow alternating periods) characterizing the mountainous Roselend environment.
The Mont Terri URL is a 300 m underground laboratory consisting of 600 m of excavated galleries along the security gallery of the Mont Terri motorway tunnel within a clay rich formation, the Opalinus Clay. Which is a proposed host rock for future deep geological disposal of radioactive waste. Cyclic seasonal variations of fractures and cracks openings were observed by Möri et al. (2010) linked to environmental conditions (temperature and humidity) in the URL galleries. Within few year, self-sealing and healing processes have been observed when the Opalinus clay is in contact with wet air (e.g. Bossart, 2004) ; inducing EDZ permeability decrease.
The pressure monitoring system was designed to follow the response of the different EDZ to barometric pumping. It consists in a borehole obturated by a simple mechanical packer and absolute barometric transducers that measured the pressure into the borehole and in the tunnel.

The temperature was also measured into the obturated borehole and in the tunnel with high resolution autonomous probes. Hygrometry was also monitored both into boreholes and gallery. In Roselend URL, this pressure monitoring system was placed into four boreholes during several months in 2009. In Mont Terri URL site, the pressures has been measured since winter 2011 in only one borehole.
The estimations of potential time-lag and attenuation variations from pressure signals ? related to gas permeability variations ? are performed through signal analysis using Lissajou curves analysis, and simulated annealing algorithm. Modeling of these time-lag and attenuation are also performed with different external sollicitation conditions such as groundwater table level fluctuation in the case of Roselend URL, or moisture content.

Ahlers, C. F., Finsterle, S., & Bodvarsson, G. S. (1999). Characterization and prediction of subsurface pneumatic response at Yucca Mountain, Nevada. Journal of Contaminant Hydrology, 38(1), 47-68.
Bossart, P., Trick, T., Meier, P.M. & Mayor, J.C., 2004. Structural and hydrogeological characterisation of the excavation-disturbed zone in the Opalinus Clay (Mont Terri Project, Switzerland), Appl. Clay Sci., 26, 429?448.
Guillon, S., Vu, M. T., Pili, E., & Adler, P. M. (2013). Field and numerical determinations of pneumatic flow parameters of unsaturated fractured porous rocks on various scales. Water Resources Research.
Lamb, H. (1911). On atmospheric oscillations. Proceedings of the Royal Society of London. Series A, 84(574), 551-572.
Möri, A., Bossart, P., Matray, J.M., Frank, E., Fatmi, H. & Ababou, R., 2010. Mont Terri Project Cyclic deformations in the Opalinus Clay, in proceedings of the Meeting, Nantes 2010, ANDRA.
Nilson, R. H., Peterson, E. W., Lie, K. H., Burkhard, N. R., & Hearst, J. R. (1991). Atmospheric pumping: A mechanism causing vertical transport of contaminated gases through fractured permeable media. Journal of Geophysical Research, 96(B13), 21933-21.
Olson, M. S., Tillman Jr, F. D., Choi, J. W., & Smith, J. A. (2001). Comparison of three techniques to measure unsaturated-zone air permeability at Picatinny Arsenal, NJ. Journal of contaminant hydrology, 53(1), 1-19.
Rossabi, J., & Falta, R. W. (2002). Analytical solution for subsurface gas flow to a well induced by surface pressure fluctuations. Ground Water, 40(1), 67-75.
Wassermann, J., Sabroux, J. C., Pontreau, S., Bondiguel, S., Guillon, S., Richon, P., & Pili, E. (2011). Characterization and monitoring of the excavation damaged zone in fractured gneisses of the Roselend tunnel, French Alps. Tectonophysics, 503(1), 155-164.

Long-term and multi-scale monitoring with passive geophysical methods of nuclear waste disposal

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Classical geophysical methods used to characterize an Excavation Damaged Zone (EDZ) in sedimentary or crystalline rock masses, enable non-invasive testing around the excavation of galleries. Seismic, acoustic emission and electric methods allow to characterize the rock mass in term of anisotropy and damage for instance, but also to monitor the EDZ evolution during an excavation process (Nicollin et al. 2010, Le Gonidec et al., 2012). Hydraulic and pneumatic methods (e.g. hydraulic conductivity, gas injection or extraction tests in boreholes) allow to delineate the EDZ and to estimate its transport property changes with time (Bossart et al, 2004). Most of those conventional techniques require controlled sources which might become unsustainable when dealing with long-term monitoring of geological repositories. In order to approach the scientific challenge of long-term and sustainable monitoring of underground repositories, geophysical methods based on the monitoring of natural signals have been proposed and are being tested in the Mont Terri Underground Rock Laboratory (URL, Swiss Jura) and soon also in the Andra URL (Bure, France) :
(1) Radon-222 (radioactive noble gas with 3.82 days of half-life and coming from the decay chain of the uranium-238 present in host rocks) is used as a geophysical tracer of transport property changes of the EDZ at different scales. Gas permeability of the EDZ is also continuously monitored in boreholes. Radon-222 activity concentration have been measured since December 2011 in different niches characterized by particular EDZ and different argillite facies.
(2) Ambient seismic noise and (3) magnetotelluric signals. A catalog of the natural sources available on site, by the use of continuous noise recording, has been realized. The obective is now to determine the potential of the innovating methods, as well as their resolutions in space and time. Hence, as a first step, in situ experiments are being developed at the Mont Terri URL in the case of ambient seismic noise and for magnetotelluric noise monitoring. Continuous recordings of ambient seismic noise have been measured since 2012, along a line of ten geophones which crosses a main fault.
From the seismic noise correlation, it should be possible to pinpoint which areas and which elastic properties are concerned by the changes observed in the obtained Green functions. Continuous recordings of electromagnetic signals coming from the ionosphere and magnetosphere should inform about the macroscopic properties of the rock mass above the Andra URL. Preliminary tests of recording of electrical field have been performed in the Mont Terri URL allowing the detection of anthropic noise (that have to be filtered) and high frequency energetic noise that could be related to ionospheric stationnary phenomena. Continuous monitoring of the magnetotelluric noises will be performed at the Andra URL (Bure, France) in 2014 with two synchronized stations at the surface and underground. Numerical modeling will also be associated to the analysis of signals recorded in the gallery and at the surface. The proposed methods are being tested at different scales of applications, from the EDZ to a large scale of a whole repository.

Bossart, P., Trick, T., Meier, P. M., & Mayor, J. C. (2004). Structural and hydrogeological characterisation of the excavation-disturbed zone in the Opalinus Clay (Mont Terri Project, Switzerland). Applied clay science, 26(1), 429-448.
Le Gonidec, Y., Schubnel, A., Wassermann, J., Gibert, D., Nussbaum, C., Kergosien, B., ... & Gueguen, Y. (2012). Field-scale acoustic investigation of a damaged anisotropic shale during a gallery excavation. International Journal of Rock Mechanics and Mining Sciences, 51, 136-148.
Nicollin, F., Gibert, D., Lesparre, N., & Nussbaum, C. (2010). Anisotropy of electrical

conductivity of the excavation damaged zone in the Mont Terri Underground Rock Laboratory. Geophysical Journal International, 181(1), 303-320.

Mechanical behavior of the induced fracture network around a drift

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Understanding hydromechanical behavior of the excavation damage zone (EDZ) around the repository structures constitutes an important issue in the context of radioactive waste disposals. Extensive experimental observations have been performed by ANDRA around drifts and shafts at the Meuse Haute-Marne underground research laboratory (M/H-M URL) in Callovo-Oxfordian claystone, considered as a potential repository geological host in France. The excavation worksite in the host layer is a scientific experimentation in itself to characterize the impacts of digging, to understand the hydro mechanical behavior of the Callovo-Oxfordian claystone and to study the excavated damaged zone (EDZ). At the main level of URL at -490 m an important induced fracture network has been observed (Armand et al, 2013) around the drifts and it is made up of two types of fractures (shear and extension induced fractures).
Within this framework, an experiment, called CDZ is (de La Vaissière et al, in press), dedicated to studying the effect of mechanical compression within the induced fractures of the claystone. The effects of mechanical loading/unloading on mechanical behavior of the EDZ and on change of hydraulic conductivity in the excavation induced fractures zone under saturation are investigated. The experimental concept consists of a single end plate, with a cross section of 1 m^2, which is used to load the fracture network at the drift wall. The 3D structure of the fracture network has been fully investigated. Extensometric measurements are performed to obtain displacements induced in the rock mass under the plate. An analytical method is used to back calculate stiffness of the fracture zone. Numerical modeling taking into account different assumption has been also performed to simulate the test and understand the behavior of the fractured zone.
This experiment gives important insights on the mechanical behavior of the fractured zone, useful for the understanding the loading of drift support in Callovo-Oxfordian claystone.

References:

Armand G, Leveau F, Nussbaum C, de La Vaissière R, Noiret A, Jaeggi D, Landrein P, Righini C (2013) Geometry and Properties of the Excavation Induced Fractures at the Meuse/Haute-Marne URL Drifts. Rock Mechanics and rock engineering DOI 10.1007/s00603-012-0339-6
R. de La Vaissière, J. Morel, A. Noiret, P. Côte, B. Helmlinger, R. Sohrabi, J-M. Lavanchy, F. Leveau, C. Nussbaum, J. Morel, Excavation-induced fractures network surrounding tunnel: properties and evolution under loading, In: Norris, S., Bruno, J., Cathelineau, M., Delage, P., Fairhurst, C., Gaucher, E. C., Höhn, E. H., Kalinichev, A., Lalieux, P. & Sellin, P. (eds) Clays in Natural and Engineered Barriers for Radioactive Waste Confinement. Geological Society, London, Special Publications,in press

THM behavior of a full scale disposal cell demonstrator in 500 m deep clay formation

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At the Meuse/Haute Marne Underground Research Laboratory, excavated in a 500 m deep clay formation, Andra carries out for several years experiments to study the possibility of disposal for long-lived and high level activity waste in deep geological repositories.

The concept of disposal cells studied for high level activity wastes consists in horizontal micro-tunnels 40 m long and 70 cm in diameter. It comprises a cell body, for package disposal, and a cell head, partly backfilled with a swelling-clay plug and then sealed with a concrete plug to provide additional safety. The micro-tunnel is equipped with a casing to allow the retrieval of waste containers. The casing in the head part is slightly larger in diameter in order to absorb the thermal dilation of the body part casing due to heating induced by exothermic packages.

Several campaigns of tests have been carried out since 2009 in order to demonstrate the feasibility of excavation of such micro-tunnels and study their behavior. A full scale demonstrator representative of the benchmark concept has been excavated at the end of 2012, with the objective to study its behaviour under thermal loading. Heat produced by waste packages is simulated using electrical heaters.

Casing in head and body parts is instrumented to monitor its thermo mechanical behaviour as well as the rock interface evolution. A peripheral instrumentation has been installed in boreholes and in the access drift to monitor the THM behaviour of the host rock. Heating, performed over a length of 15 m, has started in April 2013 with the goal to reach 90° C at the rock interface in about 2 years.

This paper presents the first results on the THM behavior of the cell demonstrator and of the surrounding rock.

Laboratory Rock Mechanics: Imaging Processes and Processing Images

Development and application of time-lapse ultrasonic tomography for laboratory characterisation of localised deformation in hard soils/soft rocks

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As with many materials, strain localisation processes are key to the deformation behaviour of rocks and soils, because, for xample, localised deformation is often precursor to material failure. Therefore the understanding of the processes leading to localised deformation, and thus to failure, in geomaterials is critical to the success of many geotechnical engineering projects. This work focuses on the analysis of localised deformation in hard soils, soft rocks and, more generally, cemented granular materials. For such materials localized deformation, in the form of localized strain, i.e., shear and compaction bands, is often associated with damage, i.e., inter and intra-granular fractures and cracks, de?bonding and breakage of particles (grain crushing). Furthermore, macrofractures are commonly surrounded by meso and micro cracks and a process zone of microfracturing precedes their propagation. To study localised phenomena such as strain and damage localisation, some kind of non-destructive, full?field measurement has to be used. Well-known techniques in geomechanics include x-ray tomography, to study material structure at the micro scale, and Digital Image Correlation (DIC) of 2D or 3D (volume) images, to measure the evolution of strain fields in a deforming specimen. DIC has proven to be a very powerful tool in the study of heterogeneous phenomena, but provides only data on kinematics and strain and not on associated property changes (e.g., elastic properties). In this work another tool, ultrasonic tomography, is suggested as a full-field measurement of the elastic property variations in test specimens through mapping of ultrasonic wave propagation velocities. Ultrasonic tomography, as complementary technique to DIC and other full-field measurements, can thus provide new insight into the deformation processes.
In rock and soil mechanics, acoustic and ultrasonic methods have long been used to measure the elastic properties of test materials, including during mechanical testing. However, such measurements have generally been limited to only a few measurement paths (usually just one) for a whole sample, thus restricting the study of heterogeneity. Ultrasonic tomography can overcome this limitation since is based on multiple measurements across a test sample, which are mathematically reconstructed to provide the potential to map heterogeneous elastic properties inside the sample. The main contributions of this work are the development of ultrasonic tomography analysis for laboratory geomechanics (both in terms of the experimental method and subsequent data analysis) and its application to analyse material deformation and, in particular, material evolution during loading (time-lapse ultrasonic tomography). A key contribution is the implementation of the Double Beam Forming technique, for the particular case of laboratory test on geomaterials, to provide improved quality data and thus extraction of more precise information. The developed ultrasonic tomography approach has been applied to investigate geomaterial behaviour in laboratory tests. In this context, experimental campaigns have been carried out on different materials, where the ultrasonic tomography has been complemented by comparisons with displacement and strain fields from 2D and 3D DIC plus structural analysis by x-ray tomography. To determine the spatial and temporal resolution of the timelapse ultrasonic tomography in a simplified situation, tests have been carried out on rock samples containing a layer of cemented soil between two blocks of rock. This particular geometry was chosen with the objective to know a priori the region of the sample where most of the damage will occur because of the stiffness contrast between the layer and the rock. The comparison between a model-based ultrasonic tomography and an x-ray tomography of the intact sample proved that the 5 mm layer of cemented soil can be well resolved and thus the resolution of the ultrasonic inversion respects the expectation. The timelapse ultrasonic tomography analysis successfully revealed that the inclined layer is stiffer than the surrounding

rock and that the latter experiences damage during the loading. DIC shows, to the contrary, a concentration of strain inside the layer while the two blocks of rock show only minor deformation. Moreover, the volumetric strain, measured by DIC, displays compaction at the boundaries between the cemented soil and the rock with dilation inside the layer. The ultrasonic tomography is not able to resolve such structure, as its spatial resolution is below the involved dimensions. The ultrasonic tomography does, however, provide information about the different mechanisms occurring inside the layer and in the rock. The fact that the deformation induces only a small effect on the velocities in the layer suggests that these deformations are mainly elastic and do not damage the material. On the contrary the surrounding rock is damaged despite only experiencing small strains. A possible explanation of this behaviour is the rupture of the natural cement that causes debonding of the grains whereas the cement between the grains in the layer is stronger and does not experience any damage.

The different full-field techniques employed in this work have been found to provide different and complementary information. The x-ray tomography, which gives a 3D map of the density, is helpful in the study of the internal structure of the sample; the DIC, applied to the X-ray tomography images (volumes) pre- and post-mortem or to the photos taken during the test, provides important information on the kinematics while the velocity fields recovered by the ultrasonic tomography are linked to the elastic properties of the material and can, therefore, be used to investigate damage processes. Furthermore, it is shown that better understanding of the mechanical behaviour of geomaterials can be gained.

Ultrasonic Tomography for Full-field Characterisation of Strain and Damage Localisation in Sandstone

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This work considers the application of ultrasonic tomography on rock specimens tested under triaxial compression to investigate the deformation mechanisms of localised shear failure.
The studied rock is a porous, fine grained, poorly cemented, quartz rich sandstone from the Vosges Mountains in northern France (22% porosity; average grain size about 300 ?m; 93% quartz). The mechanical behaviour of this particular sandstone has been investigated extensively by Bésuelle (1999) and Charalampidou (2011) for a wide range of confining pressures. More specifically, Charalampidou's work employed a range of full-field experimental methods, including ultrasonic tomography, to characterise localised deformation (compaction and shear bands) in this sandstone. The objective of the present study is to revisit the analysis of some of the specimens from Charalampidou's work, using improved ultrasonic tomography methods proposed by Tudisco (2013), to further investigate the deformation mechanisms in shear band development.
The specific set of samples considered in this work are three specimens loaded under triaxial compression with a moderate confining pressure (50 MPa) and taken to different strain values, allowing the evolution of the deformation to be investigated. In the analysis of Charalampidou (2011), the ultrasonic tomography results presented some interesting behaviours but also, some uncertainty as to the influence of artifacts from the tomographic approach: certain regions showed anomalies that can be either the behaviour of the rock during the loading or tomography artifacts. At the same time, x-ray tomography imaging of the specimens and associated 3D-volumetric digital image correlation indicated some agreement and some differences in the deformation patterns. However, as the various methods are sensitive to different physical properties, inconsistencies should not be taken as indicators of failure of one method or another. In fact, these inconsistencies could reveal more details on the acting failure mechanisms. Still, it is necessary to verify that the results reflect the material itself and not possible inadequacies of the analysis methods. The clarification of these uncertainties is the main focus of this work.
Tudisco (2013) developed further the ultrasonic tomography approach for application in laboratory geomechanics, to provide improved resolution and reduced occurrence of artifacts. More specifically, in Charalampidou's study simple straight ray theory was used as propagation model for the ultrasonic analysis, while Tudisco (2013) introduced more advanced ones (i.e. cubic rays, curved rays, sensitivity kernels), as well as improvements to the travel-time data extraction (including double-beam forming). Initial tests by Tudisco (2013), on one of the three specimens studied here, showed improved results over the previous analysis.
In the present study, the methodology of Tudisco (2013) is applied to all three specimens, in order to make a full assessment of the method in investigating the deformation behaviour of this rock. Results from the analysis will be presented and compared with complementary data from x-ray tomography and digital image correlation.

References

Bésuelle, P., 1999. Déformation et Rupture dans les Roches Tenders et les Sols Indures: Comportement Homogène et Localisation, Université Joseph Fourier, Grenoble, pp. 1-374.
Charalampidou E.M., 2011. Experimental Study of Localised Deformation in Porous Sandstones, Ph.D. Thesis, Heriot Watt University and Université de Grenoble.
Tudisco, E., 2013. Development and Application of Time-lapse Ultrasonic Tomography for Laboratory Characterisation of Localised Deformation in Hard Soils / Soft Rocks, Ph.D. Thesis, Université Joseph Fourier, Grenoble.

Time-dependent compaction in porous sandstone

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The characterization of time-dependent rock deformation is fundamental to understanding the long-term evolution and dynamics of reservoirs and aquifers. The presence of a pore fluid phase within pores and cracks in reservoir rocks has been shown to exert a significant influence on rock deformation through both mechanical and chemical processes. Mechanically, pressurized pore fluids act to weaken rocks through the well-known effective stress principle. Chemically, the presence of a pore fluid phase weakens rock by: (1) the reduction of surface free energy as the result of the absorption of pore fluid onto the internal pore surfaces, and (2) subcritical crack growth, of which stress corrosion is the most important mechanism in the shallow crust. Stress corrosion describes the reactions that occur preferentially between a chemically active pore fluid, and the strained atomic bonds close to crack tips. Experiments on single cracks have shown that this process is extremely sensitive to the applied stress and the environmental conditions (nature of the pore fluid, temperature, etc.). Under triaxial stress conditions, stress corrosion leads to highly non-linear time-dependent deformation. This allows rocks to deform and fail even under a constant differential stress over extended periods of time. For experiments performed at relatively low effective pressures, this phenomenon is known as brittle creep (or static fatigue in the engineering literature) and leads to time dependent failure. It has been observed in most rock types. Recent laboratory studies focussing on sandstone have shown that even a modest increase in the differential stress and/or the temperature leads to an increase in the creep strain rate by several orders of magnitude. In contrast, limited data on the influence of effective pressure (Peff) showed that the creep strain rate decreased significantly with increase in Peff, which suggests that the process becomes less sensitive to differential stress at higher Peff. Existing data were however all obtained in the brittle regime in which rocks failed by shear localization after a period of dilatant deformation. To our knowledge, there is a paucity of data on time-dependent deformation of sandstone at higher effective pressures corresponding to the ductile regime.

In this study, we have therefore tried to fill this gap in our knowledge by systematically investigating time-dependent compaction in a porous sandstone. Our new data were obtained on Bleurwiller sandstone, a feldspar-rich sandstone of 24% porosity from the Vosges area in France. All of our experiments were performed at room temperature and under drained conditions (constant pore pressure of 10 MPa). Conventional triaxial experiments on Bleurwiller sandstone show that brittle failure occurs up to a Peff of 10 MPa. Beyond this pressure, shear-enhanced compaction was observed in all cases and visual inspection of deformed samples revealed the development of multiple discrete compaction bands, in agreement with previous studies on the same rock. Creep experiments were then performed in this regime using a methodology similar to earlier work on brittle creep. The samples were first loaded at constant strain rate to various levels of differential stress (beyond the onset of shear-enhanced compaction) and the stress was then maintained constant while the sample was allowed to deform over time.

Our new creep data show, for our range of imposed differential stresses, that time-dependent deformation proceeded at strain rates ranging from 10-9/s to 10-5/s. In all cases, the deformation was compactant and we observed significant time-dependent porosity reduction. The three damage proxies recorded during our experiments, axial strain, porosity change and cumulative acoustic emission energy showed a very obvious correlation, suggesting that the mechanism leading to this time-dependent compaction is stress corrosion cracking. Visual inspection of samples deformed at various levels of differential stress and over periods of time between a few hours and a few days, revealed in most cases the presence of discrete compaction bands. Our new data therefore suggest that compaction bands could develop in laboratory samples at stresses significantly lower than reported in previous studies and hence closer to published estimates based on field observations.

Experimental evidence of elastic weakening from moisture adsorption on quartz- and calcite-rich sedimentary rocks.

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Elastic (e.g. Winkler & Murphy, 1995; Baechle et al., 2005) and mechanical (e.g. Baud et al., 2006; Fortin et al., 2007) weakening from water saturation are widely known to occur in sedimentary rocks. As discussed by different authors, this effect is particularly observed in carbonate rocks (e.g. Baechle et al., 2005; Vajdova et al., 2010). In particular, elastic weakening from water full saturation was shown to occur (e.g. Assefa et al., 2003; Baechle et al., 2005; Adam et al., 2006) and to be a reversible effect (Baechle et al., 2005). As a consequence from their studies, adsorption appeared as a reasonable candidate to explain such weakening.
To improve our understanding on the physics underlying this phenomenon, ultrasonic (f ~ 0.5 MHz) elastic properties are measured at room P-T conditions on a large dataset of both clean limestones (i.e. ~100% calcite) and sandstones (i.e. ~100% quartz) at very low saturations from Relative Humidity (RH) variations. To assess the amount adsorbed, mass variation and induced amount of saturation are also tracked simultaneously to elastic wave velocities. The experimental set-up is detailed in figure 1 (A):
Both rock types show dependence to adsorption, yet these dependencies differ. Limestones show clear increase in saturation with RH up to about Sw ~ 2% in some cases, but almost no weakening is observed in limestones. The exact reverse is observed in sandstones, i.e. elastic weakening but very small saturation. This result shows clear anti-correlation between saturation and elastic weakening. Furthermore, it is also shown for all rocks that P-wave and S-wave weakening are strictly equivalent.
Following Johnson et al. (1971) approach (Fig. 1 (B)), this weakening effect can be explained by surface energy variations at grain contacts. Using Murphy et al. (1984) model (i) a theoretical explanation for the equivalency between P- and S-waves weakening is inferred; and (ii) insights on surface energy changes with RH are obtained. In the case of the high porosity sandstones, surface energies fit the theoretical values at vapor saturating pressure conditions. Both reasons imply that Murphy et al. (1984) model is consistent with the experimental results.

Experimental evidence of dispersion and attenuation effects on fully-saturated sedimentary rocks.

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Interpreting sonic (f ~ 1 kHz) or even seismic (f ~ 1 Hz) field data from laboratory measurements (f ~ 1 MHz) proves to be a difficult task as fluid-saturated rocks are shown to be dispersive. To improve the current knowledge on these frequency effects, a new methodology is developed at the Ecole Normale Supérieure of Paris aiming at measuring the whole set of elastic moduli at both low (f ~ 10-3-100 Hz) and high (f ~ 1 MHz) frequencies. While high frequency moduli are inferred using the usual ultrasonic wave velocity set-up (Birch, 1960), the low frequency ones are obtained from the stress-strain method (e.g. Batzle et al., 2006; Adelinet et al., 2010; Tisato & Madonna, 2012; Madonna & Tisato, 2013). Dependence of these properties on pressure is investigated for confining up to Peff ~ 50 MPa.
Results on low frequency (f ~ 10-2-10-1 Hz) bulk modulus have previously been obtained on Basalts (Adelinet et al., 2010) and Sandstones (David et al., 2013). Yet, recent calibrations on three standard samples improved the measurements accuracy (Pimienta et al., 2013), leading to more constrained measurements of bulk moduli KLF as well as insights on bulk attenuation through the phase shift ?? (Fig. 1).
The calibrations presented in figure 1 prove to be reliable, and show both a good fit between high (KHF) and low (KLF) frequency measurements and accurate LF attenuation measurements (??K). The whole set of low and high frequency elastic properties are measured on two Fontainebleau sandstones of 7% (FoSp7) and 10% (FoSp10) porosity under dry, glycerine then water saturated conditions. Fontainebleau sandstones are chosen for their pure quartz content, thus allowing to discard effects due to clays. Furthermore, the permeability-porosity relationship is well quantified on this rock (Bourbié & Zinsner, 1985). Permeability is at about 10-15 m2 and 10-14 m2 respectively for FoSp7 and FoSp10.
For both sandstones, low (i.e. KLF) and high (i.e. KHF) frequency bulk modulus values are very close in dry conditions. Their dependence to pressure follows an increasing trend up to a constant value at higher confining pressure, which is understood as the threshold for microcracks closure. Also, the measured ?? values are down to about 0.01 to 0.02, so that 0.02 is considered the limit of accuracy of the present apparatus.
While KLF does not vary with saturation, KHF increases. Moreover, it shows smaller variation with pressure. Note also that the difference between KLF and KHF decreases with confining pressure. This is consistent with earlier results and interpretations (Adelinet et al., 2010; David et al., 2013): (i) KLF is fully drained at the frequency of study, which is consistent with Biot-Gassmann theory; and (ii) KHF is measured at frequencies high enough for the fluid to be considered as frozen. No measurable attenuation is observed.
When introducing glycerine into the sample, KHF increases as compared to the water-saturated case. KLF also shows an increase from the dry and water-saturated case. This increase of the LF bulk modulus is coupled to an increase of the phase shift, and thus of the measured attenuation. Dependence on frequency is observed for both KLF and ??, and is interpreted as the transition from drained to undrained regimes.
The results are discussed within the framework of Biot-Gassmann theory.

Neutron imaging of deformation and fluid flow in sandstones

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Understanding the mechanisms of deformation and failure in rocks and their implications for fluid flow and storage are key to a number of important industrial/environmental applications, including geologic CO2 sequestration and hydrocarbon production into/from subsurface rocks. This work aims at developing appropriate tools for full-field investigations of deformation and fluid-flow in rocks under pressure.
The most common method to analyse the deformation behaviour of rocks is triaxial compression testing where an axial load is applied to a sample under some confining pressure with the stress and strain measured at the boundaries of the sample. In such experiments, the fluid flow properties might also be measured by a range of techniques involving monitoring flow rates or fluid pressures at the ends of the test specimen. Unfortunately with such approaches it is not possible to observe the mechanisms leading to failure and the measurements (of stress, strain, flow) can only be interpreted through an assumption of homogeneous deformation within the test specimen. This assumption is very rarely valid, as failure in rocks generally occurs through some localised phenomena such as strain localisation or fracture. Therefore experimental techniques that permit full-sample observation of the deformation and flow are required. Techniques such as neutron and x-ray tomography are ideal for this purpose, as they permit visualisation of the interior of bulk specimens. The focus of this current work is the use of neutron radiography and tomography to characterise both deformation and fluid flow in laboratory-deformed specimens of rocks.
The interest in using neutrons for this study is two-fold. The first reason is the sensitivity to hydrogen, which provides a highly sensitive measurement of water distributions and movements in bulk rock samples (e.g., Hall et al., 2010; Hall, 2012). Secondly, neutrons are more penetrating, than x-rays, of dense materials such as the metals used in pressure containment vessels for triaxial experiments. Neutron imaging could thus facilitate «in-situ» 3D imaging of triaxial tests on rocks at higher confining pressures (in this context, «in-situ» refers to performing an experiment, the triaxial test, in an imaging set-up to enable 3D imaging of the sample as it deforms). A restriction of similar work using x-rays is the difficulty of producing an experimental device capable of sustaining the high pressures needed whilst remaining transparent to the probing x-rays.
The larger project, of which the experiments described below represent a small part, aims to combine in-situ loading of sandstone samples under confining pressure with imaging at different load levels to derive the strain field evolution and also to track the movement of injected fluids as the deformation evolves. The primary purpose of this current work and the results that will be presented is to prove the concepts in advance of more complete experiments.
Two sets of experiments were performed, both involving samples of a Vosges sandstone and Benthiem sandstone. The first set of experiments had the objective of testing if neutron tomography can be utilised for full-field strain mapping based on 3D-volumetric digital image correlation (DIC). Such analysis has been previously demonstrated with x-rays (e.g., Charalampidou et al., 2011). The aim of this project is to test if neutron tomography images can be used in a similar way, i.e., to assess if the contrast in neutron tomography images of such materials permits DIC analysis. This thus allows an assessment of the viability of neutron imaging and DIC for 4D strain field analysis of in-situ triaxial tests at high confining pressures. The samples analysed were a set of specimens of Bentheim and Vosges sandstones imaged using both x-ray and neutron tomographies before and after triaxial testing (triaxial tests were run at GFZ-

Potsdam and Laboratoire 3SR, Grenoble). The imaging was performed at the neutron tomography beamline (CONRAD) at the Hemholtz Zentrum Berlin.

The second set of experiments investigated the use of neutron imaging to follow fluid flow in deformed samples of rock and to perform full-field permeability measurements. The aim being to gain better understanding of the controlling factors on permeability evolution due to localised deformation by determination of what modifications to the permeability field have occurred, where and why. In extension to previous work, pressure driven fluid flow is considered and alternating injection of H2O and D2O (heavy water) are assessed. Furthermore flow in samples deformed under plane-strain conditions (using the new biaxial device for rocks at Laboratoire 3SR in Grenoble) was also investigated. These experiments were performed on the NEUTRA beamline at the Paul Scherrer Institute in Villigen, Swtzerland.

Results will be presented from both of the experimental programs and the key conclusions from the experiments can be summarised as follows.

- Neutron tomography of the two sandstones provides a different set of information to the equivalent x-ray images; whilst the overall structural information is basically the same, the neutron images reveal previously unnoticed features likely relating to more hydrogen rich materials (probably clays).
- The DIC on the neutron images was successful and reveals much the same information as the x-ray images, thus indicating the neutron tomography can be used in much the same way as x-ray tomography for 4D investigations of deformation.
- The acquisition times for the neutron imaging (at the HZB reactor source) were only slightly longer than for the x-ray imaging (using a laboratory x-ray source at HZB).
- Pressure controlled H2O-D2O alternating sample floods can be imaged using neutron radiography and reveals some interesting flow phenomena between the two fluid phases (which are currently being investigated).
- Imbibition into samples deformed under plane-strain conditions reveals fluid flow and saturation patterns that can be directly related to 2D-DIC strain field mapping performed during the loading tests (the link between strain and flow requires further investigation).

Bésuelle P., Hall S., 2011, Characterization of the strain localization in a porous rock in plane strain condition using a new true-triaxial apparatus, 9th International Workshop on Bifurcation and Degradation in Geomaterials (IWBDG 2011), Porquerolles, France, may 23-26, 2011, Org. S. Bonelli, C. Dascalu, F. Nicot, Springer, pp. 343-350.

Charalampidou, E-M. Hall, S.A., Stanchits, S., Lewis, H. and Viggiani, G., 2011, Characterization of shear and compaction bands in a porous sandstone deformed under triaxial compression, Tectonophysics, 503, 8-17.

Hall, S.A., 2013, Characterisation of fluid flow in a shear-band in porous rock using neutron radiography, Geophysical Research Letters, 40, 2613?2618.

Hall, S.A., Hughes, D. and Rowe, S., 2010, Local characterisation of fluid flow in sandstone with localised deformation features through fast neutron imaging, proceedings of 14th International Conference on Experimental Mechanics (ICEM 14), EPJ Web of Conferences, 6, 22008.

Micromechanics and AE source mechanism in stick-slip friction tests

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In this study we investigate frictional sliding and microfracturing processes during two laboratory stick-slip friction experiments performed on Westerly Granite samples using acoustic emission monitoring and the analysis of seismic moment tensors and b values. The stick-slip experiments were performed at constant displacement rate on a sample with prefabricated sawcut, and a sample previously fractured at 75MPa confinement. AE activity was recorded by sixteen P-wave sensors glued directly to sample surface providing a good spatial coverage of AE sources. Nearly 43,000 events were located in both experiments using a time-dependent 1D anisotropic velocity model. Full moment tensor inversion was performed using first P-wave amplitudes. We analyze temporal changes in the moment tensor components, b-values, and tensile angles during periodic stick slip loading. In both experiments we observe significant contributions of non-double couple components to the AE full moment tensors indicating compaction. Significant episodic changes in MT components and tensile angle correlate closely with stress and time during the stick slip cycles but show characteristic differences between samples with different fault geometry. We also observe temporal changes in b values and orientation of focal mechanisms. The AE activity from sliding along a rough fractured surface displays a broader damage zone and significant shear-enhanced compaction during large slip events. In contrast, slip along a prefabricated sawcut shows strongly localized AE activity along the fault plane and only minor compaction.

Evolution of strain localization in rock-like material in tri-axial axisymmetric compression tests from digital image correlation

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Mechanism of initiation and evolution of rupture in solids and in geometries in particular remains a largely debatable issue in spite of numerous studies. It clearly depends on the loading conditions and notably on the pressure or mean stress . At sufficiently high the material failure results from the strain localization within narrow bands. Starting from a certain value (depending on the material) the macro-failure/fracture does not occur at all and what is observed is the development (thickening) and multiplication of bands. This behaviour occurs at a confining pressure Pc = Pbdt corresponding to the transition from brittle faulting to ductile deformation (Wong et al., 1997). The evolution of this process, including the moment and place of initiation of the first band and then of the others, remains poorly known. A detection of the onset of deformation banding is however crucial for the theoretical analysis of the underlying mechanism, which is believed to be a constitutive instability resulting from the deformation bifurcation. The bifurcation analysis certainly provides a useful framework to address the problem of strain localization, but it is not completely clear what are the limits of its application to the behaviour of real materials. One of the major criteria of applicability of this theory is a correspondence between the critical hardening modulus predicted theoretically to that measured in the experiments. To make correct measurements of this parameter, one has to precisely define the onset of deformation banding and locate it on the stress-strain curve. To do this one needs a high-resolution displacement field and its evolution in the sample or at least on its surface during the deformation.

This is relatively easy in uniaxial tests since the surface of the tested sample is free and accessible for observations/measurements. In these tests (Pc = 0), the failure process is usually very brittle and dynamic. It is thus difficult to detect the pattern of strain localization preceding the fracture. At elevated confinement, when strain localization bands form in hard rocks, the sample is within the steel pressure cell, which makes it impossible to measure directly the deformation field unless using heavy and expensive X-ray tomography techniques (Besuelle et al., 2000) that can be applied in certain cases. In most cases only the post-mortem sample observation is possible.

To overcome this difficulty, we performed axisymmetric compression test with the samples made of a low-strength synthetic granular, cohesive, frictional and dilatant rock analogue material GRAM1 (Nguyen et al., 2011). This material allows performing tests at Pc up to values well in excess of Pbdt (which is of about 0.3 MPa for GRAM1) by using a transparent (made of polycarbonate) pressure cell. During an experiment, the GRAM1 sample and two rigid platens at the ends are jacketed with a very thin (~300 µm) transparent latex film. It is believed that due to both the small jacket thickness and rigidity, it follows exactly the displacement of the sample surface. A speckle-like pattern is sprayed and fixed on the jacket. The loading cell with the sample is then filled with water after which the confining pressure is applied to 0.3 MPa using a pressure generator. Then the sample is subjected to the additional axial compression controlled by an internal force transducer of 8 kN capacity. Loading is applied with displacement control at constant piston velocity of 10-6 m/sec. The experimental setup is completed by two high-resolution cameras disposed at 180° to each other. During a test, the pictures are taken simultaneously by the two cameras. Full displacement field of the GRAM1 sample surface is then calculated using Digital Image Correlation (DIC) method from the pictures taken during loading. We use COSI-Corr, implemented under ENVI by Imagin' Labs at California Institute of Technology (Leprince et al, 2007). This code is based on the properties of the Fourier transform phase and provides the full field displacement between two pictures taken at different loading stages.

Several experiments have been performed at the same Pc, Pc = Pbdt. Different tests provided similar results, although they are not exactly the same in spite that the experimental conditions were the same. There are always some fluctuations in the conditions and in the material properties/ homogeneities preventing the exact results reproduction. In each test the deformation bands do not form simultaneously but sequentially and evolve with loading. Its evolution consists in propagation and then thickening. The deformation bands pattern on a post-mortem sample corresponds very well with DIC full-field strain results.

The initiation of the first band occurs clearly before the axial stress peak, which does not necessarily means that the deformation localization occurs in the hardening regime as the axial stress peak is a nominal stress charactering the response of the structure (entire sample) and not the stress-state at the point of deformation localization. This issue is discussed in detail based on the local DIC data and the theoretical analysis and numerical modeling.

Characterization of the mechanisms of deformation at the small scale in a clay rock by in-situ X-ray micro tomography

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The principle behind the use of deep geological repositories for the storage of radioactive waste relies, among others, on the low permeability of the host rock. Since permeability is influenced by mechanical damage of the material, the study and comprehension of deformation mechanisms is crucial for the evaluation of this material as a host rock.
We have studied a clay rock with a porosity of about 16% (Callovo-Oxfordian clay rock from Eastern France, Meuse/Haute Marne ANDRA underground research laboratory). Tests in axisymmetric triaxial compression have been performed on the microtomography beamline ID19 at ESRF, starting from isotropic stress states at several stress levels (5 to 20 MPa), using a new specifically-developed triaxial cell, transparent to x-rays. Specimen diameter was about 1 mm and 3D image pixel size 700 nm. The very high spatial resolution of images obtained during the specimen loading, combined with the advanced reconstruction techniques used allows the carbonates, quartz and pyrite inclusions in the clay matrix to be distinguished very clearly.
3D Digital image correlation is applied to successive 3D images, in order to obtain the local strain field induced by macroscopic mechanical loading, at the scale of inclusions. The mechanisms of deformation such as inclusion decohesion and crack initiation in the clay matrix will be discussed.

IMPACT OF MICROSTRUCTURAL AND MINERALOGICAL HETEROGENEITIES ON DEFORMATION AND DESICCATION CRACKING OF THE TOURNEMIRE CLAY-ROCK BY COUPLING DIC AND SEM METHODS

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A cracking phenomenon due to a desaturation process of the argillaceous medium was observed on the gallery walls of the Underground Laboratory of Tournemire (Aveyron, France). At present the mechanical and geological factors which control the deformation and fracturing mechanisms are not well-known. The study presented here aims to identify the microstructural and mineralogical factors which govern the deformation mechanisms and cracking phenomenon on clay- rocks caused by humidity changes from centimeter to millimeter scales.
For this purpose, an experimental setup was designed in laboratory. It was separated in two parts: the first part uses Digital Image Correlation (DIC) and the second part the Scanning Electron Microscopy (SEM) method. This experimental device allowed to compare the strain fields induced by humidity changes on centimeter to millimeter scales and to know quantitatively the influence of the microstructure on strain fields at millimeter scale.
In a waterproof box, a sample taken from the 1996 East gallery of the Tournemire site was submitted to a shrinking process by progressive humidity steps between 98 to 33% during six months. The sample was a cube of 80mm3 withtwo centimeter sides. Two faces of the cube were recorded by one camera each during desiccation. The first camera recorded images (2560x1920 pixels) of one complete face called «large field» (2.5x1.8mm²) with a resolution of 10 µm.pixel-1. The second camera recorded one part of another face called «zoomed field» (5.5x4.2mm²) with a resolution of 2.15µm.pixel-1. The temperature was fixed to 23°C±2°C and humidity conditions were controlled by saline solutions. The sample was supported by teflon wedges to permit water exchanges on all faces and the set was put on a precision balance to follow the water content during the shrinking process.
By DIC, each series of images was compared with the final image of the desaturation process (a) to follow the evolution of the mean deformation E of each field and (b) to localize the desiccation cracks. The domains of correlation were square windows of 40x40 pixels for the two fields. After the desiccation process, the zoomed field was analyzed by merging SEM back-scattered electron images with a resolution of 0.625µm.pixel-1 and correcting electron beam drift. A mineral map of its whole surface composed of 58 million pixels is then produced and superimposes on the strain field map from DIC. In same domains as DIC windows, some textural parameters were calculated on the mineral map to quantify the local organization of the rock: the proportion of coarse grains and clay matrix, the size, the morphology, the orientation, the number and the orientation of the particles. From this experimental setup, the strain fields in two different scales were quantitatively related to the relative humidity, the water content (for millimeter and millimeter scales) and the organization of the mineralogy (for millimeter scale) of the sample.
Our preliminary results show that:
At centimeter and millimeter scales, the deformations measured by DIC method were clearly induced by the relative humidity changes. At millimeter scale, deformation is controlled by proportion of clay matrix and coarse grains and the number of micro-cracks At millimeter scale, the localization of fractures is controlled by textural heterogeneities: the proportion of clay matrix and coarse grains, the size, the orientation and the morphology of grains.

Fracture and healing ? an efficient geological process

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Fracture and healing occur in a variety of geological, biological, metallurgical and engineering processes. In geology, the repeated occurrence of fracture and healing is most common in active tectonic regions, earthquake settings and volcanic conduits, and is intrinsically related to diffusional processes, aided by catalytic fluids. Here, cycles of compression, healing by contact and tension are performed on standard soda-lime silicate liquid at high temperatures (500 to 700 °C; i.e., in the diffusive regime of the viscoelastic body). Specifically, the flat ends of two cylindrical specimens are brought into contact at relatively low strain rates (10-3 s-1) until a target normal stress is reached (1, 2.5, 5 and 10 MPa). The specimens are then held in contact whilst the normal stress is left to viscously dissipate for different time fractions of Maxwell's relaxation timescale of the liquid (0.25, 0.5, 1, 2.5, 5, 10, 20, 40, 80, 160, 320) in order to achieve different degrees of fracture healing. Strength recovery is assessed by subjecting the healed sample to a rapid tension event at 10-1 s-1 to ensure a purely brittle response. We note that healing becomes efficient when allowed to operate for at least 5 times the relaxation timescale of the material. From this point onward, we observe an exponential increase in strength as a function of healing time. High-speed infrared thermographic monitoring of the samples during each fracture and healing cycles demonstrates that a small component of heat is generated during failure.

Fracture healing dynamics are found to share similarities with sintering, whereby the kinetics of the process is viscosity and diffusion dependent, and here we aim to expand this definition to include normal applied stress constraints. At volcanoes, the recurrence of seismic swarms is perceived as a first order constraint on the dynamics and mechanics of magma ascent. The data presented here may help constrain the dynamics of the signals related to fracture and healing cycles, whilst assessing in real time the rheological state of magma in conduits. The process presented here is equally applicable to the strength recovery of tectonic fractures/faults harbouring frictional melt.

Mechanical behavior of low porosity carbonate rock: from brittle creep to ductile creep.

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Mechanical compaction and associated porosity reduction play an important role in the diagenesis of porous rocks. They may also affect reservoir rocks during hydrocarbon production, as the pore pressure field is modified. This inelastic compaction can lead to subsidence, cause casing failure, trigger earthquake, or change the fluid transport properties. In addition, inelastic deformation can be time ? dependent. In particular, brittle creep phenomena have been deeply investigated since the 90s, especially in sandstones. However knowledge of carbonates behavior is still insufficient.

In this experimental study, we focus on the mechanical behavior of a low porosity (9%) white Tavel (France) carbonate rock (>98% calcite) at P-Q conditions beyond the elastic domain. It has been shown that in sandstones composed of quartz, cracks are developing under these conditions. However, in carbonates, calcite minerals can meanwhile also exhibit microplasticity. The samples were deformed in the triaxial cell of the Ecole Normale Superieure de Paris at effective confining pressures ranging from 35 MPa to 85 MPa and room temperature. Experiments were carried on dry and water saturated samples to explore the role played by the pore fluids. Time dependency was investigated by a creep steps methodology: at each step, differential stress was increased rapidly and kept constant for at least 24h. During these steps elastic wave velocities (P and S) and permeability were measured continuously.

Our results show two different creep behaviors: (1) brittle creep is observed at low confining pressures, whereas (2) ductile creep is observed at higher confining pressures. These two creep behaviors have a different signature in term of elastic wave velocities and permeability changes. Indeed, in the brittle domain, the primary creep is associated with a decrease of elastic wave velocities and an increase of permeability, and no secondary creep is observed. In the ductile domain, the primary creep is also associated with a decreased in elastic wave velocity and an increase of the permeability. However, the secondary creep is associated with a slight increase of velocities and almost no change of permeability (pointing to recovery). This behavior observed in the ductile regime can be explained by two mechanisms: cracks propagation and plasticity. Indeed, the increase of stress induces fractures. When long term plastic phenomena take place at the tips of the cracks, these fractures close partially.

Stick-slip behaviour of saturated sandstone specimens with different saw-cut failure planes

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Active faults, with a broad variety of orientations, might be in a distinct distance to an injection/ withdrawal well. Such pre-existing faults, according to Sibson (1990), may be defined as favourably oriented for frictional reactivation, unfavourably oriented or severe misoriented depending on their attitude to the prevailing stress field. The reactivation of favourably and unfavourably oriented faults due to fluid or gas injections/withdrawals is likely to induce seismicity, if the faults are stressed critically (Townend and Zoback, 2000). Brace and Byerlee (1966) first suggested that stick-slip instabilities observed in laboratory tests may represent an analogue of seismic events. This work aims at exploring experimentally stick-slip behaviour of saturated sandstone specimens with prefabricated saw-cuts representing smooth faults of different orientation.

Cylindrical specimens of Flechtingen sandstone (~ 9% porosity), 50 mm in diameter and 99 to 103 mm in length, were cored parallel to the bedding plane. A surface-ground saw-cut was machined across the samples. Two different orientations were tested: saw-cuts inclined at 40° and 45° to the sample long axis. A 2 mm diameter borehole, leading directly to the fault plane, was drilled at the base of each specimen.

Triaxial compression experiments were performed using a servo-hydraulic loading frame from Material Testing Systems (MTS). Two Quizix pore pressure pumps controlled the applied pore pressure and measured the injected fluid volume. Initially, the specimens were loaded under hydrostatic pressure up to 55 MPa. Vacuum was applied during sample loading. Then, the samples were saturated in situ applying a constant inlet pore pressure of 5 MPa. Distilled water, injected through the borehole, was used as pore fluid. Finally, specimens were loaded up to almost 1% axial strain at a constant displacement rate of 20 μm/min. Confining pressure and pore pressure were held constant during this loading stage.

P-wave velocities and Acoustic Emission (AE) activity were recorded during the experiments. Sixteen P-wave sensors (PZT piezoceramic disks of 5 mm diameter and 2 mm thickness placed in brace housings) were glued to the surface of the specimens and sealed in a neoprene jacket with two-component epoxy. Two P-wave sensors were embedded in two metallic spacers placed at the bottom and top ends of the specimens. All sensors had a resonant frequency of 1 MHz. AE signals were amplified by 40 dB, using Physical Acoustic Corporation (PAC) preamplifiers. Half of the sensors, used for ultrasonic transmission, were emitting rectangular electrical pulse of 100 V amplitude and 3μs duration every 30 seconds. During ultrasonic transmission, these sensors were disconnected from the preamplifiers. The remaining sensors were recording the pulses. P-wave velocity measurements were made along 65 different transmitter-receiver traces. Full AE waveforms and ultrasonic signals were stored continuously in a 16 channel transient recording system (DAXBox, PRÖKEL, Germany) (Stanchits et al., 2006). During the experiments, all ultrasonic signals and AE waveforms were recorded with zero dead time between the subsequent signals. After the experiments, ultrasonic signals and AE waveforms were automatically discriminated. An automatic picking algorithm, based on the Akaike information criterion (Leonard and Kennett, 1999), was used to pick the P-wave onset times. AE hypocentre locations were calculated by minimising travel time residuals using the downhill simplex algorithm (Nelder and Mead, 1965), considering time-dependent variations in P-wave velocities and employing an anisotropic heterogeneous ultrasonic velocity model, consisting of five horizontal layers. Time dependent anisotropic velocities inside each layer were periodically updated using ultrasonic transmission measurements. First motion amplitudes were picked. An average first motion polarity for each AE event was calculated as the mean of all sensor recordings. AE events were defined as T-, S- and C-type sources (tensile, shear and pore collapse, respectively; Zang et al. 1998).

Stick-slip behaviour was observed during the triaxial compression experiments in samples with 40° and the 45° saw-cuts. However, the mechanical results and AE analysis in both samples show different patterns:

We observed more stick-slip events in the specimen with a saw-cut of 40° compared to the 45° fault at similar total shear strain. Peak differential stress at failure and stress drop increased for consecutive slip events for both samples. Stick slip events were initiated at lower stress for the 40° saw-cut. For the 40° saw-cut sample, stress drops and displacements along the fault plane are smaller than those measured in the 45° saw-cut sample. Shear stress drops range from 2.6 to 24.6 MPa and from 6.7 to 44.7 MPa and the slip displacements along the saw-cut planes range from 11 to 98 µm and from 23 to 160 µm for 40° and 45° saw-cut samples, respectively. AE locations reveal that during slip events crack damage is strongly localised along the faults, while during loading between slip events damage propagates progressively into the wall rock. This suggests that damage zone width is dominated deformation during interslip periods. AE activity leading to unstable slip events was considerably higher for 45° saw-cut sample compared to the 40° fault. Tensile and shear events dominate stick-slip cycles in 40° saw-cut samples, whereas grain crushing and pore collapse dominate AE activity in sample with 45° saw cut.

References

Sibson, R (1990). Rupture nucleation in unfavourably oriented faults. Bulletin of Seismological Society of America, Vol. 80, No. 6, pp. 1580-1604.

Townend, J, Zobac, MD (2000). How faulting keeps the crust strong. Geology, 25,5,399-402.

Brace, WF, Byerlee, JD (1966). Stick-slip as a mechanism for earthquakes. Science, 153, 990.

Stanchits, S, Dresen, D, Vinciguerra, S (2006). Ultrasonic velocities, acoustic emission characteristics and crack damage of basalt and granite. Pure and Applied Geophysics, 163, 5?6, 975?994.

Leonard, M, Kennett, BLN (1999). Multi-component autoregressive techniques for the analysis of seismograms. Phys. Earth Planet. Int. 113 (1-4), 247.

Nelder, J, Mead, R (1965). A simplex method for function minimization. Computer J. 7, 308-312.

Zang, A, Wagner, FC, Stanchits, S, Dresen, D, Andresen, R, Haidekker, MA (1998). Source analysis of acoustic emissions in Aue granite cores under symmetric and asymmetric compressive loads, Geophys. J., Int. 135, 1113-1130.

Continuous oscillatory flow analysis during triaxial deformation: Can we resolve spatial characteristics of fault evolution?

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The evolution of hydraulic rock properties during brittle failure plays a key role in the dynamics of faulting. Hydro-mechanical properties and their changes in the wake of deformation affect for example the mode of failure, the time-space characteristics of induced seismicity, and fluid flow within evolving fault zones. The pore-pressure oscillation method allows for monitoring the development of hydraulic properties during triaxial compression in the laboratory. Conventional upstream-downstream pore-pressure analysis yields effective properties of the bulk sample without a chance for resolving spatial heterogeneity. In contrast, the oscillatory flow method permits variations of the penetration depth of the pore-pressure perturbation by changing oscillation period and thus exhibits the potential for «screening» through a deforming sample. Yet, currently, technical issues and automatization problems of the evaluation procedure hamper the usage of this promising method. In this exploratory study, we focused on 1) reducing and correcting hysteresis occurring during the periodic in and out movement of the volumometer piston, 2) subtracting the trend in the volumometer record associated with changes in total pore volume, and 3) automatizing a procedure for the determination of the amplitude ratio and phase shift between the oscillatory pressure and flow signals.

Relating facies and rheological properties of rocksalt: new insights from physical properties and microstructural observations on Messinian halite of Italian Peninsula.

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The importance and economic interest on rocksalt deposits and salt bodies are well known and extensively studied. The physical and mechanical properties of salt have a profound influence on the tectonics as well as they are considered to be vital for applicative purposes such as mining, petroleum and nuclear waste storage. However, previous scientific works have mainly focused on synthetic rocksalt or commercial salt, whereas the role of natural heterogeneities and their effect on salt rheology have been not investigated quantitatively.
Here we present a comprehensive salt facies study including salt cores from the Saline di Volterra Formation (Volterra Basin, northern Italy) and salt samples from Petralia and Racalmuto salt mines (Caltanissetta Basin, Sicily) and Zinga 1 salt diapir (Crotone Basin, southern Italy).
Through microstructural observations and thin sections image analyses we could identify and describe quantitatively four salt facies in terms of end members.
Throughout optical analyses we identified four salt facies, that have been named as «green», « blue», «black» and «red» (Fig. 1) depending on the relationships between primary and secondary salt, recrystallization and deformation. The «green» facies has a great abundance in primary salt remnants (around 20% in volume) rich in primary fluid inclusions, rather rounded crystals (average roundness is 0,6) with no preferred orientation and average area of 1,9 mm2. Thin (1-2mm) clay layers are intercalated with salt. Thus is considered the less deformed and recrystallized end member. Proceeding toward increasing salt deformation, primary salt remnants are gradually dissolved. Secondary salt is formed and a progressive decrease in average crystals size, increase in crystals elongation and preferred orientation can be observed. Fluid-enhanced deformation mechanisms move fluids toward crystal boundaries, that always host complex networks of secondary fluid inclusions. So, we identified first the «black» facies, with much less primary salt remnants (around 10% in volume), more elongated (average roundness is 0,4) and smaller (average area around 1,6 mm2) crystals showing a clear preferred orientation. Some clay inclusions are also present along with salt. Then, the «red» facies has been analyzed, being the most deformed salt end member, with almost no primary salt remnants and even smaller (average crystals area is 0,5mm2), very elongated crystals (average roundness is 0,4) also with a neat preferred orientation. The «blue» facies cannot be placed on this evolutionary path, being made up of totally recrystallized (no primary salt) but only very slightly deformed (roundness is 0,6) and bigger (average area is 4,9 mm2) crystals with no preferred orientation. This facies could originate from one of the others due to dissolution/redeposition or dynamic recrystallization processes. Salt samples from Caltanissetta and Crotone Basin have characteristics that fit very well with the «green», «red» and «blue» facies, confirming the effectiveness of chosen end members.
Seismic waves velocity measurements and uniaxial compressive runs allowed to test the effect exerted by facies characteristics on the physical and mechanical properties of salt. Average seismic waves velocity on cubic sample with side of 5cm resulted faster and less variable (Vp is around 4460 m/s) in deformed and recrystallized salt («black» and «red» facies) compared to the «green » facies rich in primary salt (Vp around 4270 m/s). Dynamic Young's Modulus (average value about 38 GPa) mirrors this behavior, with lowest values related to the primary salt rich facies. The anisotropic effect induced by the deformation is evident also considering the velocities along each cube axes, being faster for X and Y axes (on average, Vp(x)=4383 m/s, Vp(y)=4422 m/s) compared to Z (vertical) axis (Vp(z)=4256 m/s). Uniaxial compressive tests, carried out at ambient temperature on prismatic samples cut from cubes referred to above, revealed the effect of the salt facies in the mechanical properties of samples. Static Young's Moduli (average value about 5,3 GPa) result much lower than the dynamic ones. In this case lowest values are related to the highly deformed and recrystallized «red» facies (2,95 GPa on average). Notably, the peak

stress (30,4 MPa on average) resulted inversely proportional to the static Young's Moduli, regardless of the salt facies. Volumetric deformation (average around 7,5%) was higher for the primary salt rich facies (about 9%).
Therefore, we found that parameters like crystals elongation, average crystals area, primary salt abundance and average crystals orientation may influence, for instance, resulting Vp (P-waves velocity), Es (static Young Modulus) and peak stress. Namely, we observed that with increasing deformation, also recrystallization degree and crystals elongation increase, while primary crystals abundance, Es and average crystals dimension decrease (cf. Fig. 1).
Results from this study indicate that the different characteristics of a salt facies influence the bulk rheological parameters and, consequently, the rocksalt deformation behavior. Although further analyses are necessary, we suggest that studies on salt bodies cannot be approached without detailed petrophysical and rheological analyses of rocksalt facies.

Characterization of the early strain localization in a sandstone rock

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Abstract

Failure by strain localization is commonly observed in geomaterials. Most of studies are performed with classical axisymmetric triaxial compression tests. The effects of confining pressure are observed on several aspects: onset of localization, pattern of localization, porosity evolution inside bands. Complex patterns of localization can be observed at high confining pressure in the transition between the brittle and ductile regime, showing several deformation bands in the specimens (e.g., [1]). However the history (time evolution) of the localization is not accessible because the observations are post-mortem. We present here new results obtained with a new true triaxial apparatus that allows observation of the rock specimen under loading. The strain field in the sample, and its evolution up to and beyond strain localization, can be measured by digital image correlation (DIC) of photographs taken through a hard transparent window.

We have studied a porous rock, the Vosges sandstone with a porosity of about 23% (from Eastern France, Vosges mountains). Tests in plane strain compression have been performed, starting from isotropic stress states at several stress levels. Results of the time evolution of the pattern of localization in the specimens are shown. Strain localization appears to start well before the stress peak, sometime at about 50% of the stress peak, by very numerous parallel and conjugated shear bands, this is observed in the rock. This early localization, for the authors' knowledge, has never been observed previously in rocks. Then, the number of active bands decreases progressively during subsequent loading, up to a very few bands at the peak and during strain softening. It is also possible to demonstrate how the localization is influenced by confining pressure. The experimental results are systematically analyzed in terms of fields of shear and volumetric strains. A post-mortem analysis has been done by optical microscopy to characterize the processes of deformation in the early localization bands detected by DIC.

References

Bésuelle P., Desrues J. and Raynaud. S., 2000, Experimental characterization of the localization phenomenon inside a Vosges sandstone in a triaxial cell. Int. J. Rock Mech. Mining Sci., Vol. 37, n° 8, pp. 1223-1237.

Microstructures induced by dynamic damaging and fracture healing by fluid circulation into a porous limestone: an experimental approach

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Fracturing and healing processes control the evolution of permeability and of the mechanical behavior of fault zone rocks. Fracturation increases the permeability of the fault rocks, creating flow-channels for the fluid circulations and consequently, enhancing the kinetics of fluid-rock processes such as healing by pressure solution. Conversely, healing processes decrease permeability by fracture closing and lead to rock strengthening. Thus, the timescale of these two processes plays an important role in the time recurrence of the earthquakes. Here we report microstructural observations on porous limestone samples, experienced rapid dynamic damaging experiments and long-term percolation experiments. Wit X-ray microtomography and FEG-SEM microscopy, we show that the heterogeneities initially present inside the sample, such as porosity or the largest calcitic grains, can concentrate the deformation. The results from percolation experiments show that microfracturation networks heal faster than the largest fractures, leading to a heterogeneous strengthening of the rock. This effect highlights the importance to take account of the rock damage states and the geometry of the fault damage zone, which could have a strong influence on the processes of earthquake nucleation and rupture propagation.

Continuous determination of hydraulic properties with high temporal resolution during triaxial deformation of sandstone

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Understanding the relation between the evolution of rock properties and of fluid pressure under different stress states is essential for predicting fluid flow during geological processes and reservoir exploitation. We conducted continuous oscillatory hydraulic experiments during triaxial compression to resolve the relation between elastic and inelastic deformation, in particular failure characteristics and hydraulic rock properties. Specifically, rather short periods were chosen for the imposed pore-pressure oscillations to yield a high resolution in strain-increment for which a set of permeability and storage capacity values could be determined. As a result, the evolution of these hydraulic properties is even constrained during imminent localized failure. Deformation experiments were performed at different strain rates (10^-7 s^-1 to 3*10^-7 s^-1) and confining pressures (10 MPa to 100 MPa) but a constant pore pressure of 20 MPa on samples of Wilkeson sandstone. Under the imposed conditions dilatant brittle failure and compactive cataclastic flow occurred at low and high effective pressure, respectively. At low effective pressures, permeability and storage capacity slightly increase while their ratio, hydraulic diffusivity, decreases during elastic deformation. Inelastic deformation has a stronger influence on the development of the hydraulic properties than elastic deformation; permeability and diffusivity tend to increase significantly while storage capacity may actually decrease. The increase accelerates when localization is approached but a drop in all properties was observed right after localization before intermediate stabilized values are reached that indicate the formation of a fault. At high effective pressures the hydraulic properties are controlled by the increasing mean effective stresses during elastic deformation leading to decreasing permeability and storage capacity and yet increasing diffusivity. During inelastic deformation permeability and storage capacity are positively correlated with stress. In the compactive cataclastic flow regime, the onset of macroscopic deformation raises diffusivity. This effect is caused by a stronger decrease in storage capacity than in permeability.

Experimental and field constraints on the mechanism of formation of natural joints (dilatancy banding vs mode I fracturing)

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Joints are the most current fractures in the shallow earth crust. They are essential actors in folding accommodation, incipient localisation and damage development of faults. They contribute to geological reservoir permeability and can affect seal integrity. Their formation mechanisms have been debated for more than a century (Pollard & Aydin, 1988). The present day widely accepted interpretation done within the framework of linear elastic fracture mechanics is that joints are mode I cracks initiating form defects/flaws and propagating with the clearcut separation of the fracture walls due to strong stress concentration at the fracture tip. In this interpretation, the plumose features or hackles (these terms cover a wide variety of diverging fractographic features decorating the fracture walls) are seen as typical of mode I cracks. The plumose topography is believed to result from the opening fracture front breakdown related to the loading mode change from mode I to mode III (the origin of this change remains unclear). In this classical interpretation, natural joints have nothing to do with the rarely observed, «dilation» bands (porosity bands) also forming perpendicular to the minor stress s3. Exotic in literature (Du Bernard et al. 2002), dilation bands are seen as end member of deformation bands (Aydin et al., 2006 ; Schultz &Fossen, 2009). This view of natural discontinuities forming perpendicular to s3 is turned upside down not only by the result of polyaxial (Jorand et al., 2011) and triaxial extension (Nguyen et al., 2011, Chemenda et al., 2011) tests on a synthetic rock analogue, GRAM (granular, cohesive, frictional, dilatant material), but also by SEM scale field observations of natural joints. The plumose topography characterizes dilatancy bands, not mode I fractures, implying that natural joints originate as dilatancy bands.

In GRAM, joint sets with joint walls bearing plumose marks were recreated for the first time. It was shown that the plumose morphology is associated with near to zero (slightly compressive or tensile) minimum stress during unloading in triaxial and polyaxial extension experiments starting from relatively high initial mean pressure P. Thus these experimental joints cannot be mode I fractures. Plumose morphology vanishes with reduction in P, the fracture surface being smooth in uniaxial tensile tests when rupture occurs at the tensile strength. On samples unloaded after they were submitted to relatively high P conditions (corresponding to the formation of the plumose marks) SEM observations perpendicular to unopened joints reveal that these features have a dilation/dilatancy band structure. They exhibit a several grain-thick zone with internal heterogeneous decohesion, but no separation of the walls. These bands have a sinuous profile which is related to the resulting plumose morphology revealed after the band opening. This shows that plumose structure is not a signature of opening mode (mode I) fracturing as previously postulated, but that of dilatancy bands/joints forming under unloading conditions at near-zero minimal stress and under relatively elevated mean stress.

The same SEM scale dilatancy band structure with grain decohesion has been evidenced on sections of plumose bearing embryonic joints in densely jointed dolomicrite, a fine grained carbonate. This strongly suggests that the current plumose bearing natural joints could form/ initiate as dilatancy bands rather than as mode I cracks, that is in more confined /deep conditions than expected. In nature, mode I (with smooth morphology) and dilatancy (plumose bearing) joints can coexist. More or less decorated joints could represent transitional cases between mode I fractures and pure dilatancy bands end-members. Further research into natural dilatancy band/ joint structure coupled with extension experiments in fine-grained rocks and theoretical/ numerical analyses is certainly a major challenge.

References:

Aydin, A. ,Borja, R. I., and Eichhubl, P. (2006). Geological and mathematical framework for failure modes in granular rock, J. Struct. Geol., 28, 83?98, doi:10.1016/j.jsg.2005.07.008.

Chemenda, A. I., S.-H. Nguyen, J.-P. Petit, and J. Ambre (2011). Mode I cracking versus dilatancy banding: Experimental constraints on the mechanisms of extension fracturing, J. Geophys. Res., 116, B04401, doi:10.1029/2010JB008104.

Du Bernard, X., P.Eichhubl, and A. Aydin (2002). Dilation bands: A new form of localized failure in granular media, Geophys. Res. Lett., 29(24), 2176, doi:10.1029/2002GL015966.

Jorand, C., Chemenda, A. I., Petit, J-P., (2012). Formation of parallel joint sets and shear band/ fracture networks in physical models, Tectonophysics, doi: 0.1016/j.tecto.2011.11.021.

Nguyen, Si-H., Chemenda A.I, Ambre J., (2011). In?uence of the loading conditions on the mechanical response of granular materials as constrained from experimental tests on synthetic rock analogue material. International Journal of Rock Mechanics & Mining Sciences, 48, 103?115.

Schultz, R.A. and Fossen, H, (2008). Terminology for structural discontinuities. AAPG Bulletin, v.92 , n°.7, pp. 853?867.

Formation of compaction bands in a porous sandstone with high density inclusions

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Compaction bands in porous sandstones have been described as tabular zones of localised deformation that accommodate pure compaction, with no macroscopic evidence of shear (e.g. Mollema and Antonellini, 1996). These deformation bands are formed normal or subnormal to the maximum principal stress direction and are accompanied by localised porosity loss (Holcomb et al., 2007). The involved micro-processes are mainly characterised by grain crushing and pore collapse. To better understand the onset and propagation of such deformation structures, a series of experimental studies has been carried out in porous sandstone specimens. In some experiments samples contained a notch acting as stress concentrator and thus, localising the onset of compaction band formation (Stanchits et al., 2009). Here we investigate the effect of high density inclusions in sandstone specimens on compaction band propagation.
Specimens of Bentheim sandstone (22% porosity) were used in this study, having a diameter of 50 mm, a length of 105 mm and a circumferential rounded notch of 4 mm depth and 0.8 mm height machined on their mid-height. Pre-deformation x-ray tomography (carried out in laboratory 3SR, Grenoble), has demonstrated the existence of high density elliptical inclusions inside the specimens ? most of them located at the mid-height of the samples (i.e. close to the region of the notch). The x-ray images had ~ 30 µm voxel size resolution.
Triaxial compression experiments were performed (at GFZ) using a servo-hydraulic loading frame from Material Testing Systems (MTS). Ultrasonic transmission signals and Acoustic Emissions (AE) were recorded throughout the duration of the tests using sixteen P-wave piezoelectric sensors, glued directly on the surface of the specimens and two P-wave sensors incorporated to the top and bottom caps. Moreover, two strain-gages were used to measure vertical displacements. Two Bentheim specimens were loaded in isotropic compression, in which the confining pressure was increased up to 135 MPa and 160 MPa, respectively. Subsequently samples were loaded in axial direction using displacement control at a rate of 20 µm/min.
AE waveforms and ultrasonic signals were automatically discriminated after each experiment. P-wave onset times were picked and AE locations were calculated, considering time-dependent variations in P-wave velocities and employing an anisotropic heterogeneous ultrasonic velocity model, consisting of five horizontal layers. Furthermore, first motion amplitudes were picked and corrected for the effects of sensor coupling and incidence angle sensitivity according to (Kwiatek et al., 2013). AE events were classified as tensile, shear, and compressive according to (Zang et al., 1998). Moment tensor inversion of AEs was also performed in order to investigate the source mechanisms and the moment tensor components.
Compaction bands in both specimens initially formed at the vicinity of the notch and afterwards propagated towards the centre of the specimens, leaving unaffected the regions of the high density inclusions, as this was demonstrated by AE locations superimposed on x-ray tomography images. A larger number of compressive AE events was observed in the specimen loaded at 160 MPa. A variation of different event types was observed in the specimen loaded at 135 MPa, although compressive events were dominant. Results will be presented from both specimens focusing on the resolved micro-processes that occurred during: a) the onset of compaction bands from the circumferential notch; b) the propagation of compaction bands at the region of the high density inclusions; c) the propagation of compaction bands far from the inclusions.

References

Mollema P.N., Antonellini, M.A. (1996). Compaction bands : a structural analog for anti-mode I cracks in Aeolian sandstone. Tectonophysics, 267, 209-28.
Holcomb D., Rudnicki, J.W., Issen, K., Sternolf, K. (2007). Compaction localisation in the Earth and the laboratory: state of research directions. Acta Geotech, 2,1-25.
Stanchits, S., Fortin, J., Gueguen, Y., Dresen, G. (2009). Initiation and propagation of compaction bands in dry and wet Bentheim sandstone. Pure Appl Geophys, 166, 843-68.
Kwiatek, G., Charalampidou, E.M., Dresen, G., Stanchits, S. (2013). An improved method for

seismic moment tensor inversion of acoustic emissions through assessment of sensor coupling and sensitivity to incidence angle. Int J Rock Mech Mining Sci, http://dx.doi.org/10.1016/j.ijrmms.2013.11.005
Zang, A., Wagner, F.C., Stanchits, S., Dresen, G., Andresen, R., Haidekker, M.A. (1998). Source analysis of acoustic emissions in Aue granite cores under symmetric and asymmetric compressive loads. Goephys J Int, 135, 1113-30.

Anisotropy of petrophysical properties for a set of porous rocks compared to microstructural anisotropy derived from ferrofluid analysis

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Anisotropy has become a major issue in geophysical studies at different scales. In particular for geophysical prospecting it provides a powerful method to analyze rock physics attributes in reservoirs or in complex tectonic settings. Several methods are currently available, among which the direct 3-D measurements of P wave velocity in many different directions on spherical rock samples, and the approximate tensorial model proposed by Louis et al. (2003; 2004). As the latter is designed to work with cylindrical samples cored in three orthogonal directions, a significant gain both in the number of measurements involved and in sample preparation is achieved compared to measurements on spheres. We have shown in previous works that the approximate model provides a relevant description of the rock anisotropy. Therefore we designed a fully automated device following this measuring scheme firstly devoted to the study of seismic anisotropy, and recently extended to permit the measurement of electrical conductivity anisotropy as well. The new setup is now able to achieve a direct comparison between the anisotropy of elastic properties and the anisotropy of transport properties.
We applied our methodology on different types of rocks (sandstones and carbonates) with different porosity values (10-30%) and permeability (1mD to 1D) for which we were able to compare the anisotropy of magnetic, elastic and electrical properties in a unified scheme. These anisotropies were related to structural and microstructural attributes derived from the ferrofluid impregnation technique, that is, combined with anisotropy of magnetic susceptibility measurements (ASM_f), one of the ways to analyze the 3-D geometry of the pore space and to infer indirectly the anisotropy of permeability. To control both the pore aspect ratio and the directional anisotropy we used the anisotropy of P-waves velocity (APV) measured on samples in dry and water saturated conditions. The comparison between both methods shows that despite the directional data are in good agreement, infer the true shape of the porosity is not straightforward. Modeling the presence of a mechanical anisotropy in the solid matrix for the sandstones makes the porosity aspect ratio obtained with APV converge towards values derived from AMS_f. However for carbonates, due probably to an intricate distribution of microstructures, the aspect ratios obtained show significant discrepancies between both methods. A key issue for the applicability of the AMS_f method is a successful impregnation limited by the size of magnetic nanoparticles (10 nm) in suspension in the ferrofluid.

Combined rock mechanics, rock physics and CT image quantification of physical processes

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Anisotropy and heterogeneity of rocks on all scales has significant importance in seismic imaging, seismic attribute analyses, AVO analysis, interpretation of sonic log data, EM monitoring and CSEM, and has become increasingly important knowledge and input for developing rock physics models in sedimentary basins. Recent years technological advances on seismic and tools and down-hole sonic logging tools calls for better understanding and description of anisotropy and heterogeneity and benchmark laboratory testing.

Driven by a general demand for complete sets of both static and dynamic moduli data from an often small and fragile volume of core material implies testing on small core samples for which we have strived to develop different experimental setups that join traditional triaxial rock mechanics and geophysics with as little compromise on the respective types of measurements as possible.

While axial acoustic velocity measurements have been a standard attribute in addition to axial and radial LVDT strain measurements in our triaxial testing rigs for a while, the increased interest in anisotropy studies pushes instrumentation in our triaxial setups further by equipping core plugs with sonic transducers along two or more orthogonal directions.

Concerning impact of core scale heterogeneity on fluid saturation and geophysical response it is valuable to measure locally. In order to resolve resistivity effects along the axis during progression of fluid displacement front during two phased fluid substitution a multi electrode sleeve and logging device have recently been produced and utilized. The system allows for sequential probing of resistivity between four ring electrodes and end caps.

Introducing direct time lapse visualization of physical process such as rock deformation and fluid substitution in combination with mechanical and rock physics testing offers a unique opportunity to correlate physico-mechanical response with quantitative 3D image analysis. For this purpose a 30MPa isotropic and a 70MPa deviator triaxial carbon fiber cell has been used, both fully equipped with resistivity and sonic velocity measuring device.

We present our research and development efforts on integrated experimental designs through different case studies.

Deformation and failure mode of the Monte Canale micro-folded gneiss

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The fabric-related anisotropy is a key control on the mechanical behavior of rocks. The majority of micro-mechanical models describe rock deformation and failure for isotropic and homogeneous materials. Experimental and theoretical work focused mainly so far on the role of a single planar anisotropy on deformation mechanisms, failure modes and strength. However, the interplay between the fabric of folded metamorphic rocks and their brittle mechanical behavior has not yet been taken in account properly. Recent experimental data obtained in uniaxial compression (Agliardi et al., 2012) reveal a systematic dependence of the strength and failure mode of folded gneiss and schist on the geometrical and mechanical interplay of different elements related to folded micro-fabric. However, lithostatic pressures are expected to have significant implications for the deformation and failure mode, and thus triaxial experiments need to be carried out in realistic confinement conditions.
We carried out triaxial compression tests on the Monte Canale micro-folded gneiss (Val Malenco, Italian Central Alps), previously characterised and tested by Agliardi et al. (2012). Tests were performed on 19 air-dry cylindrical specimens 54 mm in diameter, with length/diameter ratio in the range 2-2.5. Specimens were overcored throughout 78 mm drill cores using a diamond core drill bit. For each specimen, a meso-structural description of the folded fabric was carried out, including fold amplitude, wavelength, and the orientation of both main foliations and fold axial planar surfaces to the cylindrical sample axis (i.e. the deviatoric load direction). Triaxial tests were performed by the means of a MTS 815 servo-controlled stiff frame (Fig. 1), capable of applying an axial load up to 4600 kN and with a confining cell able to apply pressures up to 140 MPa. Specimens were instrumented with a jaw axial strain extensometer and a chain-type circumferential strain extensometer, which allow to measure the volumetric strain of the central portion of the sample and calculate the elastic moduli and the onset of dilatancy hardening. Tests were carried out at confining pressure of 40 MPa, applying axial loads at a servo-controlled strain rate of 5*10-6 s-1. Post-rupture behavior and unloading stress-strain relationships have been investigated as well, when available. Peak axial loads and Young's moduli are generally lower than literature gneiss values at correspondent confinement level (e.g. Rawling et al., 2002). Samples failed in different modes, ranging from abrupt failure with neat shear planes formation to less localized complex shear band development (Fig. 1). Microstructural observations by X-ray CT-scan, optical microscopy and SEM allowed to investigate fracture mechanisms and related fabric controls at micro-scale. Notwithstanding the effects of the application of confining pressure, observed failure modes are consistent with those already described in uniaxial compression, and show that brittle compressive failure of folded gneiss depends on the relative contribution of two mechanical anisotropies, i.e. the main foliation and the axial plane surfaces. Failure involving both anisotropies results in higher peak strength, higher axial strain and a less evident brittle macroscopic failure behavior, with respect to failure occurring only along the foliation. The micro-scale mechanisms observed suggest that folded micro-fabric exert a significant control on frictional properties, crack enucleation and propagation and the overall mechanical behavior of rock.

Physical and mechanical factors affecting stress induced electric potential field in rock

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Research into pre-earthquake electromagnetic phenomena has been growing since the 1970's, with many researchers attributing these phenomena to rock deformation [1-4]. This hypothesis is supported by laboratory-based studies which have found the flow of electric current in rock is associated with deformation and the application of stress [5-10]. While these studies have clearly demonstrated the existence of pressure stimulated currents (PSCs), the precise mechanisms responsible are still debated and include the piezoelectric effect, moving charge dislocations, the electrokinetic effect and the flow of electron and hole current sustained by an electrical boundary. In addition, the effect of numerous physical and mechanical variables on current and associated electric potential (EP) is also yet to be quantified. Furthermore, the observation of PSCs, is not ideal because the current amplitudes are very small, in the pico-Amp range. This measurement method also relies on pairs of connections to the specimen, a problem when applied to measurements made in the field because the electrodes will need to be an arbitrary distance apart, an unrealistic approach on a large scale.

Recent work by the University of Sussex (UoS) and the British Geological Survey (BGS) has utilised Electric Potential Sensor (EPS) technology, developed by the UoS [11], to remotely measure stress-induced changes in the EP of a variety of different lithology types. EP detection does not have the inherent disadvantages of PSCs detection; studies indicate large amplitude EP signals in stressed rocks [6, 12]. EPS technology is non-invasive (without resistive contact) as it does not draw real current from the sample and it is capable of single ended operation. These properties arise from the ultra-high input impedance nature the device, typical specifications of a generic EPS are input capacitance >10-15 F and input resistance ~1013 ? [11], thus it does not disturb the electric field produced in the sample. UoS has two recent publications demonstrating that the EPS can be used non-invasively; this has been successfully applied to human body signals [13, 14]. In addition, the sensors have a large bandwidth capacity ranging from quasi DC to 100MHz [12], which is ideal for measuring the electrical AC signals in rocks that are expected to be analogous to the wide frequency range of acoustic emission signals. Because of these unique properties, the EPS lends itself to easy installation and detection of the EP in the geological field. Uniaxial compressive stress tests were undertaken on a variety of sedimentary, metamorphic and igneous lithology-types. In addition, a number of other physical and mechanical parameters were also varied including strain rate, moisture content and loading profile. Cylindrical specimens approximately 108 mm in length and 54 mm in diameter were instrumented with EPS and strain gauges. Two wideband piezoelectric transducers mounted on steel platens were positioned at either end of the specimens to monitor acoustic emissions. Load was applied to the specimens using a 4.6 MN capacity servo-controlled hydraulic load frame until failure occurred, typically between 3 and 30 minutes depending on the loading rate and stress profile.

Changes in EP were detected in the quasi DC to 1 kHz band for all lithology-types. The intensity and character of the signal appears to depend on a number of factors including lithology (grain size and mineralogy), moisture content, loading rate and stress profile (linear or cyclic). Quartz rich lithology-types show significant EP activity in the wide band from an early stage of the load cycle, thus demonstrating a clear association of the stress-state with EP. The lithology-types with little or no quartz display almost no high frequency (>1 kHz) signals. However, transient signals, that contain broadband frequencies with relatively medium intensity, are still present, thus suggesting that there is a mechanism of electric field generation in addition to piezoelectric effect. In general EP signals either increase in frequency and intensity, or exhibit multiple high band transients in the run up to failure, and thus may be important as a precursory event indicator.

Further work is necessary to quantify the exact effect these physical and mechanical variables have on the EP detected by the EPS, including porosity/void space and pore fluid chemistry. In addition, modification of the EPS to measure DC EP may enable measurement of static stress thus potentially providing a valuable tool for examining the in situ stress state of rock. Following this the next major step would be determine whether EPS would be amenable to measuring stress induced EP of rock in situ.

References

1. Mizutani, H., T. Ishido, T. Yokokura, and S. Ohnishi. 1976. Electrokinetic Phenomena Associated with Earthquakes. Geophysical Research Letters, 3: 365-368.

2. Dobrovolsky, I.P., N.I. Gershenzon, and M.B. Gokhberg. 1989. Theory of Electrokinetic Effects Occurring at the Final Stage in the Preparation of a Tectonic Earthquake. Physics of the Earth and Planetary Interiors, 57: 144-156.

3. Hayakawa, M. and Y. Fujinawa. 1994. Electromagnetic Phenomena Related to Earthquake Prediction. Terra Scientific Publishing Company.

4. Tzanis, A. and F. Vallianatos. 2001. A critical review of Electric Earthquake Precursors. Annali Di Geofisica, 44: 429-460.

5. Triantis, D., I. Stavrakas, C. Anastasiadis, A. Kyriazopoulos, and F. Vallianatos. 2006. An analysis of pressure stimulated currents (PSC), in marble samples under mechanical stress. Physics and Chemistry of the Earth, 31: 234-239.

6. Eccles, D., P.R. Sammonds, and O.C. Clint. 2005. Laboratory studies of electrical potential during rock failure. International Journal of Rock Mechanics and Mining Sciences, 42: 933-949.

7. Hadjicontis, V., C. Mavromatou, and D. Ninos. 2004. Stress induced polarization currents and electromagnetic emission from rocks and ionic crystals, accompanying their deformation. Natural Hazards and Earth System Sciences, 633-639.

8. Freund, F. 2002. Charge generation and propagation in igneous rocks. Journal of Geodynamics, 33: 543-570.

9. Yoshida, S., O.C. Clint, and P.R. Sammonds. 1998. Electric potential changes prior to shear fracture in dry and saturated rocks. Geophysical Research Letters, 25: 1577-1580.

10. Brady, B.T. and G.A. Rowell. 1986. Laboratory Investigation of the Electrodynamics of Rock Fracture. Nature, 321: 488-492.

11. Prance, R.J., A. Debray, T.D. Clark, H. Prance, M. Nock, C.J. Harland, and A.J. Clippingdale. 2000. An ultra-low-noise electrical-potential probe for human-body scanning. Measurement Science & Technology, 11: 291-297.

12. Aydin, A., R.J. Prance, H. Prance, and C.J. Harland. 2009. Observation of pressure stimulated voltages in rocks using an electric potential sensor. Applied Physics Letters, 95: 124102.

13. Harland C J, Clark T D and Prance R J 2002 Electric potential probes?new directions in the remote sensing of the human body Meas. Sci. Technol. 13 163?9

14. Harland C J, Clark T D and Prance R J 2002 Remote detection of human electroencephalograms using ultrahigh input impedance electric potential sensors Appl. Phys. Lett. 81 3284?6

“Numerical Modeling through the Scales”

Constraints on constitutive models of pressure solution creep from numerical simulations and published experimental data

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Previously published constitutive models of pressure solution (PS) creep have been constructed in a form inspired by the classic grain boundary diffusion (or Coble) creep model. The PS strain rate de/dt is accordingly assumed proportional to the following product:
(1/RT) Exp[-H/RT] (p**n / d**m) Exp[q phi]
where ** denotes the power operation, H is the effective PS activation enthalpy, R the gas constant, p the effective confining pressure, d the grain diameter, n the stress exponent, m = 1 or 3 depending on whether PS is rate-limited by dissolution or diffusion, respectively, q is an empirically determined constant and the porosity phi is a decreasing function of time t. We recently performed PS creep simulations of a random pack of quartz spheres using the distinct element method and a formula derived from the theoretical PS model of Lehner and Leroy [2004] (LL). We found that the classic constitutive model mentioned above did not correctly describe the simulated creep behavior. Instead we observed two successive power law regimes of the form, de/dt proportional to 1/t**b. At early times, the strain rate was approximately constant (i.e., b = 0) for about 10 simulated years whereas values of the exponent b on the order of 0.6 - 0.7 were calculated at late times. A very similar behavior with somewhat higher values of b was observed by Visser et al. [2012], who performed PS creep experiments in conditions closely resembling those of the numerical simulations, i.e., compaction of fluid saturated packs of spherical NaNO3 grains at effective stresses lower than 5 MPa, thus avoiding significant grain cracking. By interpreting the simulated and experimental data in terms of stress exponents, we determined values of n that tended to be unusually small (Lehner, F. K. and Y. Leroy (2004), Sandstone compaction by intergranular pressure solution, In Mech. Fluid-Saturated Rocks (eds. Y. Guéguen and M. Boutéca), Elsevier Academic Press, New York, 115-168.
Visser, H.J.M., C.J. Spiers and S.J.T. Hangx (2012), Effects of interfacial energy on compaction creep by intergranular pressure solution: theory versus experiments on a rock analog (NaNO3), J. Geophys. Res., 117, B11211, doi:10.1029/2012JB009590.

Percolation pore network study on permeability and formation factor of shaly sands

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This paper is a follow up on Bernabé et al.'s (2010, 2011) study of the effect of pore connectivity and pore size heterogeneity on permeability and formation factor. In previous models, five parameters (hydraulic radius rH, pore length l, coordination number z, the standard deviation of pore radius distribution ?r and pore aspect ratio ?) used for describing the pore structure of clay-free sandstone. In this paper, we put dispersed clay (or shale) into percolation pore network by randomly filling the pore-space to investigate the transport properties of shaly sands. We simulated fluid and electrical current flow though different lattice pipe networks with different clay content. Our simulation results shows that, permeability and formation factor also obey the «universal» power law which is well-defined in percolation theory, k~(z-zc)?, 1/F~(z-zc)?, where zc is the percolation threshold, the exponent ? and ? are function of the standard deviation of the pore radius distribution. Permeability and formation factor model for shaly sand were inferred on the basis of the power law mentioned above. We also find some experimental data to test the models, the fit results is reasonable and acceptable.

P-wave attenuation in fractured rocks and the effects of the fracture contact areas

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The presence of fractures in rocks is typically associated with high values of seismic attenuation, which is considered to be mainly produced by wave-induced fluid flow (WIFF) between fractures and the pore space of the embedding matrix. That is, due to the very high compressibility contrast between the fractures and the porous background, seismic waves induce strong fluid pressure gradients followed by local fluid flow between such regions, which in turn produces significant attenuation and velocity dispersion.
Natural fractures can be conceptualized as two surfaces in partial contact containing very soft and highly permeable material in the inner region. When a fractured rock is subjected to traction or compression, such as that produced by the weight of the overlying lithological column or by tectonic activity, the fracture deforms and the contact area changes. This produces significant changes in the mechanical properties of the rock sample since as the contact area increases the fracture becomes stiffer, thus affecting the compressibility contrast between the fracture material and the background. For these reasons, the details of the contact area, or welds, of fractures are expected to play a major role in the attenuation mechanism related to WIFF.
In this work, we seek to explore the role played by the fracture contact areas on seismic attenuation and velocity dispersion due to WIFF. To this end, we employ a simple model consisting of a horizontal fracture located at the center of a porous rock sample and represented by a number of rectangular cracks of constant height separated by contact areas. The cracks are modeled as highly compliant, porous, and permeable heterogeneities, which are hydraulically connected to the background material. We include a number of rectangular regions of background material separating the cracks, which represent the presence of contact areas of the fracture. To obtain the corresponding seismic attenuation and dispersion due to WIFF, we apply numerical oscillatory relaxation tests to the synthetic samples. That is, we impose a time-harmonic vertical solid displacement at the top boundary of the sample. No flow conditions are imposed at the four boundaries, and the solid phase is neither allowed to move on the lower boundary nor have horizontal displacements at the lateral boundaries. The equivalent undrained complex plane-wave modulus, which contains the information about seismic attenuation and dispersion due to WIFF, is expressed in terms of the imposed displacement and the resulting average vertical stress at the top boundary, which is obtained by solving Biot's consolidations equations.
We explore the effects of the presence of fracture contact areas on seismic attenuation and dispersion due to WIFF by performing an exhaustive sensitivity analysis considering a rock sample containing a horizontal fracture and characterized by different different numbers, sizes, and locations of fracture contact areas. This study allowed us to verify that the geometrical characteristics of fracture contact areas play a key role in controlling the seismic signatures of fractured materials. In particular, we observe that in the case of regular distributions of contact areas seismic attenuation and dispersion levels get higher with decreasing size or increasing separation of the contact areas. Next, we verified that the details of the spatial distribution of contact areas are very important. Indeed, we observed that for the same fraction of contact area, seismic attenuation and dispersion are weakest for a regular distribution of contact areas and strongest when the contact areas are located within a narrow cluster. In addition, our numerical approach allowed us to explore the vertical solid displacement gap across fractures. We found that this parameter is strongly affected by the geometrical details of the fracture contact area and turned out to be complex-valued and frequency-dependent due to WIFF effects.
Since the effective stress to which the fractured rock is subjected strongly affects the characteristics of the fracture contact area, it is expected that there exists an implicit relationship between the seismic attenuation and dispersion characteristics and the effective stress. Using laboratory measurements of changes in fracture contact area as a function of the applied stress, we proposed a simple model for the evolution of the contact area with increasing stress. This allowed us to illustrate the kind of relationship expected to prevail between the effective stress and the seismic signatures. The modeled responses indicate that seismic attenuation and phase velocity may constitute useful attributes to extract effective stress information. Alternatively,

knowledge of the prevailing effective stress may help to determine the regions where WIFF is not expected to be a significant attenuation mechanism within the shallower parts of the crust.

Creep and relaxation tests employed to compute seismic P-wave attenuation and phase velocity in fractured media

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Fractures are present in most geological formations and they tend to dominate not only their mechanical but also, and in particular, their hydraulic properties. For these reasons, the detection and characterization of fractures are of great interest in several fields of Earth sciences, such as groundwater and contaminant hydrology, CO2 sequestration as well as geothermal and fossil energy exploration and production, among many others. Seismic attenuation has been recognized as a key attribute for this purpose, as both laboratory and field experiments indicate that the presence of fractures usually produces very significant attenuation and that this attribute tends to systematically increase with increasing fracture density. This energy loss is generally considered to be primarily due to fluid flow between the fractures and the embedding porous matrix. That is, due to the strong compressibility contrast between fractures and the embedding porous matrix, the propagation of seismic waves can generate a strong fluid pressure gradient and associated fluid flow between the two domains, which in turn generates energy dissipation. It is well known that standard numerical simulations based on Biot's poro-elastic wave equations are computationally very expensive. Alternative approaches consist in performing numerical relaxation or creep tests on representative elementary volumes (REV) of the original medium. These tests are based on the Biot's quasi-static poro-elastic equations, the so-called consolidation equations. Assuming that the heterogeneous poro-elastic medium can be replaced by an effective, homogeneous visco-elastic solid, these numerical tests allow us to compute the corresponding seismic P-wave attenuation and phase velocity. From a practical point of view, an REV is typically characterized by the minimum volume for which rock physical properties are statistically stationary and representative for the considered heterogeneous medium as whole. A more general definition of an REV is to consider it as the smallest volume over which a measurement can be made that still represents a property of the entire heterogeneous medium. The latter definition can be rephrased in the context of wave field attributes as the smallest volume over which the estimated seismic P-wave attenuation and phase velocity are independent of the applied boundary conditions. That is to say, the corresponding results obtained from creep and relaxation tests must be equivalent. For most analyses of patchy saturation as well as double-porosity media these two REV definitions are equivalent. It is, however not clear whether this remains true in the presence of strong contrasts of the material properties.

In this work, we seek to explore a proper definition of REV for periodic fractured media containing parallel fractures by comparing the seismic signatures obtained from numerical relaxation and creep tests. To this end, we build a medium composed of infinite replicas of a unit volume containing one fracture. This unit volume coincides with the smallest possible volume that is statistically representative of the entire medium. Then, we perform several creep and relaxation tests on samples composed of an increasing number of these unit volumes. The seismic P-wave attenuation and phase velocity obtained with creep tests turn out to be different, and they tend to converge to the results obtained with relaxation tests as the number of considered unit volumes increases. Conversely, the corresponding results from relaxation test are always equal independently of the number of unit volumes. These findings are expected to have direct implications for corresponding laboratory measurements on fractured media.

3-D finite-difference modelling of hydrostatic tests of porous rocks

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The poor knowledge of constitutive properties of geomaterials/rocks is a principal obstacle for the modelling of their deformation necessary for various applications. Normally, the constitutive lows are to be derived from the experimental data, but this is not a simple task as requires detailed, good quality experimental data for different loading conditions. On the other hand, it is not completely clear to which degree the nominal strains and stresses measured/calculated in the experimental tests correspond to the real strains and stress within the sample. Both nominal and real stresses and strains are respectively equal only when the sample is strained strictly uniformly, i.e., before the onset of strain localisation and if the boundary effects at the sample ends are negligible. These effects are not well known/controlled and their impact of the mechanical response on the sample (on the stress and strain distribution within it) is not completely clear. Therefore the formulation of the constitutive models should be also largely based on the theoretical considerations and numerical simulations.
One of the weak points of most of the existing constitutive models is that the constitutive parameters (such as the internal friction coefficient and cohesion) are considered to remain the same during the deformation. It is known from the experimental data that this is not true, but the corresponding dependencies/functions are poorly constrained. The dependence of the mechanical behaviour of porous rocks on the mean stress ?m is, on the contrary, rather well established. It is known, for example, that at a sufficiently high ?m the yield envelop has a cap shape and that when ?m reaches a certain value, P*, the inelastic strain occurs even in the hydrostatic tests (hence, at a presumably zero deviatoric stress). In the classical constitutive models (e.g., Mohr-Coulomb, Drucker-Prager), the inelastic deformation is caused only by the deviatoric stress. Therefore other, double-yield models have been developed where inelastic volumetric strain is induced by the hydrostatic stress and is characterised by its own parameters, such as the volume hardening modulus etc. This further complicates the models and increases difficulties/ uncertainties in experimental definition of the model parameters.
Here we introduce a single cap-type yield function ?(?m,?p), which shape corresponds to the available experimental data (? is the von Mises stress, and ?p is the accumulated inelastic equivalent shear strain). This function is parabolic in ?m and depends on ?p in a way to generate strain softening at small ?m and strain-hardening at large ?m values. For the plastic potential, the Druker-Prager function is used. This model (for which the incremental inelastic volume strain is impossible at ??p = 0 or ? = 0 if the dilatancy factor ? is finite) has been implemented into the finite-difference 3-D dynamic code Flac 3D using a time-matching explicit calculation scheme. The idea of this work is to reproduce hydrostatic tests in the 3-D numerical models with the above constitutive formulation, and to investigate the model behavior when its nominal stress-state is close to (or is exactly at) the intersection of the yield surface with the hydrostatic axis (at ?m = P*).
The ends of a cylindrical model representing a porous rock sample are in contact with the more stiff (steel) elastic platens through frictional interfaces. The whole system is subjected to a normal stress Pc applied to the external model surface, which corresponds to the hydrostatic loading of rock samples in the laboratory tests. Pc is quasi-statically increased from zero to the value in excess of P*. The nominal cumulative volume strain ? of the model was defined from the volume evolution of the whole sample and then the hydrostats Pc(?) were computed for each model. Using the hydrostats, the parameters of the constitutive model were calibrated to fit the corresponding (available in the literature) curves Pc(?) for different rocks (sandstones). The models reproduce very well the behavior of real hydrostats both before and after Pc = P* at very reasonable (far from -?, contrary to what one could expect) values raging from -0.5 to -1.2. One can clearly see how this parameter affects the hygrostat's geometry. Surprisingly, this geometry is practically insensitive to the interface friction coefficient µ at the sample ends, and also to the model resolution. The distribution of the real (not nominal) stresses within the models is, on the contrary, very sensitive to µ. This shows a dramatic impact of µ on the sample stress-strain state

(hence on the failure conditions), and the limits of the information contained in the nominal stress/strain data about the real sample state. It appears also, that the pure hydrostatic state in the solids is rather exotic and generally can be only transitional.

At $\mu > 0$, the inelastic strain starts early in the loading history (well before the condition $Pc = P^*$ is met) at the sample ends and then progressively involves the whole sample. Different points within the sample follow different trajectories (loading paths) on the yield surface. These results are in agreement with the data on acoustic emissions in the hydrostatic tests and suggest that there is probably no need in developing any specific constitutive model/mechanism for compactive deformation at high pressure. What is fundamental, on the contrary, is a consideration of the evolution of the yield surface with deformation. The presented results highlight also the necessity of taking all measures for reduction of the friction at the sample ends which can cause a strong stress and stress/strain perturbations even when μ is relatively small.

Double scale numerical FEM-DEM analysis of cohesive-frictional materials

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Recently, multi-scale analysis using a numerical approach of the homogenisation of the microstructural behaviour of materials to derive the constitutive response at the macro scale has become a new trend in numerical modelling in geomechanics. Considering rocks as granular media with cohesion between grains, a two-scale fully coupled approach can be defined using FEM at the macroscale, together with DEM at the microscale [1]. Despite an evident computational cost penalty with respect to mono-scale approaches like FEM and DEM, two-scale FEM-DEM approach allows one to perform real-size grain micro-structure modelling on real-size macroscopic problems, without facing the intractable problem of dealing with trillions of grains in a fully DEM mapped full field problem. Using this approach, microscale related features such as the inherent and induced anisotropy of the material, or material softening/ hardening with strain, naturally flow from the microscale DEM model to the macroscale FEM model.

An implementation of the FEM-DEM method in a well established, finite strain FEM code is presented, and representative results are discussed, including aspects related to strain localisation in this context.

[1] Nitka M., Combe G., Dascalu C., Desrues J. (2011) Two-scale modeling of granular materials: a DEM-FEM approach, Granular Matter vol.13 No 3, pp. 277-281

Numerical modeling of rock fracturing: from laboratory to continental scale

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Fracture propagation in brittle rock is investigated by means of numerical simulations performed at different scales, from the laboratory scale to the continental crust scale. The numerical model is based on an enhanced version of the discrete element method which was chosen for its ability to describe progressive failure mechanisms through the breaking of the bonds making up the cohesion between the constitutive particles of the simulated medium [Potyondy2004]. Using appropriate contact laws associated to a near neighbor interaction feature, the model can reproduce fundamental characteristics of brittle rock behavior such as high values of the tensile to compressive strength ratio as well as non-linear failure envelopes [Scholtes2013]. In addition, pre-existing structures such as joints or faults can be taken into account in the model by means of a specific joint model which gives the opportunity to define a tailor-made behavior of the discontinuity surfaces without suffering from the effects of the local geometry [Scholtes2012].
Compression test simulations were performed on pre-flawed samples and compared to experimental results in order to validate the numerical approach for describing the initiation and propagation of fractures in brittle rock. A special emphasis was put on the influence of the micromechanical parameters and of the initial flaw geometry (orientation, length and distance between the pre-existing cracks) on the fracturing pattern. Overall, it is shown that the numerical simulations can retrieve the failure patterns that are obtained experimentally [Shen1995]. Moreover, it is shown that the rate of micro-cracking measured as the evolution of the debonding events occurring during the simulation can provide an indicator of the failure path similar to the acoustic events recorded experimentally.
Being validated at the laboratory scale, the discrete model was then employed to study fracturing problems occurring at the scale of the continental crust. More particularly, the study focused on shear fault patterns observed on earth surface which present some deterministic features that may be related to the thickness of the brittle part of the crust [Klinger2010]. The discrete numerical model was thus used as a continental crust analog to assess the influence of the thickness of the brittle layer on the fracture patterns. As an alternative to the physical modelings performed at small scale with wet clay or sandbox, the approach allows following the progressive development of failure leading to the generation of wrench faults through the nucleation and coalescence of micro-fractures.

References

[Klinger2010] : Relation between continental strike-slip earthquake segmentation and thickness of the crust, Klinger Y., Journal of Geophysical Research: Solid Earth, 115(B7), p. 1-19, 2010 [Potyondy2004] : A bonded-particle model for rock, D. O. Potyondy and P. A. Cundall, International Journal of Rock Mechanics and Mining Sciences, 41(8), p. 1329-1364, 2004 [Scholtes2012]: Modelling progressive failure in fractured rock masses using a 3D discrete element method, L. Scholtès and F.-V. Donzé, International Journal of Rock Mechanics and Mining Sciences, 52, p. 18-30, 2012 [Scholtes2013]: A DEM model for soft and hard rocks: effect of grain interlocking on strength, L. Scholtès and F.-V. Donzé, Journal of the Mechanics and Physics of Solids, 61, p. 352-369, 2013 [Shen1995] : Coalescence of fractures under shear stresses in experiments, B. Shen and O. Stephansson, Journal of Geophysical Research, 100, p. 5975-5990, 1995

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Modeling of brittle creep of three-dimensional heterogeneous rocks

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A three-dimensional numerical model for brittle creep is proposed for the time-dependent brittle deformation of heterogeneous brittle rock. The model accounts for material heterogeneity through a stochastic local failure stress field and local material degradation using an exponential material softening law. Importantly, the model introduces the concept of a mesoscopic renormalization to capture the co-operative interaction between microcracks in the transition from distributed to localized damage. Our model also describes the temporal and spatial evolution of acoustic emissions in the medium during the progressive damage process. The model is first validated using previously-published experimental data and is then used it to simulate brittle creep experiments. Our model reproduces the classic trimodal behaviour (primary, secondary and tertiary creep) seen in laboratory brittle creep experiments. Our approach differs from previously-adopted macroscopic approaches, based on constitutive laws, and microscopic approaches that focus on fracture propagation. The model shows that complex macroscopic time-dependent behaviour can be explained by the small-scale interaction of elements and material degradation. The fact that the simulations are able to capture a similar time-dependent response of heterogeneous brittle rocks to that seen in the laboratory implies that the model is appropriate to investigate the non-linear complicated time-dependent behaviour of heterogeneous brittle rocks.

Impact of a multilayer structure on initiation and evolution of strain localization in porous rocks: field observations and numerical modeling

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Networks of localized conjugate compactive shear bands with large dihedral angles (corresponding to so-called shear-enhanced compaction bands) were generated in 3-layer plane strain finite-difference models. The central layer has elastic-plastic properties with a small positive internal friction coefficient, negative dilatancy factor, and the hardening modulus reducing during the deformation. The two other layers are elastic. The spatial organization of the networks in the central layer, resulting from the elastic-plastic instability of the 3-layer system, was shown to be dependent of the contrast of the elastic stiffness of the layers and on the friction between them. When the stiffness E of the elastic layers and/or the friction are small, the networks are rather symmetric (the bands of both orientation families are distributed homogeneously within the layer). An increase in E at high friction, results in the clustering of the bands of one orientation along a layer segment which is followed by another segment filled with the bands of the other orientation. Different network types are characterized by different band spacing which is smaller in the clustered networks. The intensity of inelastic deformation and hence of porosity reduction within the bands are also smaller in this case. The obtained band networks are very similar to those in nature where the same variability of the networks organization is observed. Available geological and mechanical data confirm the conclusions from the modeling about the origin of this variability.

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