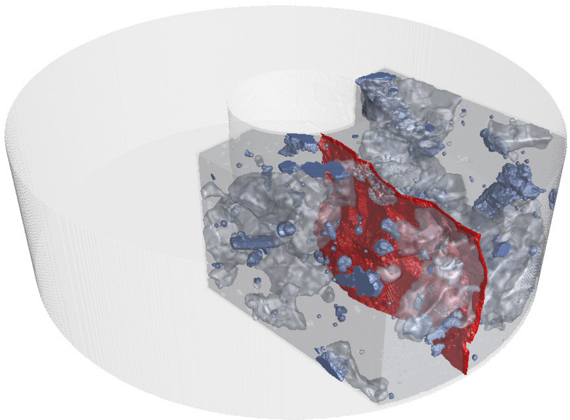
Helmholtz Centre Potsdam
GFZ German Research Centre for Geosciences

13th EURO-CONFERENCE

ON ROCK PHYSICS AND GEOMECHANICS

THE GUÉGUEN CONFERENCE

2 - 6 September 2019, Potsdam, Germany



Rock fracturing and fault activation: Experiments and models

KICT Korea Institute of Civil Engineering and Building Technology

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Local Organizing Committee

International Scientific Advisory Committee

Imprint

Editors: Hannes Hofmann and Angela Spalek

Helmholtz Centre Potsdam German Research Centre for Geosciences - GFZ, Section Geoenergy

Telegrafenberg, 14473 Potsdam, Germany

www.gfz-potsdam.de

Concept & Layout: Angela Spalek, GFZ

Print: ARNOLD group, Großbeeren

Potsdam, September 2019

The conference proceedings are also available electronically

https://doi.org/10.2312/GFZ.4.8.2019.017

Editorial

Dear Colleagues,

The Potsdam rock mechanics community welcomes you to the **“13th EURO-Conference on Rock Physics and Geomechanics – The Guéguen Conference”**. The overarching theme of the conference is **“Rock fracturing and fault activation: Experiments and models”**.

Given the increasing interest and challenges in fracture/fault development and associated induced seismicity that arose in recent years, we believe that this subject deserves special attention. Of particular relevance are laboratory experiments, underground research laboratories, field experiments, monitoring, modeling, and upscaling studies. The conference will provide a unique opportunity for international researchers and industry experts to discuss latest results and developments of this important topic, which is fundamental to safely and economically utilize the subsurface.

Following the EURO-Conference tradition, we chose a venue outside the urban centre of Potsdam. Situated in picturesque, idyllic surroundings at the shore of the Templiner See, the Seminaris SeeHotel offers a serene working atmosphere that encourages lively discussion and networking. We have prepared an appealing program with 8 keynote lectures, 47 oral presentations and 26 poster presentations given by some of the world’s leading experts in rock mechanics. Thanks to our co-organizer KICT we were able to promote participation of 17 PhD students and early career scientists.

Potsdam, a city which is surrounded by forests and lakes, offers numerous historical and cultural attractions. You will have the opportunity to experience the UNESCO World Heritage Site “Schlösser und Parks von Potsdam und Berlin” during the conference dinner at the historic “Winzerberg” and during a river cruise.

I am looking forward to an exciting conference.

HANNES HOFMANN, Chairman of the Organizing Committee
Helmholtz Centre Potsdam
GFZ German Research Centre for Geosciences
Section Geoenergy

conference program

Time	Sunday (01.09.19)	Monday (02.09.19)	Tuesday (03.09.19)	Wednesday (04.09.19)	Thursday (05.09.19)	Friday (06.09.19)
08:00 - 09:00		Breakfast	Breakfast	Breakfast	Breakfast	Breakfast
09:00 - 10:00		Opening Keynote 1	Keynote 3	Keynote 5	Keynote 6	Keynote 8
10:00 - 11:00		Session 1 Coffee break	Session 3 Coffee break	Session 5 Coffee break	Session 6 Coffee break	Session 8 Coffee break
11:00 - 12:00		Session 1	Session 3	Session 5	Session 6	Session 8
12:00 - 13:00						
13:00 - 14:00		Lunch break	Lunch break	Lunch break	Lunch break	Lunch break
14:00 - 15:00		Keynote 2	Keynote 4		Keynote 7	
15:00 - 16:00	Registration & hotel check-in open	Session 2	Session 4	River cruise "7 Lakes"	Session 7 Coffee break	
16:00 - 17:00		Poster session 1 & Coffee break	Poster session 2 & Coffee break		Session 7	
17:00 - 18:00						
18:00 - 19:00		Conference evening at historic "Winzerberg"				
19:00 - 20:00	Buffet dinner & welcome reception		Buffet dinner	Buffet dinner	BBQ	
20:00 - 21:00						

Monday, 02.09.2019

Session 1: Fluid driven fractures and seismicity

(Chairs: Arno Zang and Grzegorz Kwiatek)

9:20-10:00

Keynote 1: Physical behavior of fluid driven earthquakes

(Marie Violay, Mateo Acosta, Chiara Cornelio, Carolina Giorgetti, Corentin Noel, Francois Passelegue, Alexandre Schubnel, Stefan Nielsen, Giulio Di Toro, Elena Spagnuolo)

10:00-10:20

S1.1: Laboratory Study of the Dynamics of Stick-Slip Sliding in Large Sandstone Block Induced by Fluid Injections

(Sergey Stanchits, Volker Oye, Nicholas Seprodi, Pierre Cerasi, Anna Stroisz, Robert Bauer)

10:20-10:40

S1.2: Impact of heterogeneity, anisotropy and discontinuities on hydraulic fracture propagation – a lab study

(Ferdinand Stoeckhert, Cedric Solibida, Michael Alber)

10:40-11:10 Coffee break

11:10-11:30

S1.3: Hydraulic fracturing process in granite under different fracturing regime

(Kwang Yeom Kim, Sung Gyu Jung, Hannes Hofmann, Günter Zimmermann, Ki-Bok Min)

11:30-11:50

S1.4: Fluid-driven tensile fracture and fracture toughness in Nash Point shale at elevated pressure

(Philip Benson, Stephan Gehne, Nathaniel Forbes-Inskip, Philip Meredith, Agust Gudmundsson, Nick Koor)

11:50-12:10

S1.5: In-situ synchrotron X-ray tomography of fluid injection experiments at elevated confining pressure

(Michael Chandler, Julian Mecklenburgh, Anne-Laure Fauchille, Roberto Rizzo, Lin Ma, Patrick Dowey, Steven May, Robert Atwood, Peter Lee, Ernest Rutter, Anna Bogush)

12:10-12:30

S1.6: Fault Reactivation for Permeability Enhancement and Associated Induced Seismicity in Crystalline Rocks

(Omid Moradian)

12:30-14:00 Lunch break

Monday, 02.09.2019

Session 2: : Compaction and damage of porous rock I

(Chair: Elli-Maria Charalampidou)

14:00-14:40

Keynote 2: The physics behind sandstone reservoir compaction: the cause of induced seismicity in gas fields

(Suzanne Hangx)

14:40-15:00

S2.1: A Rock Mechanical Model for Overbalanced, Managed Pressure, and Underbalanced Drilling Applications

(Musaed N. J. AlAwad)

15:00-15:20

S2.2: Damage accumulation and wellbore stability

(Eyal Shalev, Vladimir Lyakhovsky, Gal Oren, Harel Levin, Stephen Bauer)

15:20-15:40

S2.3: High Pore Pressures: What Is Indicated by Vein-Filled Rock Masses?

(Gary D. Couples)

15:40-17:00

Poster session 1 & Coffee break

From 17:00 Conference evening at historic “Winzerberg”

Tuesday, 03.09.2019

Session 3: Laboratory fracture and rock characterization studies

(Chairs: Sergey Stanchits and Philip Meredith)

09:00-09:40

Keynote 3: Fault structure, damage and induced microseismicity - what do we learn from the lab?

(Georg Dresen, Grzegorz Kwiatek, Thomas Goebel and Marco Bohnhoff)

09:40-10:00

S3.1: The permeability of fracture intersections in basalt

(Ashley Stanton-Yonge, Catalina Sanchez-Roa, Thomas Mitchell, Yoshitaka Nara, W. Ashley Griffith, Philip Meredith)

10:00-10:20

S3.2: The effect of temperature on physical and mechanical properties of carbonate rocks

(Federico Vagnon, Sergio Vinciguerra, Cesare Comina, Anna Maria Ferrero, Giuseppe Mandrone, Chiara Colombero, Patrick Baud, Luke Griffiths, Marco Ceia, Roseane Missagia)

10:20-10:40

S3.3: Petrographic Analysis and Geomechanical Characterization of the Late Cretaceous Naparima Hill Formation, Trinidad

(Uwaila Charles Iyare, Oshaine Omar Blake, Ryan Ramsook)

10:40-11:10 Coffee break

11:10-11:30

S3.4: Using Roughness and Fragmentation Fractal Dimensions of a Volcanic Bimrock in Estimation of its UCS

(Elif Avşar)

11:30-11:50

S3.5: Inversion of fracture properties – A Genetic FWI algorithm applied to inversion of fracture stiffness from seismic waves

(Antonio Fuggi, Mark Hildyard, Roger Clark, Andy Hooper, John Brittan)

Tuesday, 03.09.2019

11:50-12:10

S3.6: Characterization of mechanical anisotropy in clayey rocks by Digital Image Correlation

(Audrey Bonnelye, Hakim Gharbi, Alexandre Dimanov, Michel Bornert, Patrick Aimedieu, Andrew King, Nathalie Conil)

12:10-12:30

S3.7: Observations on fracture toughness of mode I and mixed mode (I+II) fractures from three-point bending tests at elevated confining pressures

(Hong-Wei Yang, Michael Krause, Jörg Renner)

12:30-14:00 Lunch break

Session 4: Poroelasticity and seismicity of reservoir rocks

(Chair: Sergio Vinciguerra)

14:00-14:40

Keynote 4: Poroelastic interaction and seismicity induced by fluid productions and injections

(Serge Shapiro)

14:40-15:00

S4.1: Undrained pore pressure changes in rocks surrounding a reservoir: From poroelastic theory to fault activation?

(Rune M. Holt, Marcin Duda, Audun Bakk, Jørn F. Stenebråten)

15:00-15:20

S4.2: The mechanical behaviour of porous synthetic rocks

(Lucille Carbillet, Michael J. Heap, Fabian B. Wadsworth, Patrick Baud)

15:20-15:40

S4.3: The acoustic signature of fluid substitution in reservoir rocks

(Christian David, Joël Sarout, Christophe Barnes, Jérémie Dautriat, Lucas Pimienta)

15:40-17:00

Poster session 2 & Coffee break

From 18:00 Buffet dinner

Wednesday, 04.09.2019

Session 5: Simulation of fractures and faults

(Chairs: Guido Blöcher and Marton Farkas)

09:00-09:40

Keynote 5: Simulation of hydraulic driven fractures, joints and faults

(Heinz Konietzky)

09:40-10:00

S5.1: Role of stress tensor rotation due to pore pressure stress coupling for induced seismic hazard in georeservoirs

(Tim Hake, Moritz Ziegler, Oliver Heidbach)

10:00-10:20

S5.2: Multiphysics of faulting: influence of porosity and damage evolutions on the deformation modes within the lithosphere

(Antoine B. Jacquey, Mauro Cacace)

10:20-10:40

S5.3: Modeling crack and compaction band propagation in porous rocks with a phase-field fracture model

(Ralf Denzer, Alex Spetz, Erika Tudisco, Ola Dahlblom)

10:40-11:10 Coffee break

11:10-11:30

S5.4: Combination of experimental data and numerical simulations to unravel weakening mechanism on gypsum

(Ricardo Tomás, Philip Benson, Giacomo Pozzi, John Wheeler, Nicola de Paola)

11:30-11:50

S5.5: Non-linear anisotropic damage rheology model: theory and experimental verification

(Ivan Panteleev, Vladimir Lyakhovsky, John Browning, Philip G. Meredith, David Healy, Tom M. Mitchell)

11:50-12:10

S5.6: Simplified seismic modelling of fractured rock - how effective is a locally effective medium (LEM) compared to explicit representation of individual fractures.

(Emmanouil Parastatidis, Mark W. Hildyard, Andy Nowacki)

Wednesday, 04.09.2019

12:10-12:30

S5.7: On the seismic visibility and testability of fracture growth models

(Mark Hildyard, Emmanouil Parastatidis, Antonio Fuggi)

12:30-14:00 Lunch break

14:00-18:00 River cruise “7 Lakes”

From 18:00 Buffet dinner

Thursday, 05.09.2019

Session 6: Hydraulic, thermal and mechanical cyclic loading at multiple scales

(Chairs: Günter Zimmermann and Rune Holt)

09:00-09:40

Keynote 6: Cyclic hydraulic fracturing of granite: laboratory-scale proof of concept for the mitigation of induced seismicity

(Li Zhuang, Kwang Yeom Kim, Sung Gyu Jung, Melvin Diaz, Ki-Bok Min, Arno Zang, Ove Stephansson, Günter Zimmermann, Jeoung-Seok Yoon, Hannes Hofmann)

09:40-10:00

S6.1: Controlling fluid-injection-induced seismicity and permeability enhancement in granitic rock by fatigue hydraulic fracturing predicted from laboratory and in-situ experiments

(Arno Zang, Ove Stephansson, Günter Zimmermann, Hannes Hofmann, Kwang Yeom Kim, Jeoung Seok Yoon)

10:00-10:20

S6.2: Stimulation and fracture network creation in anisotropic rock

(C. Böse, G. Kwiatek, J. Starke, K. Plenkers, G. Dresen)

10:20-10:40

S6.3: Controlling Fluid-Induced Seismicity during a 6.1-km-Deep Geothermal Stimulation in Finland

(Grzegorz Kwiatek, Tero Saarno, Thomas Ader, Felix Bluemle, Marco Bohnhoff, Michael Chendorain, Georg Dresen, Pekka Heikkinen, Ilmo Kukkonen, Peter Leary, Maria Leonhardt, Peter Malin, Patricia Martínez-Garzón, Kevin Passmore, Paul Passmore, Sergio Valenzuela, Christopher Wollin)

10:40-11:10 Coffee break

Thursday, 05.09.2019

11:10-11:30

S6.4: Slip and Instability Mechanisms of Coal-Rock Parting-Coal Structure (CRCS) Under Coupled Dynamic and Static Loading

(Cai-Ping Lu, Yang Liu, Heng Zhang)

11:30-11:50

S6.5: Structural analysis and effect of impurity content in Salt Rock deformation under Cyclic Thermo-Mechanical Loading Conditions

(Carla Martin-Clave, Audrey Ougier-Simonin, Alec M. Marshall, Veerle Vandeginste)

11:50-12:10

S6.6: Microstructural controls on thermal crack damage during temperature-cycling experiments on volcanic rocks

(Ali Daoud, John Browning, Philip Meredith, Thomas Mitchell)

12:10-12:30

S6.7: Localization of Shear in Water-Saturated Granular Media

(Stanislav Parez, Tereza Travnickova, Liran Goren, Einat Aharonov)

12:30-14:00 Lunch break

Session 7: Compaction and damage of porous rock II

(Chairs: Christian David and Carla Martin-Clave)

14:00-14:40

Keynote 7: Stress estimation and structural observations around a subduction fault

(Marianne Conin, Yohei Hamada, Gilles Guerin, Gregory Moore, Makoto Otsubo, Kohtaro Ujiie, Armin Dielforder, Christine Regalla, Barbara John, Dan Faulkner, Asuka Yamaguchi, Matt Ikari, Gaku Kimura, Hiroko Kitajima, Demian Saffer, Harold Tobin, Masataka Kinoshita, Lena Maeda, Sean Toczko, Nobu Eguchi, the IODP Expedition 358 Shipboard Scientific Party)

14:40-15:00

S7.1: New global correlations to assess depletion-induced compaction of progressively-buried sandstone

(Sander Hol, John W. Dudley, Arjan J. van der Linden)

Thursday, 05.09.2019

15:00-15:20

S7.2: Localized versus distributed fracturing in the damage rheology model with evolving yield conditions

(Hannah Gajst, Eyal Shalev, Ram Weinberger, Shmuel Marco, Wenlu Zhu, Vladimir Lyakhovsky)

15:20-15:40

S7.3: Impact of water-weakening on mechanical strength of microporous carbonate rock: fluid substitution and ultrasonic monitoring of water-induced damage

(Davide Geremia, Christian David, Beatriz Menéndez, Christophe Barnes)

15:40-16:10 Coffee break

16:10-16:30

S7.4: Impact of shear-enhanced compaction bands on fluid flow via High-Speed Neutron Tomography

(Elli-Maria Charalampidou, Erika Tudisco, Maddi Etxegarai, Gary Couples, Nikolay Kardjilov, Stephen Hall)

16:30-16:50

S5.5: Synchrotron X-ray imaging in 4D: Multiscale failure and compaction localization in triaxially compressed porous limestone

(Patrick Baud, Lingcao Huang, Benoit Cordonnier, François Renard, Lin Liu, Teng-fong Wong)

16:50-17:10

S7.6: Fracture or Band? – A Potentially Common Transitional Type of Deformation and its Consequences for Fluid Movement through Fracture and Fault Systems

(Helen Lewis, Gary Couples, Jim Buckman)

17:10-17:30

S7.7: Full 3D investigation at microstructural scale of heterogeneous swelling strains and induced damage in anisotropic clayey rocks

(Michel Bornert, Hakim Gharbi, Andrew King, Audrey Bonnelye, Alexandre Dimanov, Patrick Aimedieu, Emmanuel Keita, Nathalie Conil)

From 18:00 Buffet dinner

Friday, 06.09.2019

Session 8: Hydraulic fracturing, hydromechanics and fracture permeability

(Chairs: Harald Milsch and Alireza Hassanzadegan)

09:00-09:40

Keynote 8: Key implementation aspects and results from the in-situ stimulation experiment at the Grimsel test site

(Florian Amann, Valentin Gischig, Joseph Doetsch, Reza Jalali, Hannes Krietsch, Linus Villiger, Nathan Dutler, Benoit Valley)

09:40-10:00

S8.1: On the anisotropy and nonlinearity of the Grimsel Granite

(Morteza Nejati, Martin O. Saar, Thomas Driesner)

10:00-10:20

S8.2: Hydraulic fracture growth in the heterogeneous strata of the upper carboniferous

(Cedric Solibida, Ferdinand Stöckhert, Lucas Witte, Michael Alber)

10:20-10:40

S8.3: Stress reorientation by earthquakes near Ganzi-Yushu strike slip fault and interpretation with discrete element modeling

(Zhandong Su, Jeoung Seok Yoon, Arno Zang)

10:40-11:10 Coffee break

11:10-11:30

S8.4: Laboratory experiments investigating the hydro-mechanical behaviour of rocks containing a single fracture

(Max Kewel, Jörg Renner, Alireza Hassanzadegan, Torsten Tischner)

11:30-11:50

S8.5: Hydraulic-mechanical characterisation of microfaults in granite – an experimental study

(Christian Kluge, Guido Blöcher, Auke Barnhoorn, David Bruhn)

11:50-12:10

S8.6: Thermo-Mechanical Investigations on the Self-propping Potential of Tensile Fractures in Sandstone

(Chaojie Cheng, Harald Milsch)

12:10-12:30

S8.7: How to publish Open Access in earth sciences

(Andreas Hübner, Britta Nölte)

12:30-14:00 Lunch break

From 14:00 Departure

SESSION 1: Fluid driven fractures and seismicity

Keynote 1: Physical behavior of fluid driven earthquakes

Marie Violay (1), Mateo Acosta (1), Chiara Cornelio (1), Carolina Giorgetti (1), Corentin Noel (1), Francois Passelegue (1), Alexandre Schubnel (2), Stefan Nielsen (3), Giulio Di Toro (4), Elena Spagnuolo (5)

(1) EPFL, Switzerland; (2) Ens Paris, France; (3) University of Durham, UK; (4) University of Padova, Italy; (5) INGV, Italy

Fluids play an important role in fault zone and in earthquakes generation. Fluid pressure reduces the normal effective stress, lowering the frictional strength of the fault, potentially triggering earthquake ruptures. Fluid injection induced earthquakes in deep reservoirs are direct evidence of the effect of fluid pressure on the fault strength. Although simple in theory, the mechanisms that govern the nucleation, propagation and arrest of these earthquakes remain poorly constrained, and our ability to assess the seismic hazard associated with induced events remains limited. Here, thanks to friction tests, we investigate the effect of fluid pressure, fluid thermo-physical and rheological properties on fault co-seismic weakening and healing. We demonstrate that in silicate-bearing rocks: at low fluid viscosity, during rupture acceleration, initial fault weakening is governed by the flash heating mechanism and is delayed in the presence of water. This mechanism is influenced by fluid thermophysical water properties. Therefore, the presence of low viscosity fluids might delay or inhibit the rupture nucleation and propagation depending on pressure and temperature conditions; at high fluid viscosity, during rupture acceleration, the initial weakening mechanism is governed by elasto-hydrodynamic lubrication (EHL). EHL efficiency strongly depends on the amount of final slip. Interestingly, similar mechanisms are gouverning fault dynamic healing. Obtaining a fundamental understanding of the dynamics of a fault system and its associated energy budget is important to assess the seismic hazard of both natural and induced earthquakes.

Contact: Marie Violay
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S1.1: Laboratory Study of the Dynamics of Stick-Slip Sliding in Large Sandstone Block Induced by Fluid Injections

Sergey Stanchits (1), Volker Oye (2), Nicholas Seprodi (3), Pierre Cerasi (4), Anna Stroisz (4), Robert Bauer (5)
(1) Skolkovo Institute of Science and Technology, Russia; (2) Norsar, Norway; (3) Schlumberger, USA; (4) Sintef Industry, Norway; (5) Illinois State Geological Survey, USA

Safe geologic sequestration of CO_2 is essential to decrease the concentration of greenhouse gases in the atmosphere. However, the injection could raise the underground pore pressure and potentially induce sliding of critically stressed faults. We report results of laboratory tests, where different fluid injections were implemented close to the stressed artificial interface of a ~1m length with the intention to induce an activation of interface sliding. We have found that increases of pore pressure in the interface up to ~1 MPa did not cause any acceleration in the interface sliding, neither in case of a locked nor sliding interface. Injection of fluid under elevated pore pressure created hydraulic fracturing in the vicinity of the interface, causing an increase of pore pressure in the interface up to ~ 6.2 MPa, and after injection shut-in, pore pressure dropped to almost zero. However, about 10 minutes later, a sudden sliding of the interface (stick-slip motion) was recorded. This kind of stick-slip event could be considered analogical to the natural earthquakes in the Earth. Two types of Acoustic Emission (AE) signals were detected: short bursts and long-lasting oscillations (tremors). The analysis of the spatial distribution of the AE energy was applied to monitor the evolution of the hydraulic fracture and thereafter – the dynamics of stick-slip. It was found that at first, the nucleation of the sliding near one edge of the interface occurred, then sliding propagated along the whole ~ 1 m long interface with an average speed of a few m/s. The speed and the energy radiated during this event were approximately 6 orders of magnitude larger than observed during quasi-static sliding preceding the stick-slip. Occurrence of this powerful sudden event in the stressed artificial interface is to be related to the injection of fluid under elevated pore pressure completed 10 minutes before the stick-slip event, creating hydraulic fracturing in the rock and causing significant increase of pore pressure in the interface. Such a suddenly occurring event could be considered a laboratory analogy to the fluid-induced seismicity, for example, earthquakes induced by wastewater disposal.

Contact: Sergey Stanchits
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S1.2: Impact of heterogeneity, anisotropy and discontinuities on hydraulic fracture propagation – a lab study

Ferdinand Stoeckhert, Cedric Solibida, Michael Alber
Ruhr University Bochum

In a hypothetical homogeneous rock mass, hydraulic fractures are supposed to be penny shaped and oriented perpendicular to the minimum principal stress. However, if the rock mass is heterogeneous, anisotropic and/or discontinuous, the geometry of hydraulic fractures might significantly deviate from being penny-shaped and aligned to the principal stress orientation.

To investigate and quantify the impact of the rock fabric on hydraulic fracture propagation, we conducted a number of laboratory experiments. These include hydraulic fractures being propagated through discontinuities, heterogeneous as well as anisotropic rocks at various levels of external stress.

In the experiments, high viscosity fluids are injected into cubic rock specimens or stacks of cuboid specimens, which are externally loaded by servo-controlled hydraulic pistons. Monitoring acoustic emissions yields insights on fracture growth processes and the interaction between rock fabric and propagating fractures.

The results of these experiments indicate that on laboratory scale rock fabric and structure might have an significant impact on fracture geometries even at reservoir stress levels. Fracture mechanical simulations are able to reproduce some, but not all of the phenomena observed in the experiments.

Therefore, we try to develop empirical relationships between the fracture geometry, external stress levels and mechanical parameters describing the rock fabric. These can be used to improve and validate fracture mechanical models as well as to assess the impact of fabric on the productivity of hydraulic fractures in deep reservoirs.

Contact: Ferdinand Stoeckhert
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S1.3: Hydraulic fracturing process in granite under different fracturing regime

Kwang Yeom Kim (1,2), Sung Gyu Jung (2), Hannes Hofmann (3), Günter Zimmermann (3), Ki-Bok Min (4)

(1)Korea Institute of Civil Engineering and Building Technology, Goyang, Republic of Korea; (2) University of Science and Technology, Daejeon, Republic of Korea; (3) GFZ German Research Centre for Geosciences, Potsdam, Germany; (4) Department of Energy Resources Engineering and Research Institute of Energy and Resources, Seoul National University, Seoul, Republic of Korea

To understand the hydraulic fracturing behavior for low permeable crystalline rock which is distinguished from other rock formation, many experimental and numerical studies have been carried out specially focusing on fracturing regime and poroelastic response. The most revolutionary work is fracture mechanics based approach to account for the fracture initiation and propagation in hydraulic fracturing process. According to this concept, hydraulic fracture initiates when the stress intensity factor exceeds the fracture toughness at the tip of the fracture at the wellbore wall and it continues to grow until the stress intensity factor is less than the fracture toughness.

This fracturing process can be divided into two different regimes depending on how the injected fluid pressure acts on the fracture surface. When the pressurization rate is low or low viscosity injection fluid is injected, the fracturing process is under toughness-dominated regime resulting in unstable fracture propagation. On the contrary, with high pressurization rate or high viscosity injection fluid, it gets close to viscosity-dominated regime leading to stable fracture propagation. Though previous works have contributed to understand the two different behaviors, in terms of fracturing regime, how these different processes evolve and affect the fracturing result has not been well investigated. In most cases, simplified approaches have been used for numerical model and analysis of experimental results.

In this study, we investigated varying fracturing process especially focusing on the evolution of fracture propagation depending on fracturing-regime influence parameters. Different pressurization rate and injection fluid viscosities are employed to realize different fracturing regimes in the granite. Acoustic emission and a couple of visual inspection techniques such as thin section analysis and X-ray imaging technique were utilized to observe the fracture pattern.

Contact: Kwang Yeom Kim
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S1.4: Fluid-driven tensile fracture and fracture toughness in Nash Point shale at elevated pressure

Philip Benson (1), Stephan Gehne (1), Nathaniel Forbes-Inskip (2), Philip Meredith (3), Agust Gudmundsson (2), and Nick Koor (1)

(1) University of Portsmouth, Rock Mechanics Laboratory; (2) Dept. Earth Sciences, Royal Holloway University of London, U.K; (3) Rock and Ice Physics Laboratory, Dept. Earth Sciences, University College London, U.K.

Fluid-driven fracturing is becoming increasingly established in the hydrocarbon extraction industry. However, whilst a large number of studies have now developed laboratory methods to simulate the process in a range of settings, and across a number of different rock types, data relating the fundamental material parameters (such as fracture toughness) to the overall rock mechanics response as a function of parameters such as confining and pore pressure remains limited. Here we report a new analysis to recover fracture toughness across a range of effective pressures using a modified thick walled cylinder test mounted within a conventional triaxial deformation apparatus. We use cylindrical samples of 90mm in length and 40mm diameter, drilled with an axial conduit 12.6 mm in diameter. A suite of Acoustic Emission sensors records microseismic activity via ports embedded in the engineered nitrile jacket, 4 of which are also used to measure radial deformation (strain) across the diameter at 90 degrees to each other. We use sample of Nash Point Shale (NPS) from the south coast of Wales (UK), drilled both normal and parallel to cross-bedding to investigate anisotropy effects. Conventional semi-circular bend tests indicate ambient fracture toughness of 0.24 – 0.30 MPa $m^{1/2}$ in short transverse mode (along bedding), and 0.71 to 0.73 MPa $m^{1/2}$ in divider mode (cutting across bedding) orientations.

From a larger dataset of some 50 experiments performed under confined conditions, we have analysed a subset of 6 experiments with conduit drilled parallel to bedding and another 3 experiments with conduit drilled normal to bedding. The fluid injection pressure required to fracture the shell of NPS increases with both applied confining pressure and bedding, ranging from 10 MPa to 36 MPa parallel to bedding and 30 to 58 MPa normal to bedding as confining pressure is increased from 2.2 to 25 MPa. We note that the pore fluid undergoes a number of oscillations after the initial fracture, and that this effect is more common in experiments at a lower confining pressure. Using this oscillation to infer the relative propagation of the fracture (i.e. in a staged process) via the increasing cumulative AE energy and the model of Abou-Sayed (1978) for initial flaw size, we calculate a new fracture length after each oscillation. This analysis produces a fracture toughness ranging from 0.50 to 2.76 MPa $m^{1/2}$ (parallel to bedding) and 2.98 to 4.05 MPa $m^{1/2}$ as confining pressure increases from 2.2 to 25 MPa. When analysed in terms of an effective pressure, taking into account the fluid pressure at each stage of fracture growth, we find that the fracture toughness is linear with effective pressure, increasing from 0.36 to 4.05 MPa $m^{1/2}$ as effective pressure increases from 1.7 to 22 MPa. In addition, we note that the linear increase of fracture toughness with effective pressure is unaffected by the presence of anisotropy.

Contact: Philip Benson
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S1.5: In-situ synchrotron X-ray tomography of fluid injection experiments at elevated confining pressure

Michael Chandler (1), Julian Mecklenburgh (1), Anne-Laure Fauchille (2), Roberto Rizzo (3), Lin Ma (1), Patrick Dowey (1), Steven May (1), Robert Atwood (4), Peter Lee (5), Ernest Rutter (1), Anna Bogush (5)

(1) University of Manchester, (2) Ecole Centrale de Nantes; (3) University of Aberdeen; (4) Diamond Light Source, (5) University College London

A suite of laboratory-scale fluid injection experiments were conducted on 20mm diameter shale samples at elevated confining pressures between 20 and 50 MPa. Experiments were conducted on Bowland, Haynesville, Kimmeridge, Mancos and Whitby shales, as well as Solenhofen limestone. An Aluminium pressure vessel was specially developed to perform these fluid injection experiments with in-situ X-Ray Tomography on the I12 beamline at Diamond Light Source, UK. Tomographs with a voxel edge-length of 17µm were generated in this way and have been used to correlate fractures to the layering in the materials.

Here, the breakdown pressures of the various rock samples were seen to increase linearly with confining pressure as has been seen in previous studies, with little difference between sample materials. However, here, two distinct linear trends are interpreted, offset by around 10MPa. The tomographs demonstrate that the higher of these two trends corresponds to the development of new fractures, while the lower trend corresponds to reopening in samples featuring existing fracture populations.

Tomographs were recorded throughout the application of the confining pressure, and subsequently, the injection of fluid into the central boreholes in the samples. These tomographic images have been used to investigate the closure of existing fractures during the application of the confining pressure, as well as the development of new fractures induced by the fluid pressure. In general, the primary fracture opened up parallel to the borehole, independent of the orientation to bedding. However, borehole-perpendicular primary fractures were observed in some of the more laminated shales, and secondary, bedding-parallel, fractures were induced in many samples with the borehole perpendicular to bedding.

Post-experiment SEM images of the regions around the main fractures demonstrate substantial differences in the characteristics of the damaged region around the main fracture body between materials. In Haynesville shale, the damaged zone appears to mostly contain reactivated microfractures lying parallel to bedding, while in the more homogenous Bowland shale, this small-scale damage has a wider range of orientations.

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S1.6: Fault Reactivation for Permeability Enhancement and Associated Induced Seismicity in Crystalline Rocks

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Acoustic emissions (AE), radiated from asperity damage, and the evolution of the surface roughness were analyzed to obtain insights into several stages in shear reactivation of natural fractures in granite. The results of this study revealed that the real contact and damage areas only occur on asperities that are facing the shear direction and their surfaces are steeper than a specific threshold. Two threshold angles were proposed: 1) contact threshold angle in which asperities with angles higher than this threshold will stay in contact, and 2) damage threshold angle in which asperities with angles higher than this threshold will be damaged.

It was observed that under low effective normal stresses, in the case of high pore pressure, a shear displacement as low as 1 mm can reduce the contact area to 10%, which means an increase in the mechanical aperture up to 90%. This explains how shear reactivation of pre-existing natural fractures can significantly increase the transmissivity of the rock mass for applications such as enhanced geothermal systems (EGS) in crystalline rocks.

The rate, cumulative, b-value, and magnitude of the AE events were correlated to the shear stress-shear displacement of the tested rock joints. Shear reactivation of the tested natural fractures in this study demonstrated a fracturing process similar to natural earthquakes showing: 1) a small number of hits before the peak, 2) a sudden release of AE energy at the peak, 3) a large number of hits after the peak, and 4) finally decreasing hits rate obeying the Omori's law.

Locations of the AE sources were determined from propagation velocity of acoustic waves and the traveling time from the event source to the AE sensor. These sources correspond to damage zones that are caused by active asperities in the shearing process, mostly asperities facing the shear direction. The distribution of the source locations and their associated magnitude helps to detect location, size, and the magnitude of the damage during each stage in the shearing process. Presence of the AE events with low energy before shear stress peak revealed that slip may start from zones with less frictional resistance and then it will be controlled by rough asperities with higher frictional resistance.

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Keynote 2: The physics behind sandstone reservoir compaction: the cause of induced seismicity in gas fields

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As we are transitioning away from high-carbon energy sources, such as coal and oil, toward zero-carbon energy sources, such as geothermal energy and renewables, natural gas may play a key role as a low-carbon alternative. However, subsurface exploitation of the Earth's natural resources, such as oil, gas and groundwater, removes the natural system from its chemical and physical equilibrium. With global energy and water demand increasing rapidly, while availability diminishes, densely populated areas are becoming increasingly targeted for exploitation. Indeed, the impact of our geo-resources needs on the environment has already become noticeable. Hydrocarbon production has led to subsidence and seismicity in offshore and onshore hydrocarbon fields. In the Netherlands, tens of centimetres of subsidence occurring above the gasfields of Groningen and Friesland, and associated induced seismicity, are key issues in the news. This may impact the potential for natural gas in aiding in the energy transition.

In this contribution, I will consider what processes may control the progress of compaction in sandstone gas reservoirs, and how this can lead to induced seismicity. Attempts to evaluate which of these processes are the most important by means of laboratory experiments are revealing that their rates are strongly affected by fluid-rock interactions, i.e. by pore fluid pH and chemical composition. Interestingly, these effects, along with microstructural and acoustic or microseismic emission studies, offer a new way of probing the mechanisms that control compaction of gas and other reservoirs, and hence of arriving at mechanism-based models for compaction creep and its role in controlling subsidence and associated seismicity. At the same time these type of experiments can shed light on alternative uses of subsurface storage space. Would it be possible to mitigate reservoir compaction by injection of chemical agents? And what will be the long-term impact of geothermal energy production, storage of CO_2 or temporary storage of renewable energy, such as in the form of compressed air, hydrogen or synthetic fuel?

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S2.1: A Rock Mechanical Model for Overbalanced, Managed Pressure, and Underbalanced Drilling Applications

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In this work rock mechanics principles are used to elaborate a mathematical model to predict wellbore pressure required for safe overbalanced (OBD), managed pressure (MPD), and underbalanced (UBD) drilling based on laboratory evaluation of representative core samples from the formation to be drilled. The elaborated model combines the linear-poroelastic solution of stresses around circular boreholes and Mohr-Coulomb failure criterion. The model compares the induced stresses caused by the application of drilling (wellbore pressure) with the allowable induced stresses based on laboratory measurements of the formation mechanical properties (unconfined compressive strength and poison's ratio), failure criteria (apparent cohesion and angle of internal friction), in-situ principle stresses, and wellbore trajectory (vertical, directional, or horizontal).

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S2.2: Damage accumulation and wellbore stability

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The introduction of a wellbore opening at depth with a free surface to tectonically stressed rocks perturbs the natural stress field and may promote rock failure along the borehole walls. This often results in an elongation of the borehole cross section in the direction of the minimum principal stress orthogonal to the borehole axis. The classical approach to borehole stability analysis is based on Mohr-Coulomb failure criterion to the stress distribution around a circular opening in an elastic material. This approach is popular because it allows for successful determination of stress orientation. However, it neglects time dependent processes that can lead to continuous failure events that often occur in crystalline rocks and reported/observed in several deep boreholes (e.g., KTB, Kola, Siljan Ring). The elongated shape created by breakouts enhances unstable conditions due to stress concentration near the elongated axes. The Mohr-Coulomb failure analysis fails to explain wellbore stabilization that occurs after breakouts.

In this study we present results of three-dimensional simulated breakouts and well stability using a damage rheology model for poro-elastic rocks. The model includes damage- and porosity-dependent yield criterion constrained using laboratory measured elastic and damage properties of a porous arkosic rock (Zenifim formation). We show that for crystalline Westerly granite properties, the shape of the well cross section grows continuously and does not stabilize. Using elastic and damage properties of the porous arkose with rock strengthening, the occurrence of breakouts stabilizes the wellbore and inhibits further failure.

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S2.3: High Pore Pressures: What Is Indicated by Vein-Filled Rock Masses?

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It is common to read, or hear it said, that very high pore pressure leads to very low effective stress, and thus that the overpressured rock mass deforms in a brittle and dilatant fashion. This prediction (and associated interpretation of events) is often applied to those rock units that are serving as seals, and so the belief is that seals fail when the pore pressure builds to extreme values. This paper counters that view. Using a newly-published micro-mechanics analysis that provides a phenomenological understanding of poro-elasticity, the role of elevated pore pressure is shown to cause an increase in stress, with the effective stress becoming larger due to a more-rapid rate of increase in stress than in pressure. The same conclusion is reached if we consider the rock mass to be pre-fractured, and this response is, again, opposite to the received wisdom for fractured rocks.

So, what interpretation do we apply to the processes that caused a supposed seal interval to be disrupted by mineral veins filling fractures – a feature common in many tectonic settings? The interpretation posed here is that such observations of veins are evidence of bulk dilation of the rock mass, with pore waters flowing TO the sites of vein formation. The large number of pore volumes required to deliver the dissolved vein-fill material indicate that the fluids arrived from elsewhere. Likely, the 'elsewhere' is at greater depth, and possibly not too far below. The cause of the dilation could be anything, but one option is the volume expansion of the subjacent rock mass, in which the pore fluid pressure was progressively increased (because of the addition of relative water mass and consequent poro-elastic effects). Because of lateral strain constraints, the increased bulk volume causes a small degree of uplift. If this uplift is not uniform, due to whatever geological reasons, the overlying rock units will be subjected to bending, with concomitant dilational (and compactional) strains, and thus deformations. If the high-pressure pore fluids find a pathway through the overpressured rock mass, and out of it, which is not easy to explain, the fluids can flow from there into the dilated region and deposit their dissolved content to make the veins.

In this model, veins within a 'caprock' are not indicators of local extreme pore pressure, but instead, they represent the outflow from a nearby overpressured region. The veined caprock sequence is, therefore, still an indicator of high pore pressures, but its characteristics are related to a more-complicated process, and a different process model, than have been applied heretofore. The position of the extreme pore pressure is not in the place with veins; instead, that place is positioned in a gradient region on the margin of the high fluid energies. We can still call that rock unit a caprock, but we should not use the veins to infer high pore pressures where we see them – they are indicators of high pore pressures elsewhere. The effective-stress argument, which has survived for many decades, is invalid.

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P1.1: Fracture aperture and flow evolution due to confined shear displacement using X-ray computerized tomography on crystalline and clay-rich rocks

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Shearing of fractures and faults causes permeability changes by altering the distribution of void space within the fracture. Common methods to estimate the effects of shearing on fracture aperture, roughness, and connectivity are typically incapable of providing in-situ observations. We investigate in-situ changes in fracture aperture distribution with progressive shear displacement using a novel X-ray transparent core-holder in two crystalline rocks (Westerly granite and Carrara marble) and one shale sample (Opalinus shale). The so-called Calibration-Free Missing Attenuation method was applied to quantify and map the distribution of highly-resolved fracture apertures with a spatial resolution of (0.25 x 0.25) mm^2. The method enables the estimation of fracture aperture across the rough-walled fracture with reliable uncertainty estimates that give a high resolution fracture aperture map at each progressive shear displacement step. Simultaneously, pulse tracer injection experiments were carried out while acquiring X-ray CT scans to obtain time-series images of transport through the rough-walled fractures. Solutions of deionized water mixed with KCl (saturating fluid) and KI (tracer fluid) were used due to their contrasting CT numbers. We observe that shearing increases the fracture aperture with displacement, thereby increasing the fracture volume and reducing the surface contact area of the fracture walls. The displacement creates flow anisotropy due to roughness induced dilation of the fracture, and the magnitude of aperture change is controlled by the initial roughness. The direct imaging of flow through the fracture allows us to determine channelization and stagnation zones within the fracture. The use of laboratory studies are advantageous because they provide high resolution fracture aperture maps, which can be up-scaled to the field. These observations can potentially be used to assess changes in fault hydraulic properties as a function of slip distance associated with seismicity.

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P1.2: Measurement of the thermal diffusivity for several types of rocks at high pressures and high temperatures using a pulse method

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Thermal conductivity of minerals and rocks under high temperatures and high pressures is a key parameter to understand the dynamic mechanism of the Earth's interior, temperature distribution and thermal evolution of the Earth.

We measured the thermal diffusivity for several types of rocks at pressures of 0.5–2.0 GPa and temperatures of 300–1073 K using a pulse method on a cubic press apparatus. The results show that:

1. Corresponding to the temperature and pressure ranges of 285~973 K, 0.5~2.0 GPa; 274~973 K, 1.0~2.0 GPa; 278~973 K, 1.0~2.0 GPa; 278~973 K, 0.5~1.0 GPa; 278~973 K, 0.5~2.0 GPa; 280~973 K, 0.5~1.0 GPa; 278~973 K, 1.0~2.0 GPa and 278~973 K, 1.0 GPa, the thermal diffusivities for albitite, granite, granodiorite, gabbro, basalt, garnet amphibolite, eclogite and pyroxenite are in the ranges of 0.80~1.35, 1.02~1.94, 1.00~1.84, 0.92~1.45, 0.78~1.28, 0.77~1.41, 0.95~1.64 and 0.92~1.96 $mm^2 s^{-1}$ respectively.

2. Corresponding to the temperature ranges of 285~973 K, 280~973 K, 274 K, the pressure coefficients for albitite, garnet amphibolite and granite are in the ranges of 0.05~0.09 GPa^{-1}, 0.17~0.10 GPa-1, 0.09~0.04 GPa^{-1}. At 273K, the pressure coefficients for granodiorite and eclogite are 0.08 GPa^{-1}, 0.04 GPa^{-1}; At 278~973 K, the pressure coefficients for gabbro and basalt are in the ranges of 0.13~0.08 GPa^{-1}, 0.08 GPa^{-1}.

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P1.3: Compressive and tensile strength of Naparima Hill organic mudstone

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The compressive and tensile strength are key parameters required to design and model hydraulic fracturing in hydrocarbon reservoirs, especially in tight unconventional reservoirs. Unconfined and triaxial compressive strength, and indirect tensile strength measurements were made on dry samples at room temperature from 7 different outcrop locations of the Naprima Hill formation. The late cretaceous Naparima Hill formation is a prolific oil source rock of the SE Caribbean and generates most of the crude oils produced from the southern and Columbus Basins, Trinidad. Many researchers have considered this formation to also be a prospective unconventional reservoir ('source rock reservoir'). Petrographic and X-ray diffraction mineralogy studies on the rock samples revealed four distinct lithofacies: (a) siliceous argillite filled with calcite veins, (b) siliceous-calcareous argillite interbedded with black chert, (c) Chert-rich calcareous-siliceous argillite with calcareous foraminifera, and (d) siliceous argillite with chert nodules. The unconfined strength range from 44 - 209 MPa. Brazilian testing, used to determine tensile strength, show results of 9 - 36 MPa. There exist a good correlation, R-squared = 0.87, between the unconfined strength and tensile strength. Triaxial strength test were conducted at 10, 50, 90 and 130 MPa confining pressures. Mohr-Coulomb failure envelopes were determined, and the values of the angle of internal friction range from 25° to 31° and the cohesion values range from 23 to 86 MPa. The results shows that value of cohesion decreases with increasing angle of internal frication. All samples experienced brittle failure except for samples within facies b and d at 90 and 130 confining pressure, where ductile failure was observed. The results shows that the unconfined and tensile strength are mainly controlled by the lithofacies, whereas the triaxial compressive strength is controlled by the lithofacies, microfractures and mineralogy.

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P1.4: Experimental study on the difference between gas and water permeability and the mechanism of permeability evolution in response to the presence of water in clay-rich fault and reservoir rocks

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Clay minerals are common constituents of fault zones, especially at the shallow portions where fault rocks usually contain abundant clay minerals. Gas permeability of clay-bearing rocks is usually higher than that measured with water as the pore fluid. Besides the Klinkenberg gas slippage effect, the hydrophilic properties of clay minerals subjected to water may have strong influences. The response of pore structure and mechanisms of permeability under dry and wet conditions should be different. Clay minerals are also common constituents of reservoir rocks, such as shales, mudstones, and sandstones. Significant clay hydration can occur in clay-bearing formations during geo-engineering activities, such as fluid injection and CO_2 sequestration in reservoirs, which may influence the hydration state of clay minerals. However, the role of clay hydration associated with massive gas-to-water exchange and how such hydration affects the stress state, fluid transport, and mechanical behaviors of reservoir formation rocks is still not well understood. To better understand the mechanism of permeability and pore structure evolution in response to the presence of water in clay-bearing rocks, we performed detailed fluid transport experiments on synthetic quartz-smectite, quartz-illite mixtures, and natural fault gouge, as well as clay-deplete sandstones. Experiments were performed on a fluid flow apparatus with effective pressures (Pe) cycling between 5 MPa and 105 MPa. Each sample was subject to nine pressure cycles, along which permeability and porosity were measured under both dry and water-saturated conditions.

Results show that the permeability of all the samples investigated decreases with the increasing of Pe. Gas permeability exhibits strong pore pressure dependence, which can be explained by the slippage effect. Permeability results measured by water are lower than the gas results. The permeability trends observed for samples after the presence of water can be explained by the evolution of porosity, as can be determined from the bulk volume and XRD measurement results. These data indicate that the reduction of permeability can be explained by the hydration expansion of clay minerals that decreases the pore volume. A conceptual model incorporating clay expansion and grain rearrangement is proposed to describe the evolution of permeability and pore structure after the presence of water in clay-rich rocks. Based on these results we further discussed the implications for fluid transport in clay-rich fault zones and the effect of clay hydration on the stress state, fluid transport and mechanical behaviors in reservoir formations following the operation of fluid injection.

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P1.5: Relations between pore pressure and acoustic emissions in critically stressed wet sandstone

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Injection-induced seismicity poses a risk to public safety, infrastructure and perception. Cases of wastewater disposal deep underground present the greatest seismic hazard. Currently, relations used in risk assessment are based on injection volume and rate. However, the physical mechanism of fault initiation is known to be a reduction in the effective normal stress. Information of its components, the stress state and fluid pressure, are generally unavailable in the field. Experimentation on cores of 0.05 m diameter and 0.1 m length is undertaken to establish relations between pore pressure and acoustic emissions, a proxy of seismicity. Wet sandstone is held at high differential stress and confining pressure to replicate crustal conditions and subsequently injected into while acoustic emissions are monitored. The stress state is determined from mechanical behaviour and acoustic emissions during compression. Injection pressure is stepped to allow pressure equilibration and acoustic emissions to cease before it is increased until macroscopic failure occurs below the minimum principal stress. Previous experiments have been in initially dry conditions, and this has limited their applications. The relations and one-dimensional flow of fluid in a bounded homogenous porous medium will form an induced seismicity model to be calibrated to the catalogue of events. Model applications are in the inversion of rock properties and critical pressure, a measure of the proximity of optimally orientated faults to failure.

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P1.6: Creep behavior of Bowland and Posidonia shale at In Situ pc, T conditions

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We conducted constant stress deformation experiments at elevated confining pressures, pc = 50 – 115 MPa, and temperatures, T = 75 – 150 °C, on Posidonia (GER) and Bowland (UK) shale to unravel their long – term creep properties at simulated reservoir conditions, also with respect to petrophysical and mechanical properties. Depending on applied pc – T conditions and sample composition, recorded creep curves exhibit either only a primary (decelerating) or additionally a secondary (quasi steady state) and subsequently a tertiary (accelerating) creep phase during deformation. Creep strain is enhanced and a transition from primary towards secondary and tertiary creep behavior is observable at high temperature and axial differential stress and low confining pressure. Posidonia shale, which is rich in weak constituents (clay, mica, organic content), creeps faster when compared to either carbonate – or quartz – rich Bowland shale. Electron microscopy performed on polished thin sections was conducted to observe microstructural features, revealing that the primary creep strain is mainly accommodated by deformation of weak minerals and local pore space reduction. In addition, micro crack growth occurred during secondary creep. We used an empirical correlation between creep strain and time based on a power law to describe the decelerating creep phase, also accounting for the influence of confining pressure, temperature and axial differential stress. The results suggest that the primary creep strain can be correlated with mechanical properties determined from short – term constant strain rate experiments such as static Young's modulus, triaxial compressive strength or brittleness.

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P1.7: Numerical investigation of hydraulic stimulation and related induced seismicity in Pohang fractured geothermal reservoir, South Korea

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In this study, we investigate numerically the hydro-mechanical behaviour of fractured crystalline rock due to hydraulic stimulations at the Pohang Enhanced Geothermal site in South Korea. Several hydraulic stimulations were performed in wells PX-1 and PX-2. Based on the well test analysis of these stimulations the fracturing mechanism is associated with hydro-shearing in well PX-1. We use the commercial code FracMan (Golder Associates) that enables studying dynamic hydro-mechanical coupled processes in fractured media in three dimensions combining the finite element method with a discrete fracture network. The software is used to simulate fluid pressure perturbation and related stress redistribution at fractures during hydraulic stimulation in PX-1. This can be combined with critical stress analysis on fracture surface to derive location and magnitude of microseismic events. The calibrated reservoir model allows different injection strategies to be tested. Ahead of future field applications, this methodology may be applied at other sites to optimize stimulation strategies, if sufficient data are available.

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P1.8: Laboratory experiments and discrete element method grain based models exploring the thermo-mechanical behaviour of intact sandstone and discontinuities

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Coupled thermo-mechanical processes present challenges in a number of areas of geological understanding. Thermal loading can occur due to the natural geothermal gradient or the introduction of an anthropogenic heat source such as in the case of the disposal of radioactive waste in geological environments. Different minerals and micro-defects in rock result in heterogeneity at a grain scale, affecting the mechanical and thermal properties of the material. Changes in strength and stiffness can occur from exposure to elevated temperatures, causing thermally induced intergranular micro-cracking within the rock. In this study we investigate thermal micro-cracking at a grain scale through both laboratory experiments and their numerical simulations. We performed laboratory triaxial experiments on intact specimens of fine grain sandstone at a confining pressure of 5 MPa and room temperature (20°C), as well as heating to 50°C, 75°C and 100°C prior to mechanical loading. Additionally, we repeated these experiments under the same thermo-mechanical conditions on specimens with single pre-existing discontinuities running through the specimens at 30° from the vertical, allowing shearing to occur on the discontinuity under triaxial conditions. The laboratory experiments were then replicated using discrete element method (DEM) models. The geometry and granular structure of the sandstone was replicated using a Voronoi tessellation scheme to produce a grain based model (GBM). Strength and stiffness properties of the Voronoi contacts were calibrated to the laboratory specimens. Grain scale thermal properties were applied to the GBM according to mineral percentages obtained from quantitative X-ray diffraction (XRD) analysis on laboratory specimens. Thermo-mechanical coupling was then undertaken to reproduce the thermal loading rates used in the laboratory, before applying a mechanical load in the model until failure. Laboratory results show a reduction of up to 15% peak strength with increasing thermal loading between room temperature and 100°C for intact specimens, whereas specimens with discontinuities present an initial increase in discontinuity peak shear strength with increasing thermal loading to 50°C, before a reduction in peak shear strength at 75°C and 100°C. The GBMs highlight the buildup of thermally induced localised stresses within the intact specimens due to the grain scale heterogeneity of thermal properties, resulting in the initiation and accumulation of tensile thermal micro-cracks, causing reduced strength. The discontinuities allow room for thermal expansion and results in thermal overclosure. Such overclosure results in an initial increase in peak shear strength, until maximum thermal overclosure is reached, thermal micro-cracking then occurs, as observed in the intact specimens causing a reduction in strength. Petrographic analysis of laboratory specimens is planned to confirm the thermal micro-cracking observed in the grain based simulations. A better understanding of grain scale thermal micro-cracking has numerous implications in subsurface engineering design, in addition to providing an improved understanding of the processes governing the observed behaviour.

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P1.9: Velocity anisotropy response to failure in travertine

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Understanding continental carbonate deposits is of increasing importance due to their great hydrocarbon reservoir potential, particularly with the development of lacustrine carbonate plays within the 'pre-salt' of the South Atlantic. These deposits possess significant heterogeneities related to complex depositional and diagenetic processes, creating challenges when modelling their structural, geomechanical and seismic properties. Characterisation of the velocity anisotropy will provide key parameters for use in geomechanical modelling of such deposits. The relationship between the anisotropy and failure type (i.e. dilational or compactive) may further help in recognising either fault related conduits or barriers. To this end, an integrated petrophysical and geomechanical study has been carried out on shallowly buried Italian travertine samples, which characterises any heterogeneities, and examines the controls these heterogeneities have on failure mechanisms and the resulting changes in acoustic and seismic properties.

Changes in travertine facies, with variable porosity and pore types, are observed over millimetre to metre scales, and are dependent on the depositional environment (i.e. hydrodynamic setting, surface topography, microbial community etc.). Differences in characteristics across these facies result in highly anisotropic, heterogeneous deposits. Each layer of these travertines, therefore, can have widely varying mechanical properties, which influences the failure mechanisms and sonic response. Sonic velocity analysis was used to measure the elastic transverse isotropy of samples during failure (triaxial testing), providing quantification of the relationship between stress anisotropy and acoustic properties.

Results indicate that P-wave anisotropy is sensitive to changes in anisotropic stress, indicating that the fabric of travertines has a significant impact on the velocity response to changing stress fields and associated micro-deformation. The study shows that the mechanical properties of these travertines are largely dependent on the dominant facies type, which in turn influences faulting and the seismic anisotropy of these deposits. These results provide an enhanced understanding of the control of facies type upon failure mechanisms, faulting styles and, ultimately, acoustic properties in travertines.

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P1.10: Effective stress laws for permeability and deformation of clayey sandstones

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Rock physics properties depend sensitively on the interplay of confining and pore pressures, and the dependence can be described by corresponding effective stress laws. In a microscopically homogeneous assemblage, the effective stress coefficients for permeability (κ), strain (α) and pore volume change (β) are predicted to be equal to or less than unity. Because extensive measurements on clayey sandstones have shown their coefficient for permeability to be greater than unity, such sandstones are considered to be microscopically inhomogeneous. In a recent investigation of effective stress behavior of limestones with dual porosity, Wang et al. (2008) observed that their effective stress coefficients for not only the permeability but also pore volume change are greater than unity. To our knowledge there have not been any investigations of the effective stress behavior simultaneously of permeability and deformation in sandstones. Accordingly we conducted such a study on water-saturated samples of the clayey Berea and Boise sandstones, at confining pressures of 16-62 MPa and pore pressures of 10-14 MPa. Because hydrostatic compression of a porous rock typically involves an initial nonlinear stage 1 of elastic crack closure and a subsequent linear stage 2 of pore deformation, to investigate how these two fundamentally different modes of deformation may impact the effective stress behavior we characterized the effective stress coefficients in these two stages separately. Our data show that the coefficients κ for permeability of both sandstones are uniformly greater than 1, which accords with published data. Furthermore we observed values of κ during stage 1 to be significantly smaller than in stage 2. We also obtained some of the first measurements of the effective stress coefficient for pore volume change in sandstones. Values of β for both sandstones are uniformly less than 1. The coefficient α for axial stain is less than unity, with values in stage 1 larger than in stage 2, in agreement with published data. Our simultaneous measurement of all three effective stress coefficients provide the critical data for comparison with the prediction of Berryman (1992), who considered an assemblage made up of two porous constituents and derived a relation connecting α, β and κ. Our comparison shows that the difference in effective stress behavior between the nonlinear stage 1 and linear stage 2 can be attributed to the decrease of rock compliance with elastic crack closure. Synthesizing our new sandstone data, recent limestone data and theoretical analyses, we propose to define in the β-κ space two fundamentally different regimes for the effective stress behavior: Regime I for microscopically homogeneous rocks with $\beta \le \kappa \le 1$, and Regime II for microscopically inhomogenous rocks with $\kappa > 1$. The latter regime may be partitioned further into a Regime IIA represented by clayey sandstones with $\beta < 1$, and Regime IIB represented by limestones with dual-porosity with $\beta > 1$.

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P1.11: A New Laboratory Method for Measuring Hydraulic Fracture Permeability at Reservoir Conditions

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Unconventional reservoirs are gaining more interest due to their significant potential in generating more resources in the oil and gas industry. The economic viability of these reservoirs, usually through hydraulic fracturing processes, owe their success to a number of technologies such as horizontal drilling, new hydraulic fluids and 'proppant', and fracturing methods. However, the efficiency of the process requires not only the knowledge of the fracture mechanics of the rocks but also how the newly generated fractures influence the macro-scale pore connectivity (permeability). Here we report a new method to investigate key rock physics data (such as fracture density, elastic wave velocity, Acoustic Emission, permeability) using a triaxial cell fitted with a new sample assembly to permit direct fracture by over-pressurised pore fluid. By combining this with a 3D printed 'liner', we are then able to relate the simulated in-situ permeability of freshly generated fracture networks to the micro seismic response and as a function of burial conditions. We used sample of Crab Orchard Sandstone (cylinders drilled normal and parallel to cross-bedding) of 90mm length and 40mm diameter. These are drilled with a central borehole of 12.6mm diameter pressurised with either water or oil to induce tensile failure using confining pressures up to 50 MPa (approximately 2 km) and up to a temperature of 200°C to simulate shallow reservoir conditions.

Our initial results show that both confining pressure and anisotropy (via bedding orientation) significantly affect the fluid pressure required for fracture, as well as fracture orientation. Acoustic emission (AE) hit rate maxima correlate with initial fracture, and when located, AE hypocentres trace out the fracture and associated damage zone. The measured fracture flow rate was used to calculate a permeability based on measured radial strain used as a proxy for crack aperture. Permeability of the fractured rock (10^{-15} m^2) is some three orders of magnitude higher than the virgin material (10^{-18} m^2), and progressively decreases after fracture propagation with increasing confining pressure. Fracture permeability is higher with water as pore fluid, as expected, compared with oil due to viscosity effects. Our initial conclusions are that permeability (and variation with confining pressure) with the higher viscosity oil is more heavily influenced by fracture asperity effects than the lower viscosity water at the same confining pressure. In addition, flow rates are higher at low confining pressure, and permeability reduction from pressure cycling is not recoverable (a pronounced hysteresis effect is recorded). Further experiments to link AE and flow and pressure cycles are planned to provide a better model to understand the coupled fluid mechanics of hydraulic stimulation in terms of radiated energy, and potentially use this data to ensure effectiveness and safety control during hydraulic fracture stimulation in the field.

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P1.12: Rock and Geo-material Fracture toughness testing using a novel circular shape test specimen and under modes I, II and III loading

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The stability and integrity of geo-materials such as rock masses and soil is an important issue in geotechnical, mining and civil engineering fields. Brittle fracture and un-stable crack growth in such materials may result in catastrophic failures such as rock fall in slopes or hazard in mines. The fracture toughness of rock and soil is a suitable index for characterizing the resistance of geo-materials against initiation and then propagation of cracks inside them. This parameter can be used as a fundamental input data for many rock and soil related projects such as mining, underground excavation, tunneling, geo-thermal, rock and soil slope stability analysis, rock fragmentation, rock cutting, hydraulic fracturing and well drilling. The fracture toughness of geo-materials can only be determined experimentally using suitable testing methods that are compatible with the overall characteristic conditions of such materials. Disc and circular shape specimens are favorite configurations for conducting mechanical tests such as fracture toughness experiments on geo-materials. Till now four testing specimens and methods namely short rod (SR), chevron bend (CB), cracked chevron notched Brazilian disc (CCNBD) and semi-circular bend (SCB) specimens have been proposed and accepted by the ISRM for obtaining the mode I fracture toughness of rocks. In addition, recently, the punch thorough shear (PTS) test specimen has been proposed by ISRM for obtaining mode II fracture toughness of rocks. However, other alternative and suitable test methods are still employed by the rock fracture toughness researchers. In this research a simple and novel test method is proposed for fracture toughness determination of rock and other geo-materials. The specimen that is called “edge notch disc bend – ENDB” is a disc specimen containing an edge crack emanating from the one side of disc through the specimen diameter. The specimen which can be prepared easily from rock or soil cores is tested using the conventional three-point bend fixture. While under symmetric loading conditions the ENDB specimen would be subjected to pure mode I or tensile fracture, by changing the location of loading supports or altering the direction of crack plane relative to the orientation of loading rollers, both shear type deformations (i.e. mode II and mode III) can be introduced by the ENDB specimen. The finite element ABAQUS code was employed for 3D modeling of the ENDB specimen to compute numerically the modes I, II and III stress intensity factors (SIFs) thorough the crack front and for different geometrical and loading conditions such as the geometry of specimen, loading roller distances and also the orientation of crack relative to the loading rollers. The practical ability of this test specimen was then examined experimentally for conducting the fracture toughness tests on some geo-materials such as marble, granite, compact soil and gypsum and determining the values of KIc, KIIc and KIIIc. For each loading mode a suitable formulation was derived to determine the corresponding value of critical stress intensity factor at the onset of fracture. The fracture toughness ratios (i.e. KIc/KIIc, KIc/KIIIc and KIIc/KIIIc) were compared for the tested materials and the worst-case loading mode was identified for each geo-material. The morphology of fracture surface and the path of growing crack were also studied under different modes. The obtained mode I fracture toughness values were in typical ranges reported in the literature for the investigated geo-materials demonstrating the validity of suggested ENDB test method for determining KIc as an alternative test methods in geo-materials. Consequently due to some advantages such as simple geometry, ease of manufacturing process from rock and soil cores, simple testing set up and ability of producing all three basic fracture modes (i.e. modes I, II and III), makes the suggested ENDB test specimen a good candidate sample for fracture toughness study in geo-materials.

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P1.13: Photogrammetry and Distinct Element modelling analysis of the morphological evolution of stream-channels and sinkholes at the Dead Sea

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The rapid regression of the Dead Sea leads to a dynamic reaction of the hydrogeological system. During the last decades, subsurface channels, springs, depressions, sinkholes and canyon systems have evolved on both sides of the lake in a salt-karst system. We use near-field photogrammetry and Distinct Element numerical modelling to analyse the dynamic formation of geomorphic features at the eastern shoreline, near Ghor Al-Haditha in Jordan.

Stream-channel morphology analysis revealed a clear influence of the dynamic regional hydraulic system on shape and evolution of channels at Ghor Al-Haditha. Channels widen and deepen and develop meanders influenced by the base-level fall of the Dead Sea. Subrosion driven subsidence and sinkhole formation is a further component that has an effect on channel development and has been documented for representative examples of the area.

A 2D Distinct Element Method (DEM) code (PFC2D_V5) is used to simulate the evolution of such subsidence-related single and clustered sinkholes, and associated larger-scale depressions. Subsurface material in the DEM model is removed by a feedback loop to produce an array of cavities; this simulates a network of subsurface groundwater conduits growing by chemical/mechanical erosion. The growth of the cavity array is coupled mechanically to the surroundings such that cavities can grow also in part by material failure at their margins, which in the limit can produce individual collapse sinkholes.

The key parameter in sinkhole and stream-channel morphology estimation is the mechanical strength. Low-strength cover material promotes wide and flat sinkholes as observed in the former Dead Sea lakebed. Middle to high strength cover material favours narrow and deep sinkholes as observed in the alluvial fans of the former Dead Sea shorelines. A high strength void space host material also provides stable cavity formation at the shallow subsurface. Besides the layering, the depth and form of the subrosion zone has a influence on the developed stress pattern in the subsurface that favours sinkhole formation and leads to the development of subsurface channel patterns.

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Notes

Keynote 3: Fault structure, damage and induced microseismicity - what do we learn from the lab?

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Seismic events induced at about reservoir depth and large enough to be felt at the surface and thus raising public concern are commonly found to result from reactivation of preexisting faults. Faults typically display characteristic structural patterns that evolve in space and time resulting in complex anastomosing networks of slip zones showing aspects of band-limited self-similarity across a broad range of spatial scales. Individual slip zones show surface varying roughness and are embedded in zones of distributed damage. Field studies and laboratory experiments suggest that structural heterogeneity and fault zone roughness may affect seismic characteristics such as earthquake magnitudes, recurrence intervals, b-values, radiated energy, stress drops and source type distributions. In an effort to investigate the evolution of faulting-related damage and related microseismic activity we performed an extensive series of experiments on granite, quartzite and sandstone rock samples with 40-50 mm diameter and 100-125 mm length. The tests were performed in a servo-controlled MTS loading frame in triaxial compression at confining pressures between 20-150 MPa. The experiments include fracture tests of intact samples and stick-slip tests on saw-cut and pre-fractured samples with varying roughness. In addition, hollow cylinder hydrofracturing tests were performed were performed.

Acoustic emissions (AE) were continuously recorded and ultrasonic velocities were monitored in 20-40 s intervals using up to 16 P-wave sensors attached directly to the sample surface. Full waveforms of AEs were stored in a 16-channel transient recording system (Proekel, Germany) with a bandwidth of 16 bit and 10 MHz sampling rate. Event location is based on automatic P-wave picking and updated time-varying velocity models. We calculated full moment tensors (FMT) using P-wave amplitudes corrected for incidence angle and coupling. Spatio-temporal changes in AE event densities, fault mechanisms, local damage and stress distribution, FMT components, and magnitude-frequency distributions (b-values) from fracture tests and multiple stick-slip events were analyzed and compared to post-mortem fault structures using optical microscopy and Xray tomography.

In general, we observe a correlation of fault roughness with AE hypocenter patterns indicating fault asperities. Spatio-temporal changes in AE activity and b-value distributions correlate with changing AE source mechanisms, in particular varying contributions from non-double components (NDC). Major stick-slip events associated with pronounced stress drops are spatially correlated with large AE events possibly indicating shearing of asperities along combined R- and P-type shears. Post-slip increase in b-values and increasing NDC contributions possibly indicate gouge compaction by grain crushing and sliding. Our studies suggest that the observed seismic characteristics are controlled by boundary conditions (confining pressure), sample material (porosity), and spatio-temporal changes in fault zone structure and stress heterogeneities.

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S3.1: The permeability of fracture intersections in basalt

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Fluid transport within low porosity rocks in the Earth crust is primarily controlled by fracture permeability developed by brittle deformation processes. Field and numerical studies consistently show that the maximum permeability correlates with the direction of greatest fracture connectivity, generally corresponding to the orientation at which fractures intersect. Thus, the dominant permeability has been associated with fracture intersections. However, the transport properties of fracture intersections and quantifying their enhancement on permeability has received surprisingly little attention. Furthermore, how higher permeabilities are maintained at depth under conditions of increasing confining pressures where fracture apertures are expected to close remains a subject of debate. Here we produced an axial fracture intersection using a Brazilian test apparatus on samples of the low porosity (ca. 4%) Seljadur basalt (SB), Iceland, with a measured intact rock permeability of $1x10^{-19}$ m^2 (Nara et al., 2011, Perez-Flores et al. ,2017). Each sample was subjected to two separate tensile loadings at 90 degrees to each other, in order to create two approximately perpendicular axial fracture planes with a single axial intersection. Samples were then pleased in a hydrostatic permeameter, where we measured the permeability at increasing effective pressures in order to look at the pressure dependence of permeability in intersecting fractures. We compare permeability measurements to that of samples with 1) a single axial macrofracture, and 2) three unconnected axial macrofractures. We observe that intersection permeability is between one and two orders of magnitude larger than single fracture permeability. Additionally, the intersections show a significantly lower pressure sensitivity; relatively high permeabilities are maintained at increasingly higher effective pressures (30 to 90 MPa), where intersection permeability is consistently two orders of magnitude greater than single and triple fracture permeability (approximately $1x10^{-15}$ m^2 to $1x10^{-17}$ m^2). This confirms that fracture intersections are significantly harder to close at higher effective pressures, suggesting that they might play a critical role in maintaining permeability at intermediate to deeper crustal levels. These results may significantly improve the understanding on the development of permeability with brittle deformation as fractures form, coalesce and intersect, and on the intersections capability of maintaining permeability under increasing effective pressures.

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S3.2: The effect of temperature on physical and mechanical properties of carbonate rocks

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The physical and mechanical behaviour of carbonate rocks is influenced by five main factors: mineralogy, structure, temperature, stress and time. The effect of temperature on carbonate rocks has been considered only in recent years, since volcano deformation, high temperature gradients in the upper crust and rock-engineering applications, such as drilling, deep petroleum boring, geothermal energy extraction, nuclear waste disposal, CO_2 sequestration, ornamental purposes, etc., require its study. The thermal damage consists of accumulation of damage induced by the propagation of pre-existing cracks and the enucleation of additional ones induced by the differential thermal expansion within and between grains. These processes have a profound effect on physical and mechanical properties. Overall a progressive decrease in physical characteristics related to the temperature increase can be observed, mirrored by an increase in porosity. In terms of mechanical properties the higher is the temperature, the lower is the strength; however, in carbonate rocks, for temperature up to 200°C, hardening effects can also be observed. In this study, the effect of key temperatures on physical and mechanical properties of several carbonate rocks has been investigated. Three different carbonate rocks were analyzed: limestones, marbles and dolomites. They were collected in different of the Americas: marble and limestone samples came from the Los Humeros caldera complex, Puebla, 180 km east of Mexico City, Mexico. Marbles and dolomites came from the quarries of Carvalho, Sao Joaquim and Paraiso, Italva, 350 km north east of Rio de Janeiro in Brasil. The Los Humeros caldera comprises Pleistocene to Holocene basaltic andesite-rhyolite volcanic rocks and was originated after two main caldera-forming eruptions and multiple voluminous plinian eruptions. The volcanic rocks of this geothermal field were emplaced on intensively folded Mesozoic sedimentary rocks belonging to the Sierra Madre Oriental, that was exposed to local metamorphism due to intrusion of Granitic and syenitic plutons of Cenozoic age and basaltic dykes. The brasilian marbles and dolomites come from the Campos Basin where the main formation (Macabu formation) is composed by silicified carbonates formed by the reaction of hot igneous intrusions with carbonate rocks, due to the intracontinental rift associated with extensive intracratonic tholeitic volcanism along the continental margin with intense normal faulting that has exposed carbonate rocks to multiple episodes of heat.For each core sample porosity, ultrasonic pulse velocity (UPV), electrical resistivity (ER) and UCS were evaluated at different target temperatures (from 200°C to 600°C). In situ coda wave interferometry and permeability has been measured for selected samples. Correlations between destructive and non-destructive tests were found and deeply analyzed in the light of rock type. In agreement with previous studies, Vp velocity, density, UPV, wet electrical resistivity, uniaxial compressive strength and Young's moduli decrease as temperature increases. By contrast, peak strain, porosity and permeability increase. Microcracking damage, cataclastic flow and decarbonation are the leading parameters of this degradation and can successfully tracked by the evolution of the physical properties at a given targeted temperature.

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S3.3: Petrographic Analysis and Geomechanical Characterization of the Late Cretaceous Naparima Hill Formation, Trinidad

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The late Cretaceous Naparima Hill Formation is a prolific oil source rock of the SE Caribbean, with its northern South America (Venezuela and Colombia) equivalent being the La Luna Formation. The late Cretaceous Naparima Hill Formation generates most of the crude oils produced from the Southern and Columbus Basins Trinidad, accumulated in Tertiary fluvial-deltaic sand reservoirs. With the total organic carbon (TOC) of this formation being >2% and crude oil produced from the Naparima Hill Formation, many researchers have considered this formation to also be a prospective unconventional reservoir ('source rock reservoir'). Understanding the Geomechanical properties and lithofacies is essential for effective exploitation of these unconventional reservoirs. Outcrop samples of the Naparima Hill Formation were collected along the northern flank of the southernmost surface expression of the Central Range uplift approximately 10 km north of the prolific Southern Basin. Petrographical analysis was carried out on 11 sample locations by way of X-Ray Diffraction, optical microscopy and scanning electron microscope. Results revealed many lithofacies within the Naparima Hill Formation, mainly siliceous mudstones, with very few samples being calcareous with low clay content and occasional Foraminiferal tests filled with calcite and commonly filled with oil. Most samples show a textural relationship between organic matter and inorganic minerals. Post- deposition alteration is characterized by mineral dissolution, veining and high-density microfractures.

Permeability, P- and S-wave velocity, and porosity measurements were carried out on the 11 sample locations at room temperature to characterize the Naparima Hill formation. We measured the permeability and the velocity using the transient pulse decay technique and through-transmission method respectively, on fluid-saturated samples at effective pressures up to 130 MPa. Permeability, P-wave and S-wave velocity results range from 10^{-3} to 10^{-5} mD , 2558 to 4951 m/s and 1372 to 2891 m/s respectively, with no significant change with effective pressure. The porosity was measured using gas expansion method at atmospheric pressure condition. The porosity values range from 5 to 30%. The study revealed that mineral composition, microfractures, lithofacies and diagenesis play an important role in understanding the mechanical behaviour of the Naparima Hill Formation.

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SESSION 3: Laboratory fracture and rock characterization studies

S3.4: Using Roughness and Fragmentation Fractal Dimensions of a Volcanic Bimrock in Estimation of its UCS

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Tuesday, 03.09.2019

Bimrocks (block-in-matrix-rocks) mainly made up of a mixture of competent rock blocks floating in a matrix material are quietly problematic rock masses because of its complex engineering behavior. It is extremely difficult and/or impossible to recover high quality, undisturbed drill core samples recommended by standards or to prepare representative laboratory specimens for laboratory studies and evaluate uniaxial compressive strength (UCS) of bimrocks. In this study, a pyroclastic rock mass (a kind of a volcanic bimrock) in which an ancient semi-underground (hill) settlement and a church were founded by hand carving about 1500 years ago have been studied. The rock samples subjected to the experiments were collected from within and around these structures. Fractal theory is widely used to quantify the roughness characteristics and grain size distributions of fractured and/or fragmented rock masses. In this study, the area perimeter method was used to estimate the roughness fractal dimensions (DR) of the blocks of bimrock. And the grain size distributions of blocks were used to determine the fractal dimension of fragmentation (DF) of the bimrock core samples. The relationships between the UCS and the DR, DF and apparent number of blocks (BN) included in bimrock cores have been investigated. By considering the difficulties of representative sampling from bimrocks according to testing standards, in order to estimate its UCS from above-mentioned parameters statistically significant empirical models were also developed. The results revealed that the DF and DR may be good indicators to predict the UCS of welded volcanic bimrocks, and the fractal dimension theory provides significant contribution to the estimation of the UCS. Besides, it is evident from the results, there is an exponential relationship between the volumetric block proportion (VBP) and the UCS values as in the most of the previous studies. However, unlike the results of these studies, this exponential relationship is inversely proportional, accordingly the UCS values are decreasing while the VBP increasing. It was determined that the matrix component and the bimrock have approximate UCS values and the UCS values of the bimrock are also relatively low. For this reason, it has been concluded that the empirical equations to be proposed in predicting the strengths of such rocks would be better to take into account the specific UCS intervals and the ratio of the UCS values of bimrock and the matrix component.

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S3.5: Inversion of fracture properties – A Genetic FWI algorithm applied to inversion of fracture stiffness from seismic waves

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Fractures have a predominant influence on the mechanical and hydraulic behaviour of a rock mass since they decrease the whole stiffness of the intact rock as well as define conductive pathways through which fluids can flow. We expect changes in mechanical properties before, during and after fracture growth or activation.

Given that amplitude and phase of seismic waves experience a dramatic change when propagating through a fractured rock mass, seismic methods, as an inverse process, can be an effective tool for a non-invasive investigation of fracture parameters as well as a methodology to monitor fracture growth patterns and stress state.

We have developed a method utilising a novel stochastic Full Waveform Inversion (FWI) employing Genetic Algorithms (GAs) to quantify fracture-specific stiffnesses (normal and tangential) for a set of parallel fractures in a synthetic sample. For the aims of this project, it is essential to make use of accurate and efficient numerical models of wave interaction with fractures in order to reproduce with high level of accuracy the full waveforms recorded at receiver locations. We use a tool, WAVE, which is a fully-elastic finite difference modelling code that implements a discrete fracture representation, and has been used to simulate wave propagation in a realistic fractured medium.

The methodology has been validated using transmitted waves in the inverse process, mimicking ultrasonic laboratory data on a specimen, where we model numerically the laboratory experiment to estimate the specific stiffnesses of each individual fracture.

First numerical experiments have been carried out considering a 2-D synthetic sample with 6 parallel fractures. In this experiment the inversion process exploits a population of 100 models (also called individuals) which evolve at most in 200 generations to converge to the best solution. The bounds of the model space are consistent with the experimental evidence available.

Preliminary results indicate that this method is successful in finding the best set of fracture stiffnesses from observed data, and showed a robustness with respect to the number of model parameters tested.

Further developments of the method will have a two-fold approach. In a first instance it will be extended to invert for other fracture parameters such as fracture orientation, location, and fracture density (for fracture assemblies). Successively, we will explore the potentiality of this method by inverting for fracture parameters before and after a change in the stress state, fracture growth or fracture activation by keeping the same monitoring system.

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S3.6: Characterization of mechanical anisotropy in clayey rocks by Digital Image Correlation

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Clayey rocks inherently present strong bedding anisotropy, which conditions their physical and mechanical properties. We applied 2D and 3D Digital Image Correlation techniques in order to characterize the mechanical behavior of Callovo-Oxfordian clayey rocks, subjected to uniaxial unconfined compression. We specifically focused on the initiation and the development of damage at the microscale with respect to the bedding anisotropy. We used crack-free cylindrical specimens with 8 mm in diameter and 16 mm in length. Aiming to concentrate stresses and trigger controlled initiation of damage, some of the specimens were drilled in order to produce a borehole perpendicularly to their axis. The bedding of the samples was oriented at 0°, 45° or 90° to the loading direction. During the uniaxial compression the samples were monitored by either optical microscopy, or by synchrotron X-ray computed tomography. For both situations we used specific types of axial loading machines, adapted to the different observation techniques. Optical monitoring allows for fast acquisition, but the tests realized under synchrotron X-ray investigation last several hours. In this case, the sample water content was preserved as close as possible to saturation by imposing 95 % relative humidity atmosphere in the deformation apparatus. In both cases the natural material contrasts allowed to assess respectively the development of the 2D or 3D strain fields by Digital Image Correlation and to track the damage initiation and evolution. Our first observation concerns the similarity of the 2D and 3D strain patterns. We further demonstrate the development of two types of superimposed strain fields. The first one relates to the classical sample geometry and the stress concentrator borehole. But, the second one clearly reflects the sample microstructural anisotropy and its strong influence of the bedding orientation on the micro-cracking propagation geometry.

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S3.7: Observations on fracture toughness of mode I and mixed mode (I+II) fractures from three-point bending tests at elevated confining pressures

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Fracture toughness is one of the key parameters to characterize brittle rock fracturing. Yet, its measurements are mostly performed at ambient pressure, though rock fracturing frequently occurs at elevated pressures even in geotechnical applications. One challenge involved in analysing tests at elevated pressure is the lack of a generally accepted evaluation procedure, analogous to the ISRM suggested methods for tests performed at ambient pressure. We present results of an experimental investigation into the effect of confining pressure on fracture toughness of Mode I fractures gained from three-point bending tests on notched specimens of four rocks (Padang granite, Bentheim sandstone, Solnhofen limestone and Carrara marble). Several test parameters were examined including notch geometry (either single edge crack round bar, SEC, or chevron edge notch round bar, CEN), bending rate (from 10^{-5} to 10^{-3} mm/s), and the sealing method (varnished or jacketed, differing in whether notch is pressurized or not at elevated pressures) used to prevent the confining medium (oil) to penetrate specimens. Mixed-mode (I and II) tests were conducted on jacketed SEC specimens by shifting the notch relative to the load points. Fracture toughness was corrected for jacketed specimens (where the notch is pressurized) to account for the effect of confining pressure with the aid of numerical simulations. Observations reveal that Mode-I fracture toughness increases almost linearly with confining pressure for jacketed specimens and is consistently larger than that for varnished specimens that exhibit a logarithmic relation to confining pressure. Compared to the sealing method, the effects of notch geometry and bending rate are less significant, though the effects appear to be amplified at elevated confining pressures. For example, toughness becomes less independent with bending rate and the difference in the fracture toughness for SEC and CEN specimens increases with confining pressure for jacketed specimens. The effective fracture toughness for mixed-mode fractures increases with confining pressure. Also the contribution of the Mode II component to the effective toughness becomes larger with confining pressure.

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SESSION 4: Poroelasticity and seismicity of reservoir rocks

Keynote 4: Poroelastic interaction and seismicity induced by fluid productions and injections

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Tuesday, 03.09.2019

Productions and injections of fluids in rocks can induce significant earthquakes. Induced seismicity is observed by hydraulic fracturing of shale and stimulations of enhanced geothermal systems. Earthquakes can be caused by long-term developments of oil and gas fields. Understanding and monitoring of fluid-induced seismicity is necessary for controlling its seismic risk. A quantitative characteristic of a potential seismic reaction of rocks to fluid operations is required. The seismogenic index is such a quantitative characteristic. It quantifies induced seismicity potentially produced by rocks in response to an injection of a unit volume of a fluid. The higher the seismogenic index, the higher the hazard of induced earthquakes. Can we use this characteristic for predicting seismicity caused by underground fluid extractions (e.g., oil or gas production)? This is indeed possible. An example is the Groningen gas field. One can show that the presence of the production-induced seismicity there indicates a low probability of an injection-induced seismicity. This European gas field (the Netherlands) is a large-area sedimentary hydrocarbon reservoir under usual tectonic conditions (normal faulting). The results presented here are of importance for forecasting and controlling the potential hazard of earthquakes induced by underground saltwater disposals and by productions of geothermal and hydrocarbon energy. The talk provides an overview of physical and geomechanical fundamentals of the induced seismic hazard, of approaches to its control and of various relevant case studies.

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SESSION 4: Poroelasticity and seismicity of reservoir rocks

S4.1: Undrained pore pressure changes in rocks surrounding a reservoir: From poroelastic theory to fault activation?

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Rocks surrounding a depleting oil or gas reservoir, or an inflating CO_2 storage reservoir, are characterized by extremely low permeability in order to provide seals over geological time. It is well established that pore pressure change in a reservoir leads to stress changes around it, however, it is less recognized that this also implies pore pressure change outside the reservoir. Based on soil mechanics concepts, short-term (undrained) pore pressure change is described by two Skempton parameters commonly referred to as A and B. Because of the large scale and the prevalent low permeability of the rocks surrounding the reservoir, short term in the field is likely to be on the scale of several years.

In shale, which is the most common overburden rock, Skempton's parameters can be deduced from anisotropic poroelasticity theory. This has been verified by controlled laboratory experiments along different stress paths and with different orientations of the core samples. Given the laboratory data, geomechanical models for stress changes around the reservoir can be used to estimate pore pressure changes in the field. The pore pressure change depends on stress path and Skempton parameters. The in-situ stress path is governed by geometry, by elastic contrasts and by non-elastic behavior. Although pore pressure most likely will increase as a result of injection and decrease because of production, the opposite scenarios are also possible, depending on stress path, the value of Skempton's A and the specific location.

The presentation will include a brief review of the theory in addition to laboratory results. Focus is on pore pressure measurements during controlled stress path experiments in a triaxial apparatus, including derivation of the Skempton parameters. In addition, analysis of laboratory derived stress path and pore pressure dependent wave velocities at seismic and ultrasonic frequencies will be briefly described, in order to link to time-lapse ("4D") seismic.

Besides the generic outcome of linking laboratory measurements to geomechanical models, a field example will be given to demonstrate estimated pore pressure response as a result of pore pressure change in a reservoir. The possible impact of pore pressure on faulting and fault activation in rocks surrounding the reservoir will be discussed. Elements of this discussion is how Skempton parameters change when moving from an elastic towards a failure state, which is likely to affect the failure process. Also, the orientation of the stress field with respect to the symmetry plane of the shale plays an important role.

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SESSION 4: Poroelasticity and seismicity of reservoir rocks

S4.2: The mechanical behaviour of porous synthetic rocks

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Experimental rock mechanics studies underpin our understanding of the relationship between microstructural attributes and bulk mechanical properties of natural materials. Considerable progress has been made but intrinsic variability from sample to sample and structural heterogeneity remain limitations to the study of the contribution of each microstructural parameter independently.

Synthetic rocks for which these parameters can be predetermined and designed provide the means to circumvent the inherent parameters interdependence and variability of natural rocks. Sintering spherical glass beads has been previously shown to be an effective method to produce quality, reproducible solid synthetic rock samples for which matrix fracture toughness falls into the range of natural rocks. Importantly, this method allows for a tight control on microstructural attributes (e.g., pore and grain size and shape) and porosity. During the fabrication process, populations of solid glass microspheres of predetermined size distribution are heated above their glass transition temperature. Above this glass transition temperature, the glass beads act as viscous liquid droplets. Time-dependent coalescence of droplets that share contact then causes the bead-pack to evolve into a connected system, creating a porous granular material of known microstructural geometries and final porosity.

We predetermined the final parameters for each sintering experiment using the vented bubble model and we prepared suites of samples with monodisperse grain size distributions using spherical beads of diameter ranging from 80 µm to 1 mm. Samples were prepared in order to cover a wide range of porosities. We systematically measured porosity and gas permeability before running hydrostatic experiments and triaxial deformation tests. These tests were conducted on water-saturated samples, in drained conditions (with a fixed pore pressure of 10 MPa), at room temperature, at a constant strain-rate and at effective pressures ranging from 20 to 190 MPa.

The porosity-permeability trend for our synthetic samples is in good agreement with those for porous sandstones, adding veracity to our approach. Additionally, first results show remarkable repeatability for the same experimental conditions. Our hydrostatic curves show a sharp breaking point corresponding to critical effective pressure beyond which most grains are crushed while pore space undergoes a substantial reduction. We observe a strong dependence between the porosity of our synthetic rocks and the critical pressure for grain crushing. We used a combination of triaxial experiments and hydrostatic compression experiments to map out the failure envelopes for our synthetic rocks, the shapes of which are similar to those for porous rocks. Our novel approach allows us to parameterize specifically for the importance of porosity and grain or pore size on the mechanical behaviour of porous materials in general, and move beyond empirical approaches to naturally variable materials.

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SESSION 4: Poroelasticity and seismicity of reservoir rocks

S4.3: The acoustic signature of fluid substitution in reservoir rocks

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During the production of hydrocarbon reservoirs, EOR operations, storage of CO_2 underground or geothermal fluid exchanges at depth, fluid substitution processes can lead to significant changes in rock properties which can be captured from the variations in seismic waves attributes. In the laboratory, fluid substitution processes can be investigated using ultrasonic monitoring.

The motivation of our study was to identify the seismic attributes of fluid substitution in reservoir rocks through a direct comparison between the variation in amplitude, velocity, spectral content, energy, and the actual fluid distribution in the rocks. Different arrays of ultrasonic P-wave sensors were used to record at constant time steps the waveforms during fluid substitution experiments. Two different kinds of experiments are presented: (i) water injection experiments in oil-saturated samples under stress in a triaxial setup mimicking EOR operations, (ii) spontaneous water imbibition experiments at room conditions.

In the water injection tests on a poorly consolidated sandstone saturated with oil and loaded at high deviatoric stresses, water weakening triggers mechanical instabilities leading to the rock failure. The onset of such instabilities can be followed with ultrasonic monitoring either in the passive mode (acoustic emissions recording) or in the active mode (P wave velocity survey).

In the water imbibition experiments, a methodology based on the analytical signal and instantaneous phase was designed to decompose each waveform into discrete wavelets associated with direct or reflected waves. The energy carried by the wavelets is very sensitive to the fluid substitution process: the coda wavelets are impacted as soon as imbibition starts and can be used as a precursor for remote fluid substitution. It is also shown that the amplitude of the first P-wave arrival is impacted by the upward moving fluid front before the P-wave velocity is. Several scenarios are discussed to explain the decoupling between P wave amplitude and velocity variations during fluid substitution processes.

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P2.1: Time-dependent analyses of first motion derived focal mechanism solutions and machine learning algorithms in rock deformation laboratory experiments

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Acoustic Emissions (AE), the laboratory analogue to tectonic seismic events, recorded during conventional triaxial deformation tests allow for an unprecedented amount of information on the evolution of fractured media within a controlled environment. This study presents the results of a new, robust, derivation of first motions calculated from AE-derived focal mechanism solutions (FMS) to analyse the induced deformation of samples of Alzo Granite and Darley Dale Sandstone between 5 and 40 MPa. Selected samples have been subjected to thermal treatment up to 600°C to induce additional thermal damage. For each event, 12 AE traces were recorded. Arrival times, for event location, and the polarity of the first motion were automatically picked. AE were organised into localised groups by minimising the RMS error between polarity signatures of each AE and these were then fitted to idealised FMS models of shearing, tensile and collapsing. Selection was dependent on the RMS error of normalised amplitudes between observed and modelled data. To complement the analysis machine learning algorithms (bootstrapped forest walks) are trained on these results to identify frequency dependent variations between the different mechanisms and improve confidence. Results highlight time-dependent trends in the dominance of mechanisms that correlate with specific deformation sequences (i.e. dynamic failure) of the samples. These data provides new insight into the potential forecasting of deformation and failure mode for different lithologies at the laboratory scale and provide support to the search of links between seismic signals and field scale fracturing processes.

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P2.2: Impact of partly sealed fractures on hydro-mechanical properties of a granite block

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The fluid flow in Enhanced Geothermal Systems (EGS) is dominated by hydraulically stimulated fractures that are the key elements of their hydraulic performance and sustainability. At the fracture scale, the flow performance is influenced by the aperture distribution which is strongly dependent on the fracture roughness, the geological fracture sealing, the relative shear displacement, and the amount of flow exchange between the matrix and the fracture itself. On the mechanical side, stiffness and strength of partly sealed fractures might alter or reinforced the mechanical behavior of the fracture zone in particular with respect to new stimulations. In order to quantify the impact of chemical soft stimulation in EGS reservoir on the hydro-mechanical properties of a fracture-matrix system that includes fracture-filling material, we conducted numerical flow through experiments of a granite sample hosting one single partly sealed macroscopic fracture. In order to mimic the chemical alteration of the fracture-matrix system we sequentially changed either the elastic moduli of its individual components (rock matrix, fracture-filling material such as barite and the transition zone in between) or the distribution pattern of the fracture-filling material by means of a hydro-poro-elastic coupled simulation. Navier-Stokes flow is solved in the 3-dimensional rough aperture and Darcy flow in the related poro-elastic matrix. By means of this model, an evaluation of the local channeling effect through the fracture at microscopic scale (mm-scale) for different mechanical properties of the fracture filling material and loading, was performed. Based on the obtained results, we derived a macroscopic (m-scale) change of the hydraulic-mechanical behavior of the fracture-matrix system, e.g. permeability change, fracture strength, and elastic moduli.

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P2.3: Anisotropic poroelasticity and permeability under true triaxial stress conditions: measurements and modelling

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In the upper crust, most rocks spend most of their life cycle in the poroelastic regime; that is, fluid-saturated and undergoing deformation in response to the stresses acting on them. Under most natural condition, the stress in the crust is truly triaxial and varies with direction, such that, $\sigma_1 > \sigma_2 > \sigma_3$. This leads to the nucleation and propagation of aligned, anisotropic crack arrays. Hence, the poroelastic response and fluid permeability are also anisotropic.

While the theoretical basis for understanding the anisotropic poro-elastic response of rocks has recently been developed, this has never been tested experimentally under the most realistic crustal conditions of true triaxial stress (TTS). The theory suggests that parallel crack arrays generate much higher anisotropy in the poroelastic response compared with radially-distributed crack arrays. However, experiments have only previously been conducted under Conventional Triaxial Stress (CTS; where, $\sigma_1 > \sigma_2 = \sigma_3$), which do not fully represent the in situ conditions. Hence, to fully address these directional variations, measurements need to be made under Truly Triaxial Stress (TTS) conditions.

We report preliminary results from a unique True Triaxial Apparatus (TTA) in the Rock & Ice Physics Laboratory at University College London, that allows measurement of anisotropic poroelasticty and permeability on water saturated rock samples under TTS conditions. The apparatus comprises a 150 MPa thick-walled pressure vessel mounted in a four-pillar loading frame with two axially mounted, servo-controlled 250 tonne actuators which provide the maximum principal stress (σ_1). Four radially-located servo-controlled, 25 tonne loading rams are mounted in two integral reaction rings, and provide the intermediate (σ_2) and minimum (σ_3) principal stresses on either 50x50x50 mm cubic samples or 40x40x100 mm cuboidal samples.

A sample assembly has been constructed which allows pore fluid access to all six loading platens so that permeability can be measured along any of the three principal axes during deformation. Fluid pressure within the cell enables a pore fluid pressure to be maintained within the sample, and sealing is achieved by a digitally-printed polymer jacket that surrounds the sample and seals to the loading platens in the same manner as used in other state-of-the-art biaxial and triaxial cells.

Initial tests have been conducted on cubic samples of Darley Dale sandstone (DDS) to measure the poroelastic coefficients and the fluid permeability. The anisotropy of the poroelastic response means that, in order to to capture the directional variability, these coefficients become tensor quantities. Both drained and undrained conditions are imposed, together with multiple loading paths, to investigate the influence of truly triaxial stress states. These data are then used to inform and validate the theoretical models of poroelasticity.

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P2.4: Hydro-fracturing experiments in highly porous and permeable sandstone

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Fluid permeation is an unwanted result of a hydraulic fracturing test, where the injected fluid permeates through the porous rock instead of building up the borehole pressure. In this way, hydro-fracturing is impeded. Different parameters, such as low fluid viscosity, low injection rate and high rock permeability, contribute to fluid permeation. Highly porous and permeable materials are particularly prone to this effect; therefore sleeve fracturing tests (i.e. an internal jacket separates the injected fluid from the porous media) have been carried out to generate hydraulic fractures. The side effect, however, is the increase of the pressure breakdown (between 3 to 6 times higher than the case without the jacket), which results in higher volume of injected fluid and in higher seismic activity.

To better understand this phenomenon, we performed hydraulic fracturing experiments on highly porous and permeable sandstone. The samples came from Bentheim sandstone formation (Bad Bentheim, Germany), which has porosity around 25% and permeability up to 10-12 m^2. The experiments were performed in a servo-controlled triaxial testing machine and the simulated conditions were representative of a depth of 2.5 km. Axial and radial strain were measured through LVDTs and extensometers respectively, while P-wave velocities and acoustic emissions were monitored via an array of 12 pzt transducers. Samples were cored axially and two metal plugs were inserted at both ends, with only the upper plug being open to allow the injected fluid to pressurize the center of the borehole. In two over four samples, we employed a thin silicon film around the free section of the borehole, with the purpose of impeding fluid permeation. The experiments were conducted in two stages, where the build-up of confining and axial stresses preceded the fluid injection stage, where two different injection rates were used (10 and 20 ml/min).

Consistently with previous studies, our results showed that hydraulic fracturing occurred only when the silicon films was used, while fluid permeation, followed by sample saturation, occurred without the film. When the sample broke, it generated two fractures at 180° each other, parallel to the axial stress. We also observed that the fluid pressure rate did not increase linearly, but was instead characterized by different trends, likely representing the mechanical behavior of the silicon film and its interaction with the porous material. Importantly, the breakdown pressure was only 25% higher than the expected pressure in case no silicon film was employed. This has a crucial consequence, because it shows that hydraulic fracturing in highly porous and permeable rock can be achieved without relatively large 1) amount of injected fluid, 2) fluid pressure drop and 3) seismic activity.

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P2.5: Evolution of elastic wave velocities and amplitudes during triaxial deformation of anisotropic Freiberg gneiss

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A suite of triaxial compression experiments was performed on dry cylindrical samples of foliated Freiberg gneiss cored in different orientations relative to the foliations (0°, 30°, 45°, 60°, and 90°). Experiments were performed at two different confining pressures, 2.5 MPa and 5 MPa, representative of the overburden in the research mine "Reiche Zeche", and an axial strain rate of 10^{-5} s^{-1}. Simultaneously, ultrasonic S- and P-waves were axially transmitted. Velocities of waves propagating parallel to the foliation are higher than those propagating perpendicular to the foliation during all stages of the experiments. Wave velocities increase slightly during initial deviatoric loading and then decrease with increasing differential stresses as samples fail along a single shear fault at peak stress. Amplitudes of first breaks start decreasing at differential stresses exceeding about half the peak stress. Seismograms of waves traveling perpendicular to the foliation exhibit the smallest amplitudes qualitatively indicating attenuation anisotropy. The observed differences in amplitudes in the samples may be partly due to wave scattering associated with the layering of components that cause the foliation, and partly due to slip on pre-existing and developing microfractures. Information on velocity and attenuation anisotropy aids constraining velocity models for localization of induced seismic events during hydraulic stimulation.

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P2.6: The application of pore pressure oscillation method to determine permeability and storage coefficient in a fractured rock

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The fundamental transport property of a rock is its diffusivity, which is essentially controlled by the permeability and the storage coefficient of the rock. A simultaneous measurement of them has been previously examined in intact rock samples using either pore pressure oscillation or radial flow oscillation methods. The oscillation method utilizes the attenuation and phase change of a periodic pore pressure oscillation as it propagates through the rock sample. In this study, we examine how the presence of an induced macroscopic fracture modifies the transport properties.

We performed numerical studies to simulate pore pressure oscillation in a fractured rock sample by employing a finite element software. Biot theory of poroelasticity was employed to couple fluid flow and deformation in the rock matrix. The hydro-mechanical behavior of the fracture is governed by Barton-Bandis model. The fracture aperture is stress dependent and the cubic law describes the fracture permeability.

Moreover, we carried out sensitivity analysis studies on the pore pressure amplitude, frequency and effective pore pressure and analyzed the oscillation data using Fourier Transform processing. In addition, we compared the results with the experimental data. The results follow the same trend. The observed frequency dependence of the permeability and storage coefficient are negligible.

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P2.7: Comparisons between Brittleness index equations and their relationship with Fracture Toughness for a shale formation

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The brittleness index(BI) is commonly used in the industry as a quality estimation to select the most suitable sections for fracking. Although several empirical correlations have been defined to estimate the BI, it is still being an ambiguous term. The objective of this study was to compare and evaluate different equations of the BI for a specific section of an unconventional shale asset. Moreover, to investigate the relationship between BI and the fracture Toughness (FT) estimated from a pseudo-Compact Tension (pCT) Test.

A detailed mineralogical (XRD and QUEMSCAN), rock mechanics and direct FT measurements (Muñoz A. et al.) data from six samples of the shale formation plus well logs were available. Six Brittleness index definition were compared (Jarvie et al.,2007; Rickman, Mullen et al., 2008; Luan et al., 2014; Sun et al.,2013 and Jin et al., 2014). Jarvie's equation assumes that quartz content controls the brittleness of the shale. Chen's estimation is based on young modulus and lame constant and it exhibits a high positive correlation with Jarvie's proposal even though it is computed with different parameters. Although Rickman, Mullen, Luan, and Sun are also calculated with the elastic properties, the resulted profiles show a completely opposite BI behavior.

Alternatively, when comparing the BI proposed by Jin, a mineralogical definition that includes the calcite as a brittle content, a remarkably positive correlation with the Rickman, Mulle, Luan and Sun proposal was found. Also, a high correlation (0.83) between this BI and the calcite content was obtained, which suggest that calcite-rich zones are among most brittle ones, contrary to the Jarvie's obtained profile were the BI is controlled by the quartz content.

A comparison between the BI values and FT were evaluated. A high negative correlation was found between the FT and the BI defined by Jarvie and Chen. The other methods show a high positive correlation. However high brittleness index is related to low FT, therefore the BI defined by Jarvie and Chen is in agreement with the linear elastic fracture mechanics theory.

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P2.8: Stress distribution along heterogeneous faults

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In recent decades, much focus has been placed on understanding the internal structure of large-displacement tectonic fault zones and how it relates to the mechanical, hydraulic and seismic properties of the fault. Typically, the structure of natural fault zones is envisaged to be a fault core, or a wider region consisting of strands of multiple fault cores, surrounded by a damage zone. The fault core is a relatively narrow, localized zone containing highly strained products such as fault gouge and is the region where the majority of fault slip is accommodated. In nature, large/mature faults can extend for tens to hundreds of kilometres and intersect many different rock-types. Therefore the fault gouges that make up the fault core can be comprised of many different lithologies, with different mechanical properties, and have significant spatial variation along the fault resulting in mechanical heterogeneity. Understanding how stress builds up during the inter-seismic period across regions with different physical properties is of paramount importance for elucidating processes involved with earthquake nucleation. We present experimental results where heterogeneous faults are simulated in the laboratory by placing gouges of different composition adjacent to each other in different geometric arrangements using a direct shear setup. During shearing, arrays of high-resolution strain gauges are used to track how the stress builds up across the different gouge patches positioned at different points along the fault. Gouges with different frictional properties are used along the fault to test how the bulk and local strength evolves when frictionally ‘weak’ (e.g. clay) materials are deformed next to materials with much greater friction coefficients (e.g. quartz). Here we present new preliminary data from these simulated heterogeneous fault experiments as well document the microstructural evolution with fault displacement.

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P2.9: Mechanical compaction of Hollington Sandstone

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Mechanical compaction and the concomitant porosity loss in porous rocks represent a set of important response mechanism to applied stress, with attendant effects on fluid transport and extraction. The conditions under which this physical mechanism becomes localised and irrecoverable in sandstones, and the microstructural evolution involved still require clearer understanding. The mechanical compaction behaviour of Hollington sandstone was investigated at confining pressures up to 240 MPa and constant pore pressures of argon gas and water ranging up to 80 MPa at room temperature. This porous sandstone, typical of many sandstone petroleum reservoirs, is weakly-cemented but cohesive with porosity of 25% and mean grain size of 121 µm. Porosity and microstructural characterisation employing conventional methods was complemented by high resolution (5x5x5 μm^3) three-dimensional X-ray computed tomography, which enabled quantification and three-dimensional visualisation of the starting material. Hydrostatic pressure loading of the samples in a pressure vessel connected to a pore volumometer revealed the critical pressure (P*) for the onset of grain crushing and pore collapse to be about 190 MPa above the pore pressure. This is confirmed by observations of grain debris in the recovered samples and from three-dimensional visualisation of the X-ray tomographs to characterise microstructural evolution. It is also consistent with acoustic velocity measurements conducted at ambient temperature during hydrostatic loading as a complementary method to determine the onset of permanent pore collapse, which show a flattening of the increasing velocity trend at about 180 MPa above the pore pressure, before a brief decrease in velocity and subsequent return to an upward trend. This effect suggests the accumulation of microcracks, which reduces the stiffness of the rock resulting in lower velocity, followed by increase in stiffness as the rock compacts and hence a return to increasing velocity trend. Beyond the critical pressure (P*), inelastic compaction occurs. These experiments will be extended to non-hydrostatic compaction to generate compaction bands and investigate the microstructural controls of their formation and their effect on permeability and seismic velocities.

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P2.10: Numerical analyses of temperature controlled fault reactivation during diking

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Volcano deformation and fracturing play a fundamental role in pre-eruptive processes and are characterised by an increase of the seismic activity in the volcanic edifice and its basement. Earthquake swarms are associated with magmatic intrusion within the volcanic edifice via feeding dikes, which cause a disturbance in the stress, temperature and pore pressure of the host rocks. This contribution investigates the effects of a single dike intrusion in terms of induced seismicity. The temperature increase induced by the magmatic source generates thermo-mechanical strains and pressurizes the pore fluids, changing the state of stress on the rocks accordingly. Pre-existing and critically stressed faults could be reactivated during this process. We have performed finite element numerical transient analyses of coupled thermo-hydro-mechanical processes with the open source platform OpenGeoSys to investigate the relationships between seismicity increase and faults in the far field induced by diking. The model is plain-strain bi-dimensional and accounts for the full equations of state of water up to the supercritical point. We investigate the time effects and time delay on the mechanical response caused by the diffusion of temperature and pressure and performed case scenarios with different rock permeability. Rate and state theory is applied with a constitutive model for modelling the rate of seismic production increase.

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P2.11: Impact of fluid-injection scheme on injectivity enhancement of granite by laboratory hydraulic fracturing under true triaxial stresses

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Hydraulic fracturing tests were performed in the laboratory on cubic granite specimens with a side length of 100 mm, under true triaxial stress conditions combined with acoustic emission (AE) monitoring. Six different injection schemes were applied for investigating influence of the injection scheme on hydraulic performance and induced seismicity during fracturing. Three of them are injection rate controlled: constant rate continuous injection (CC), stepwise rate continuous injection (SC), cyclic progressive injection (CP); and the other three are pressurization rate controlled: stepwise pressurization (SP), stepwise pulse pressurization (SPP), cyclic pulse pressurization (CPP). Test results show that the SPP scheme achieves the highest increase in injectivity among the six injection schemes. The CP scheme has the lowest induced seismicity while improvement in injectivity is the least. The CPP scheme achieved a reasonable improvement in both increasing injectivity and decreasing induced seismicity, and is suggested as a promising alternative injection scheme. Microscopic observation on thin sections of fractured specimens was employed. Eighteen hydraulic fractures in ten specimens fractured by different injection schemes were measured using the ImageJ software for a quantitative evaluation at mineral scale. Intragranular fractures splitting microcline, orthoclase and quartz grains dominated (>70%) in all cases irrespective of injection schemes. The SPP scheme creates the largest fracture length which could explain the highest injectivity among all the testing schemes. The testing cases with relatively low magnitudes of the maximum AE amplitude correspond to short fracture lengths and small portions of intragranular fractures in microcline grains. Quartz grains are more fractured than microcline and orthoclase grains. Quartz chips are frequently observed adjacent to hydraulic fractures, and this is highly related to the preexisting microcracks abundant in quartz grains, which degrade the grain strength and interact with hydraulic fractures during the fracturing process.

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P2.12: Fracture Permeability and Saturation Effects on Hydrothermally Altered Rocks from a Philippine Geothermal Field and Pre-Thermally Treated Cornish Granite

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Seismic geophysical methods are not commonly applied in geothermal energy exploration and development compared with oil and gas. However, the use of such methods and models has the potential to greatly improve the use of routinely measured surface networks in geothermal areas in terms of seismic attribute changes in space and time, with the aim of improving our understanding of deep geothermal systems and processes. To date, linking rock physics properties to such geophysical data has been rare. This would be especially beneficial in terms of evaluating enhanced permeability and fracture density to parameters such as elastic wave velocity and elastic models since the effects of geothermal processes to field seismicity and seismic attributes remain a challenge.

Here we present the results of a new laboratory study that examines the seismic attributes of fresh and hydrothermally altered rocks from a Philippine geothermal field (SNGF) while undergoing shear fracture development and permeability evolution via tri-axial deformation experiments. Cylindrical samples of 100 by 40 mm were prepared and two notches cut to stimulate shear fracture formation in a known 30-degree plane. This fracture was accessed by pore fluid via two pre-cut miniature boreholes drilled at both ends of the samples along the length and offset with each other. Using these, the formation and evolution of a natural fracture and damage zone and resulting permeability can also be examined. This setup allows the experiment to gather a range of micro-seismic data and elastic wave velocities in different ray paths and key rock physics attributes (e.g. static and dynamic moduli) whilst the fracture permeability develops.

Initial results reveal a significant reduction in all seismic attributes (P/S-wave velocities and elastic moduli) after fracture development except for Poisson's ratio which shows the opposite. This opposite signature is again observed whilst increasing the confining pressure after failure and positively affecting most seismic attributes while negative on Poisson's ratio. Further, reduction in fracture permeability coincides with increasing P and S wave velocities, dynamic bulk modulus, Lame's first coefficient and Young's modulus. Pilot high temperature experiments focusing on Acoustic Emission show significant occurrence of events during and after pore fluid decompression that results from rapid fluid movement, and phase changes from liquid to gas, in the damage zone. The resulting data trends are correlated to each other to establish relationships between properties. With this, we present a link between temperature and fracture permeability and how this is manifested in terms of seismic data. The results of the study will be important in interpreting surface seismic models of volcanic geothermal fields in the Philippines and how it relates to crucial reservoir parameters.

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P2.13: How to publish Open Access in earth sciences (A. Hübner)

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Open Access to scientific literature and research data has significant advantages for researchers as well as for society as a whole. Researchers might gain from increased citation rates and from higher visibility of their research outputs, while researchers as well as the public benefit from a better accessibility of scientific literature and data. Increasingly, funding organisations such as the European Commission in the context of Horizon 2020-funded projects or the 16 national and international members of "Plan S" demand that publications that result from projects funded by them are made openly accessible.

This presentation outlines the different ways of publishing text and data in Open Access. After a brief overview of reasons for publishing Open Access, it offers a practice-oriented introduction into what researchers need to do in order to publish Open Access. Topics include different routes for publishing texts in Open Access (in Open-Access-Journals or self-archiving), financing options for Open Access publication costs (such as Article Processing Charges), open licences, and strategies of how to avoid "predatory publishers". Researchers will learn how to find high quality Open-Access-Journals as well as repositories to publish research data or postprints of their research articles.

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Notes

SESSION 5: Simulation of fractures and faults

Keynote 5: Simulation of hydraulic driven fractures, joints and faults

Heinz Konietzky
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The presentation concentrates on discrete element based numerical simulations of hydraulic driven fractures, but an equivalent continuum base approach is also mentioned. The simulations are based on either pre-determined fracture propagation paths, but also on Voronoi body based approaches without pre-defined fracture propagation paths. The simulations are fully hydro-mechanical coupled, but do not consider leakage, that means an impermeable matrix is assumed. Basic numerical simulation results are verified by comparison with analytical solutions. The presented simulations cover lab tests, but mainly large scale fracturing processes.

The underlying techniques cover 2- and 3-dimensional simulations and consider such phenomena like:

- stress shadow effect- influence of stress or strength barriers on the fracture propagation
- interaction of hydraulic driven fractures with existing faults
- influence of inhomogeneous stress field on fracture extension
- simulation of single and multi-stage tests
- induced seismicity triggered by hydraulic fracturing incl. seismic wave radiation and simulation of source mechanism.

The main application is hydraulic fracturing and stimulation for extraction of deep geothermal energy, but the methodology is also applicable for any kind of leaching processes, in petroleum engineering, the evaluation of the integrity of geological barriers or problems of natural or induced seismicity.

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S5.1: Role of stress tensor rotation due to pore pressure stress coupling for induced seismic hazard in georeservoirs

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In southern Germany deep geothermal power plants are used for heat supply and further projects are planned. With the onset of geothermal production the first local seismicity was recorded in some reservoirs (e.g. Unterhaching, Poing, Dürrnhaar). Responsible for that might be the induced local stress change due to pore pressure (PP) changes around production sites. It often assumed that these stress changes are equal in all principal stresses (Terzaghi's law) and only depend on the distance to the source of PP change. However, in reality the pore pressure stress coupling (PPSC) leads to deviations from this simplification. The PP changes have two effects on the principal stress components. First they are affected differently whether they are oriented radial or tangential to the source and second the orientations differ from the initial orientation of the stress tensor. The difference of stress changes according to PPSC in comparison to Terzaghi's law is not systematically quantified yet.

In order to quantify the difference between PPSC and Terzaghi's law a generic, fully coupled 3-D hydro-mechanical model is used to simulate the injection of a fluid into a reservoir. Realistic injection rates and durations were tested in various reservoir settings. The basic injection term is ten years with an injection rate of 50 l/s. Two scenarios are computed using either Terzaghi's law or PPSC. To compare them the slip tendency as a measure for the stability of faults with a given fixed orientation is derived from the stress state simulation. The slip tendency is calculated with respect to the optimal oriented fault plane towards the initial stress field. In the nearfield of the injection point tensile stresses are encountered. Here the stability of the stress state is estimated by the dilation tendency, which is similar to the slip tendency but accounts for the failure due to tensile failure (mode I).

The change in slip tendency from 0.05 before the injection to 0.1 at the end of the injection is 20m away from the injection point using the stress state according to PPSC. Using the stress state resulting from Terzaghi's law the same change in slip tendency reaches up to 90m away from the injection point. Also the resulting slip tendency after Terzaghi's law is radial symmetric. In contrast the slip tendency after PPSC forms petal lobes around the injection centre. An equal effect on all normal stress components leads to a radial symmetric shape. A different shape results from an effect on the stress tensor dependent on the orientation of the stress components. Hence, in certain settings Terzaghi's law overestimates slip tendency. We present reservoir settings where the rotation of the stress tensor influences the change in slip tendency significantly. Thus, it is beneficial using the PPSC instead of Terzaghi's law to simulate the behaviour of the subsurface during the production of a geothermal power plant. An increase in productivity may be achieved with a PPSC approach due to an enhanced precision of the slip tendency.

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S5.2: Multiphysics of faulting: influence of porosity and damage evolutions on the deformation modes within the lithosphere

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Two main deformation modes are thought to control the long-term strength of the lithosphere: frictional – pressure-dependent – brittle deformation, and Arrhenius-type thermally activated creep. Dynamic changes in terms of forcing conditions (from natural, tectonic driven to anthropogenic ones) can also exert changes in the strength profile. The shape of a strength profile determines at which depth differential stresses could be accumulated and therefore impose self-consistent bounds to the amount of energy which could be released in a seismic or aseismic way. To estimate this amount of energy, some attention has been given in the community to quantify the value of the friction coefficient in fault zones. Several studies have reported lower values of the friction coefficient in existing fault zones as the ones predicted by Byerlee's law. In addition, describing the evolution of the friction coefficient after onset of faulting or reactivation of existing faults requires to account for microstructural effects but also for the presence of fluid.

Understanding the evolution of localised deformation in a semi-brittle semi-ductile regime has therefore become of relevance in the geodynamic community to (i) understand the behaviour of fault zones in the vicinity of the brittle-ductile transition and also in the geo-engineering community to (ii) mitigate risk of induced seismicity when targeting high-enthalpy unconventional geothermal resources as found in volcanic settings, where the thermal conditions may activate ductile deformation at shallower depths than expected. This contribution aims at describing the multiphysics coupling characterising the evolution and stability of localised deformation and therefore in a broader sense of faulting mechanics, by means of a damage poro-visco-elasto-viscoplastic rheology.

We make use of the numerical simulator LYNX (Lithosphere dYnamic Numerical toolboX), which relies on an implicit multiphysics coupling of the physics describing the deformation multiphysics as occurring in the rigid portion of the lithosphere including thermal, mechanical and hydraulic feedbacks. In particular, we include effects that control the microstructure evolution and its feedbacks on the macroscopic deformation and frictional behaviour, formulated in terms of damage evolution. We also account for the presence of fluid (via porosity evolution) and how it impacts the strength of lithospheric rocks and can exert a control on the dominant deformation mode.

In this contribution, we present a thermodynamically-consistent physical framework to describe the physical processes controlling deformation dynamics in a semi-brittle semi-ductile regime. We will focus in particular on (i) the role of damage weakening and its impact on the evolution of localised deformation and (ii) the role of porosity evolution as a driving mechanism to dilatant brittle deformation. These two aspects allow us to gain insights into the influence of localised deformation onto the strength of lithospheric rocks and on their hydraulic behaviours, and therefore on the evolution fault zones. We will present numerical examples describing the dynamics of these two aspects ranging from laboratory to lithosphere scales.

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S5.3: Modeling crack and compaction band propagation in porous rocks with a phase-field fracture model

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In this work, we propose a phase-field model for simulating the evolution of mixed mode cracks and compaction bands in porous rocks. The work is based on a split of the classical energy release rate into a Mode-I and Mode-II part. Additionally, we model compaction bands by means of energy release under compression load. We discuss the theoretical background of the proposed method in the framework of a phase-field fracture model followed by a brief description of the the numerical formulation. We use continuous NURBS basis function for the spatial discretization of the coupled field equations. The coupled field equations are then solved with a staggered approach that allows for robust solution of the incremental update of both the displacement and phase fields. For the purpose of validation, the behaviour of samples of artificial rock, with either a single or double saw cuts, under compression has been studied. The simulated results are compared to experimental data, both qualitatively and quantitatively. It is shown that the proposed model is able to capture the commonly observed propagation pattern of wing cracks emergence followed by secondary cracks and compaction bands. Additionally, the typical types of complex crack patterns observed in experimental tests are successfully reproduced, as well as the critical loads.

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S5.4: Combination of experimental data and numerical simulations to unravel weakening mechanism on gypsum

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Several mechanisms are known for the weakening recorded on faults during seismic slip, such as thermal pressurization or flash heating. The presence of water plays an important role in some of these mechanisms through, either enhancing weakening, e.g. by the increase of pore fluid pressure, thermal expansion, or inhibiting them, e.g. by phase transition control of temperature. Dehydration of hydrous minerals due to frictional heating can be an important source of water and it changes the mechanical properties of the fault. To investigate these interactions, we performed high (1m/s) and low velocity (0.01m/s) shear experiments using powdered gypsum at a range of normal stresses. The results of those experiments were integrated with a numerical model in order to calculate temperature changes, the amount of dehydration reaction and pore fluid pressure.

At low velocity, the frictional strength is approximately constant throughout the experiment at ~0.8. At high velocities (above 0.1m/s), frictional strength evolves from high peak values (~0.8), attained during the first few centimetres of slip, to low quasi-steady state values between 0.2 and 0.4, varying with the normal stress. At the slip-weakening, the deformation localises within a thin principal slip zone. Frictional heating within the slip zone causes gypsum dehydration to bassanite, which propagates progressively within the fault gouge. Preliminary numerical models at high velocity show that the heat consumed during the endothermic reaction is a few orders of magnitude lower than the heat generated due to friction and the water released significantly increases the pore fluid pressure above the normal stress.

These experiments suggest that the temperature within the fault gouge is strongly controlled by frictional processes and that the temperature sink due to the reaction is comparatively small. The pore fluid pressure is strongly controlled by initial porosity and permeability conditions.

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S5.5: Non-linear anisotropic damage rheology model: theory and experimental verification

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The nonlinear elastic response of damaged rock under arbitrary three-dimensional loading is well established by observations on different scales. Distributed rock damage, in the form of cracks, joints and other internal flaws, develops initially during rock-forming processes and affects physical and mechanical rock properties. On-going tectonic loading and variations in the loading path (including stress rotation) leads to significant increase in damage and the formation of topologically different forms of damage than those formed previously. In the framework of continuum damage mechanics, the observed degradation of the effective elastic properties is treated by a non-dimensional scalar or tensor damage variable, which characterizes an appropriately chosen volume of rock, so that the distribution of the internal flaws (e.g. microcracks in a laboratory specimen or small faults in the Earth's crust) within this volume may be considered uniform. In this study, we extend the isotropic nonlinear damage rheology model with a scalar damage parameter to a more complex formulation that accounts for anisotropic damage growth under triaxial loading. The model takes account of both the anisotropy of elastic properties (associated with textural rock structure), and the stress- and damage-induced anisotropy, as well as the dependence of elastic properties on the type of loading. The suggested generalization keeps the main advantages of the isotropic nonlinear scalar damage model, including elastic non-linearity of fractured rocks, transition between material degradation and healing, and the effects of micro-crack opening and closure (i.e., the abrupt change in the effective elastic moduli upon stress reversal). We assume orthotropic symmetry and introduce a second-order damage tensor, the principal values of which describe damage in three orthogonal directions associated with the orientation of the principal load axis. Different damage components, accumulated under triaxial loading conditions, allows us to reproduce both stress-strain curves and damage- and stress-induced seismic wave velocity anisotropy. For calibration and verification of the model parameters, we use experimental results from deformation of dry sandstone under both conventional and true triaxial stress conditions. Cubic samples were deformed in three orthogonal directions with independently controlled stress paths (with both equal and different values of the intermediate and minimum principal stresses). To characterize crack damage, changes in ultrasonic P-wave velocities in the three principal directions were measured, together with the bulk acoustic emission output. Experimental results show that, for both types of loading, the onset of damage in the direction of the minimum principal stresses is controlled by the magnitude of the differential stresses and does not depend on the magnitude of the mean stress. The parameters of the developed model were constrained using the conventional triaxial test data, and provided good fits to the stress-strain curves and P-wave velocity variations in the three orthogonal directions. The predicted damage component in the minimum principal stress direction increased significantly, while the components in the other directions remained essentially unchanged. Numerical simulation of the true triaxial test data demonstrates that the anisotropic damage rheology model adequately describes both nonlinear stress-strain behavior and P-wave velocity variations in rock samples.

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S5.6: Simplified seismic modelling of fractured rock - how effective is a locally effective medium (LEM) compared to explicit representation of individual fractures

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It is vital in oil and gas, mining, nuclear waste disposal, and construction to have detailed knowledge of fractures in the rock mass, and particularly to understand the mechanical properties of the fractures which are linked with permeability and stability of infrastructure. Seismic waves can be an effective method to retrieve these properties particularly when measurements are coupled with forward and inverse modelling. These seismic models then need an appropriate representation of the fracturing. The fractures can be modelled either explicitly, considering zero thickness frictional slip surfaces (e.g., Schoenberg 1980, Pyrak-Nolte, et al., 1990, Hildyard 2007), or by considering an effective medium (e.g., Crampin, 1981, Hudson, 1981) which incorporates the effect of the fractures into the properties of the medium, creating anisotropy in the wave velocities. In this work, we use a third approach which is a hybrid of the previous two (e.g., Coates and Schoenberg 1995). The area close to the predefined fracture is treated as an effective medium and the rest of the medium is made homogeneous and isotropic, creating a Localised Effective Medium (LEM). We have shown (Parastatidis et al., 2017) that the LEM model can closely match an explicit model in reproducing waveforms recorded in a laboratory experiment. The LEM model performs close to the explicit model when the wavelength is much larger than the element size and relatively larger than the fracture spacing. By the definition of the LEM model, we expect that as the LEM layer becomes coarser the model will start approaching the effective medium result. However, what are the boundaries of the LEM and is there a balance between the stiffness, the frequency and the thickness, where the LEM performs close to an explicit model or approaches the effective medium model? To define the limits of the LEM we experiment varying fracture stiffness and source frequency. We then compare for each frequency and stiffness the explicit and effective medium with five models of LEM with different thickness. Finally, we conclude that the thick LEM layers with lower resolution perform the same with the thinner and finer resolution LEM layers for lower frequencies and higher fracture stiffness.

Wednesday, 04.09.2019

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S5.7: On the seismic visibility and testability of fracture growth models

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For many engineering applications in rock we are interested in predicting the growth and evolution of fractures and fracture zones. Fracture evolution should of course be seismically visible. Firstly through brittle growth generating seismic waves (seismic events or microseismic events). Secondly through the mechanical changes caused by fracturing changing the nature of seismic wave propagation. This of course is the rationale for seismic monitoring whether passive or active. We can envisage a point in numerical development where fracturing models are used to predict the evolution of fracture zones with the predictions controlled and moderated through a feedback loop from seismic monitoring. To do this requires that the models also provide accurate seismic waves for comparison with monitored waveforms.

In this work we generate simplified models of progressive fracturing and demonstrate both types of seismic visibility. We record microseismic waveforms from growth events and we pass active seismic waves through the models to determine how we can model the evolution of the active seismic signature of the fracture or fracture zone. From this we learn what is essential in the fracture growth models to encapsulate seismic visibility. For example it is the mechanical coupling of the fracture surfaces rather than just the presence of the fracture surfaces which controls altered seismic behaviour. The work demonstrates that accurate and efficient modelling of seismic waves are necessary to achieve this goal (coupling with and moderation from seismic measurements), especially since the wave modelling needs to be three dimensional to correlate with measured waveforms. Since one is limited to simplified fracture processes in these codes it is likely that a coupled approach will ultimately be best, transferring information between specialised fracture growth codes and specialised seismic codes.

The work aims to highlight potential and to lead to a clearer understanding of how prediction of fracture zone evolution can eventually can be coupled with monitoring processes through seismic models. The work links to and in many ways depends on our other work developing simplified seismic models of fracturing and full waveform inversion of fracturing.

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Keynote 6: Cyclic hydraulic fracturing of granite: laboratory-scale proof of concept for the mitigation of induced seismicity

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Hydraulic fracturing (HF) in crystalline rock has become increasingly important in geothermal development, especially for enhanced geothermal system (EGS). However, induced or triggered earthquakes reported from EGS sites is one of the main technical hurdles encountered. New hydraulic treatments with minimal environmental impact (i.e., controlled and mitigated induced seismicity) are of great interest. The replacement of conventional HF, which employs continuous injection, by cyclic HF (CHF) that produces cycles of alternating high and low injection rates or injection pressures is suggested to assist reduction of induced seismicity. Multiscale demonstration of the cyclic hydraulic treatment was conducted within the Work Package 5 of the EU Horizon 2020 international collaboration project “Demonstration of soft stimulation treatments of geothermal reservoirs” (Acronym: DESTRESS). Proof of concept of cyclic treatment by laboratory hydraulic fracturing under X-ray CT observations was led by Korea Institute of Civil Engineering and Building Technology (KICT).

We developed experimental techniques and performed a series of hydraulic fracturing equipment allowing for different sizes of rock samples and various injection schemes to be tested. Laboratory HF and CHF tests on intact granite cores containing preexisting microcracks were performed under both biaxial and true triaxial stress conditions, combined with acoustic emission (AE) monitoring. Injectivity of fractured samples were measured by injection test for evaluation of hydraulic performance. Computed tomography and thin section microscopy were applied for grain-scale observations on hydraulic fractures to help further understand hydraulic fracturing mechanism. Experimental findings show that CHF systemically reduced the breakdown pressure (BP) by ~20% and the maximum amplitude of AE by ~14 dB on average, compared with conventional HF. At the grain scale, intragranular fracturing dominated regardless of the injection pattern, whereas intergranular fractures between quartz and feldspar grains were more frequently observed in CHF, which explains the reduction in BP. Cyclic injection tends to form fracturing paths of least resistance thus to mitigate maximum amplitude of AE during fracturing. In addition, CHF creates complex fractures with more branches. However, CHF increases injectivity less than conventional HF and this is likely due to the lack of single predominant fracture in CHF fractured samples. Fractures generated in conventional HF contributed greatly to the increase of fluid flow. A modified CHF consisting of combination of cyclic injection and pulse pressurization at the peak of each cycle was tested and gave an improvement in both injectivity and decreasing induced seismicity, and is suggested as a promising alternative injection scheme for cyclic hydraulic treatment.

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SESSION 6: Hydraulic, thermal and mechanical cyclic loading at multiple scales

S6.1: Controlling fluid-injection-induced seismicity and permeability enhancement in granitic rock by fatigue hydraulic fracturing predicted from laboratory and in-situ experiments

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The ability to control injection-induced seismicity in energy technologies like geothermal and shale gas is an important factor for assessing the safety, the seismic hazard and the life time of reservoirs. Since fracture propagation is an unavoidable process in energy extraction, we propose a new approach to optimize the seismic radiated energy with respect to the hydraulic energy during fluid injection by using cyclic and pulse pumping schemes. We use data from laboratory and mine-scale injection experiments performed at a decimeter and a decameter scale in granitic rock. We observe that the seismic radiated energy and the permeability enhancement process strongly depend on injection style and rock type. Replacing the conventional constant flow rate scheme by cyclic/pulse injection with variable flow rates (1) lowers the fracture breakdown pressure, (2) modifies the seismic event distribution, and (3) has an impact on the resulting fracture pattern. As possible explanation, we introduce the concept of fatigue hydraulic fracturing which is the result of pressure cycles and depressurization phases during which crack tip stresses are relaxed. Cyclic fluid pressure oscillations with a secondary pump allow for an efficient rock fragmentation process. During hydraulic fatigue a significant portion of the hydraulic energy is converted into damage and fracturing of rock. This finding appears to have potentially significant implications for managing the economic and physical risk posed to communities affected by fluid-injection-induced seismicity.

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S6.2: Stimulation and fracture network creation in anisotropic rock

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Anisotropy is considered to influence fracture activation and propagation, likely affecting the formation of fracture networks. Currently, seismic data from hydraulic stimulation in crystalline anisotropic rock under in-situ conditions are sparse and it is difficult to detect and locate seismic events and to obtain accurate velocity models at the mine scale. However, a better understanding of the seismic response to stimulation and the prevailing stress conditions in anisotropic rocks could lead to the more controlled creation of artificial fracture networks.

During July 2018, a mine-scale hydraulic stimulation experiment was conducted at the Reiche Zeche underground lab in Freiberg, Germany in an anisotropic (10–20%) metamorphic gneiss formation. The STIMTEC experiment was designed to investigate stimulation processes involved in hydrofrac and hydroshear activation aiming at permeability enhancement in deep geothermal projects. During the first phase of the experiment periodic pumping tests, high resolution seismic monitoring using Acoustic Emission (AE) and broadband sensors, structural mapping of the tunnel walls and borehole cores, combined with acoustic logs and impression packers were analyzed to characterize the hydraulics of the stimulated test volume. The next phase will include drilling into selected stimulated intervals in an effort to investigate the fracture network in more detail.

Active seismic measurements included ultrasonic transmissions performed from the injection well, as well as sledge hammer and center-punch tools used in tunnels surrounding the stimulated test volume. The resulting waveforms, recorded with the AE monitoring system, show that the elastic wave anisotropy is controlled by the foliation of the host rock with faster P-wave velocities parallel than perpendicular to the foliation. A small number of AE events were observed during the frac and several refrac stages (5–70 AE per stage) in six of the ten injection intervals. A significant extension of the seismic event cloud was observed during periodic pumping tests (30–240 AE per cycle). In addition to resolving the temporal and spatial seismicity distribution, we present different approaches to establish the anisotropic velocity structure in the test volume. It has recently been shown that the volume affected by the stimulation as characterized by a change in velocity extends further than the seismically activated surrounding of the injection borehole likely better reflecting the stimulated reservoir volume (Doetsch et al., 2018). However, obtaining the velocity structure accurately is challenging due to local velocity variations (possibly related to damage/fault zones and the tunnel excavation damage zones) overprinting the anisotropic velocity structure. An iterative approach to resolve background anisotropy and heterogeneity is applied.

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S6.3: Controlling Fluid-Induced Seismicity during a 6.1-km-Deep Geothermal Stimulation in Finland

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We show that near-realtime seismic monitoring of fluid injection allowed control of induced earthquakes during the stimulation of a geothermal well near Helsinki, Finland. The injection well OTN-3, was drilled down to 6.1 km-depth into Precambrian crystalline rocks. The last 1km of the well was deviated 45° from vertical. The inclined section was divided into several injection intervals. A total of 18159 m3 of fresh water was pumped into crystalline rocks during 49 days in June- and July, 2018. The stimulation was monitored in near-real time using (1) a 12-level seismometer array at 2.20-2.65 km depth in an observation well located ~10 m from OTN3 and (2) a 12-station network installed in 0.3-1.15 km deep boreholes surrounding the project site. Earthquakes were processed within a few minutes and results informed a Traffic Light System (TLS). Using near-realtime information on earthquake rates, hypocenter locations, magnitudes, and evolution of seismic and hydraulic energy, pumping schedule was either stopped or varied between wellhead-pressures of 60-90 MPa and flow rates of 400-800 l/min. This procedure avoided the nucleation of a project-stopping red alert at magnitude M2.1 induced earthquake, a limit set by the TLS and local authorities. The original seismic catalog was extended to over 43000 earthquakes with ML between -1.2 and 1.9. The selected high-quality portion of this catalog was relocated using double-difference technique to improve hypocenter precision. Over 2000 relocated earthquakes were used to investigate the spatio-temporal evolution of seismicity, seismic energy release, faulting mechanism complexity, earthquake interactions (clustering, stress transfer) and maximum magnitude in response to injection operations. We found hypocenter distribution, Gutenberg-Richter (GR) distribution and relation between hydraulic and radiated energy suggest (re-)activation of network of distributed fractures. The temporal behavior of GR b-value, as well as a lack of temporal (Omori-type) correlations in a presence of spatial localization of earthquakes suggest very limited earthquake triggering and stress transfer at low level of ambient stress. The maximum ob-served magnitudes scale with stored elastic energy (~hydraulic energy), following a fracture-mechanics based model of Galis et al. (2017), and suggesting a possible physics-based approach to controlling stimulation induced seismicity in geothermal projects.

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S6.4: Slip and Instability Mechanisms of Coal-Rock Parting-Coal Structure (CRCS) Under Coupled Dynamic and Static Loading

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The slip and instability mechanisms of coal-rock parting-coal structure (CRCS) under coupled dynamic and static loading were investigated using theoretical analysis and numerical simulations, and the fracture and instability processes were described by monitoring the displacement, strain and acoustic emissions (AEs) of coal and rock parting blocks. Based on the parameters of dynamic load, three different effects on slip and instability characteristics of CRCS were presented, and the effect mechanisms of static stress and amplitude and frequency of dynamic stress wave were analysed in detail. Finally, the direct effect on the slip and instability strength of CRCS and the frequency range of dynamic load for generating synchronous slip along two discontinuities sandwiched between coal and rock parting blocks were discussed. This work is relevant for early warning coal-rock dynamic disasters that are triggered by the slip and fracture instability of CRCS under coupled dynamic and static loading in coal mines.

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S6.5: Structural analysis and effect of impurity content in Salt Rock deformation under Cyclic Thermo- Mechanical Loading Conditions

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Salt caverns have been identified as an efficient natural container for underground gas storage. Such type of energy storage can accommodate fluctuations in energy demand in the electricity grid by storing gas and providing high withdrawal and injection rates depending on their working gas capacity. Recently, hydrogen storage in salt caverns combined with gas turbines has been investigated as a means to provide low-carbon power generation to the UK's electricity grid. Salt caverns are created by drilling in a salt rock formation and using water to wash out salt by dissolution. Salt rock is considered an excellent geological lithology for the construction of storage sites due to its physical properties such as very tight fabric, resulting in a very low permeability, which makes it a favourable sealing material to host gas and fluids. Salt rock predominantly consists of halite but can contain inclusions, or also known as impurities, of gypsum, clay and other minerals or mudrocks. The presence of these impurities can affect the elastic properties of salt rock under deformation.

Core samples were obtained from Permian Salt Rock formation at Boulby Mine and tested under cyclic thermo-mechanical conditions. The mineralogical analysis of the samples using a transmitted light microscope and X-Ray Diffraction (XRD) analysis indicates composition of 85-90% halite, 5-10% anhydrite, and up to 3-5% kieserite and/or carnallite. The temperature and confining pressure in the cyclic tests were designed according to the three generally expected scenarios for rock salt cavern conditions for underground gas storage. These three test designs include: 1) 200- 500 m depth with a confining pressures of σ=12 MPa and corresponding temperatures of T=25°C and 55°C; 2) 800- 1200 m at σ=25 MPa with T= 25°C, 55°C and 75°C and 3) 1500- 2000 m at σ=45 MPa with T=55°C and 75°C . All samples were subjected to cyclic axial loading conditions with a deviatoric stress from 4.5 to 7.5 MPa at a rate of 0.5kN/s over a duration of 48 hours, providing 7200 number of load cycles. Results demonstrate that the rheological behaviour of samples was slightly different depending on the impurity content or the temperature- confining pressure scenario tested. The rheological behaviour of the different salt rock specimens changed after a certain number of cycles. Salt rock samples with higher content of anhydrite tend to show a greater inelastic deformation than samples with higher content of halite. Samples tested at higher confining pressure show higher final deformation (final strain), whereas the increase of temperature acts as an elastic deformation driver resulting in a slightly lower final strain. Petrographic analysis on core samples, before and after cyclic thermo- mechanical testing, reveals more information on microstructural characteristics (in particular at contacts between halite crystals and second phase minerals) that may underpin the macroscale deformation mechanisms in the samples. The mechanical and microstructural analysis of salt rock, in relation with impurity content, aims to identify the potential risks of Underground Gas Storage in Salt Caverns with different purity of halite.

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S6.6: Microstructural controls on thermal crack damage during temperature-cycling experiments on volcanic rocks

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The evolution of crack damage in volcanic and geothermal systems is largely controlled by the mechanical and thermal stresses acting on them. It is therefore important to understand the response of volcanic rocks to thermo-mechanical loading. Here, we present results from a series of thermal stressing experiments in which acoustic emission (AE) was recorded contemporaneously with changing temperature during both heating and cooling of three igneous rocks of different origin, mineral composition and grain size; Slaufrudalur Granophyre (SGP), Nea Kameni Andesite (NKA) and Seljadalur Basalt (SB). We use the onset of AE as a proxy for the onset of thermal cracking and the AE rate as a proxy for the rate of cracking.

Samples of each rock type were subjected to both a single heating and cooling cycle to a maximum temperature of 900°C, and multiple heating/cooling cycles to peak temperatures of 350°C, 500°C, 700°C and 900°C (all heated at a constant rate of 1°C/min, and cooled partially at a constant rate of 1°C/min and partially at the natural rate of <1°C/min). As further evidence of thermally-induced cracking, comparative measurements of porosity, permeability and P-wave velocity were made on each sample before and after thermal treatment. We find that the vast majority of thermal crack damage (as evidenced by AE output) is generated during heating in the coarser grained SGP but, by contrast, the vast majority is generated during cooling in the finer grained NKA and SB. In addition to the maximum temperature to which the rock has been exposed, the total amount of crack damage generated due to heating or cooling appears to be dependent on the mineral composition and, most importantly, the microstructure (grain size and grain arrangement). We further note that the number of AE hits generated in SGP during a single heating-cooling cycle is about an order of magnitude higher than for either NKA or SB.

We have have also explored the possibility of a Kaiser temperature-memory effect (analogous to the well-known Kaiser stress-memory effect) during cyclic heating and cooling experiments. We find a clear temperature-memory effect in SGP, but no evidence of this effect in either NKA or SB. We similarly suggest that this difference is due to microstructural and mineralogical control on thermal cracking, which we attribute to a combination of thermal expansion mismatch between different mineral phases and large grains acting as mechanical inclusions within a fine-grained matrix.

Knowledge of thermal stress history and the presence of a Kaiser temperature-memory effect is potentially important in understanding magma chamber dynamics, where the cyclic nature of mechanical and thermal inflation and deflation can lead to sequential accumulation of damage, potentially leading to critical rupture.

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S6.7: Mechanics of fluid-saturated granular gauges under seismic oscillations

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Slip on geological faults is localized within narrow shear bands in the gauge zone. Often, the shear bands are located at the boundary between the gauge and the damage zone. Using a recently developed multi-scale model to couple grain + fluid evolution, we study the location of shear bands within a well-drained gauge. While in dry granular layers there is no preferred position of shear bands, we show that water-saturated systems tend to localize shear on their boundary under some conditions. The conditions favoring boundary localization are high shear velocity, gauge thickness and low gauge permeability and confining stress. We propose a scaling argument to describe the pressure deviations in a shear band, and use that to predict the conditions for shear localizations on the boundary.

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Keynote 7: Stress estimation and structural observations around a subduction fault

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Over the last decade significant effort has been made in understanding the stress state at the toe of subduction zones, with implications for coseismic slip propagation, tremor and slow slip event generation and tsunamigenesis. At those locations, the state of stress is controlled primarily by topography, mechanical coupling between the down going and the upper plates, and the mechanical behavior and effective properties of the rocks that control the amount of stress that can be supported. Taking into account topography and the effective properties of the rocks, including the weakening effect of fractures, the knowledge of the stress state can thus provide insights on the mechanical coupling on the subduction fault. The NanTroSEIZE project has been drilling and coring in the Nankai accretionary margin over the last 13 years. During the last expedition in 2019, a new site, C0024, was drilled through the outer wedge, few km landward of a previous Site, C0006. Those two sites penetrate the hanging wall of the frontal thrust, and supposedly crossed it at Site C0006, or at least the top of it at Site C0024, at 813mbsf. We perform a classical stress analysis from borehole breakouts and fracture observations at the borehole wall, to infer the far field stress orientation and magnitude, and properties of the associated subduction-related fault. Preliminary results suggest a stress state favorable for a normal faulting regime at shallow to intermediate depths, that may slightly evolve toward a strike slip regime close to the décollement. Those results and the limited fracturing observed at the borehole wall in the hanging wall of the fault, suggest that the tectonic stress related to the mechanical coupling on the frontal thrust is low. SHmax is oriented towards the northwest, sub parallel to the plate convergence vector. These results are in good accordance with previous results at Site C0006. A breakout reorientation of 20° is observed at the borehole wall across the supposedly top of the frontal thrust, and may suggest either the solicitation of weak planes such as the fractures observed at the borehole wall, or a stress decoupling between the hanging wall and the footwall of this 813mbsf structure.

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SESSION 7: Compaction and damage of porous rock II

S7.1: New global correlations to assess depletion-induced compaction of progressively-buried sandstone

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Compaction and subsidence risk is among the most significant geomechanical risks known to the industry. Subsequent effects in the Wells, Reservoir and Facilities Management (WRFM) space include shearing of wells, subsurface deformation extending to induced seismicity, and catastrophic damage or instability of platforms. Recognizing and quantifying such effects is initiated in an early stage of the petroleum development projects that are deemed sensitive to this, and requires information about the initial 3D stress state and expected pore pressure change, as well as the rock compressibility.

To assist the assessment of depletion-induced reservoir compaction in sandstones, we developed a new set of correlations that fully respect the operative microphysical mechanisms. This was done by re-analyzing triaxial compressive strength and uniaxial-strain compressibility data for sandstones from fields located in progressively buried basins and subjected to normal faulting stress conditions. Our work resulted in the following new correlations: a) a linear relationship between Apparent Cohesion (AC) the field's Virgin Vertical Effective Stress, b) an exponential relationship between the uniaxial-strain compressibility Cm and the AC, and c) a polynomial relationship between the horizontal depletion path constant γh and the AC.

The correlations reveal that two distinct types of constitutive behavior exist as 'non-cohesive' and 'cohesive' domains separated around an AC of 8 MPa. Non-cohesive sandstone, with an AC<8 MPa, generally has a high Cm during depletion with a significant contrast between first and second loading. This is accompanied by variable, but generally smaller radial stress change. Cohesive sandstone, with an AC>8 MPa, has a strongly decreasing Cm with increasing AC, with minor contrast between first and second loading. This is accompanied by a strong decrease in radial stress change with AC during depletion. This rock type behaves increasingly elastic with increasing AC. The very low values of γh (0.45-0.55) at AC>30 MPa are consistent with the idea that the Biot-Willis coefficient α decreases with increasing rock stiffness. The transition between the cohesive and non-cohesive domains occurs at a depth of approximately 1 km, or deeper when the formation is subjected to significant overpressure.

Accepting the correlations reported here, allows for a first-order quantification of sandstone compaction where no Cm and γh data exist, or when existing data need to be verified. Boundary condition is that the sandstone should situated in a progressively-buried basin, subjected to a normal faulting stress state. Future efforts will focus on developing the (micro)mechanical understanding to further describe these trends and incorporate the understanding into existing modelling tools.

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S7.2: Localized versus distributed fracturing in the damage rheology model with evolving yield conditions

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The process of rock faulting is different for crystalline verses highly porous granular rocks. While the first tend to form highly localized discrete slip surfaces, the later may develop tabular zones of deformation bands in several areas prior to the formation of a slip surfaces and total yield. On the other hand, some pre-failure phenomenon, such as the Kaiser effect, are observed in a wide range of rocks and materials and showcase the similarity between damage formation process in different materials.

We study the localization pattern of the brittle deformation in a framework of the damage poro-elastic rheology model with an evolving yield envelope. Using a series of semi-analytical 1-D solutions, we obtain different patterns of the brittle deformations including damage localization, de-localization, and transition between the two phases, which allows the formation of runaway slip-surfaces as well as deformation bands prior to faulting. We connect the obtained deformation pattern with the amount of elastic energy stored in the bulk of the material, and the dependency of the yield cap on the accumulated damage.

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S7.3: Impact of water-weakening on mechanical strength of microporous carbonate rock: fluid substitution and ultrasonic monitoring of water-induced damage

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The mechanical weakening generated by water on different rocks has been observed by several authors. However, the water weakening mechanisms are still poorly understood, especially in carbonate rocks.

In the present work, a microporous carbonate rock with about 40% porosity, the Obourg chalk from Mons basin (Belgium, Campanian in age), has been tested in dry and fully-water saturated condition in order to first observe and second understand these mechanisms. Conventional triaxial tests were conducted on 80 mm in length and 40 mm in diameter core samples at different confining pressures. Injection tests were also performed in a way to minimize the effect of pore pressure when injecting water into a dry sample loaded at a differential stress close to the failure stress, in order to avoid a variation in the effective stresses.

The results from these tests show that water weakening has a strong impact on the mechanical strength of this chalk. The results for the water saturated samples compared to the dry ones show a remarkable strength decrease. Furthermore, the results from the injection tests reveal us that, while keeping the stresses acting on the sample constant, as soon as the water starts to invade the pore space, the weakening processes lower the mechanical strength enhancing the creep rate. Moreover, the amount of water needed to observe an acceleration in strain rate depends on the stress state: a lower volume fraction of water (with respect to the pore volume, e.g. 10%) is needed when the stress state is close to the dry failure envelope, whereas a higher volume fraction of water is needed close to the wet failure envelope.

Ultrasonic monitoring is a powerful tool to detect and asses the rock deformation. In our triaxial setup, the samples are instrumented with six P-wave ultrasonic transducers for passive and active acoustic monitoring. We used a sampling time interval from 150 to 60 seconds which gives, in turn, for each triaxial test, up to about 24000 waveforms recorded. Results from active seismic survey showed that deformation can be accurately monitored by the velocity variation which is very sensitive to the stress and strain state in the chalk samples. The P-wave absolute value and relative variation during the deformation are different between the different pathways among the six transducers, revealing the anisotropic nature of this chalk from a seismic and mechanical point of view.

The outcome from these tests highlights the necessity of considering water weakening processes when dealing with stimulating methods like enhanced oil recovery or hydraulic fracturing, where stress variations caused by fluid injection may not be the only problem that one has to consider.

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S7.4: Impact of shear-enhanced compaction bands on fluid flow via High-Speed Neutron Tomography

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Shear-enhanced compaction bands were identified in porous sandstone outcrops and were also reproduced at the laboratory-scale. These bands are characterised by textural changes due to grain fragmentation and crushing. Such micro-processes locally alter the pore connectivity and lead to local changes in porosity and presumably permeability. Thus, shear-enhanced compaction bands may impact fluid flow in a number of geo-energy applications, such as hydrocarbon production in subsurface reservoirs and CO_2 storage into aquifers.

The mechanical behaviour of these bands was previously captured via a number of non-destructive experimental techniques. This work focuses on the impact of shear-enhanced compaction bands on the rock-fluid system. Here, we present water imbibition tests with in-situ High-Speed Neutron Tomography (HSNT) performed at the CONRAD beamline at Helmholtz Zentrum Berlin (HZB). Sandstone samples, containing pre-existing, lab-induced, shear-enhanced compaction bands, were wrapped in Teflon tape, placed in a heat-shrunk FET membrane and settled in a cap fixed at the rotation stage. A small reservoir was connected to the cap through an electro-operated valve so that water supply to the cap could be controlled during the experiment. HSNT involved 300 radiographies acquired during sample rotation over 180° (back and forward since a full rotation was restricted by the experimental set-up). The acquisition time for each radiography was 0.2 sec, which results in a total time of 1 min per tomography. Both image reconstruction and the flow front detection and tracking have been achieved by using in-house software.

Our results show that in-situ HSNT tracks successfully the 4D water-front in samples with shear-enhanced compaction bands. The advantage of using neutrons (as opposed to x-rays) is the high contrast between material and pore water. Neutrons are sensitive to hydrogen and thus, any fluid containing it. The curvature of the water-front slightly changes as it propagates through the network of bands. When the water-front is approximately at the level of the bands, shear-enhanced compaction bands are visualised by HSNT, however, when the saturation of the sample increases, this is not feasible anymore. Flow speed maps demonstrate local increase in flow speed inside these bands, which are characterised by intense grain fragmentation, compaction and porosity loss. These micro-processes presumably lead to local increase in capillary pressure, thus saturation locally accelerates. The high capillary pressure of such bands likely plays a role in all multi-phase situations. Local changes in pressure could lead to faster reactivation of these bands.

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S7.5: Synchrotron X-ray imaging in 4D: Multiscale failure and compaction localization in triaxially compressed porous limestone

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An understanding of the failure and strain localization in a porous rock is of fundamental importance in rock physics. Confined compaction experiments on porous rocks have revealed a broad spectrum of failure modes. Techniques such as acoustic emission location and velocity tomography provide kinematic information on the partitioning of damage and localization of strain. Complementary observations on deformed samples using microscopy and micro-computed tomography (CT) can also be used to image microscale damage and its distribution. Only by synthesizing such measurements on multiple scales could one infer the multiscale dynamics of compaction localization and similar rock failure phenomena. Located at the European Synchrotron Radiation Facility, the HADES rig allows direct in situ 3D imaging of the whole rock sample as it is triaxially compressed. The microCT data provide an integrated perspective of the spatiotemporal evolution of damage and strain localization on scales ranging from grain to continuum. We conducted an experiment on Leitha limestone (with an initial porosity of ~22%) at a confining pressure of 20 MPa. With increasing differential stress, the sample strain hardened and two distinct yield points can be identified in the stress-strain curve. The spatiotemporal evolution of local porosity and damage were analyzed at multiple scales. At a mesoscopic scale of 10 voxels (65 microns), the time-lapse microCT images reveal the strain partitioning associated with the first yield point and development of strain localization with the second. The latter development of five discrete compaction bands is the first unambiguous observation of such a bifurcation phenomenon in a porous carbonate rock, with geometric attributes comparable to compactions bands observed in porous sandstones. The CT data on the voxel-scale elucidate in refined details the nucleation and propagation of discrete compaction bands under quasi-static loading, as well as the micromechanical processes, which in the past can only be inferred from a synthesis of kinematic observations of AE activity and post-mortem observations of microstructure and damage.

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S7.6: Fracture or Band? – A Potentially Common Transitional Type of Deformation and its Consequences for Fluid Movement through Fracture and Fault Systems

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Deformed upper crustal rocks in general, and those with some characteristics of shear-dominated deformation bands in particular, are well known to be prone to a complex distribution of shear plus dilation and, in porous rocks, shear plus compaction features. This results in an often difficult-to-predict pattern of pore and "fracture" network connectivity and permeability increase and decrease over the background values in different parts of what is geometrically the same feature. Anecdotally these features are a common component of many fault zones as well as existing as naturally-occurring individual features and they have also been produced experimentally in the rock mechanics laboratory in several different lithologies. Here we describe experimentally-created versions of the natural features that exhibit the textural characteristics of bands, but many of the fluid flow effects of open fractures, and which appear to be a transitional type of deformation with some similarities to the concept of dilational shear bands but with different, patterned, distributions of the different elements. The resulting complex spatial arrays within the cylindrical laboratory-deformed, layered, rock samples show a clear relationship with the lithological layering of the rock (laminite & coquina) materials' contrasting textures. These material controls are similar to observed relationships with lithological boundaries commonly observed with macro-scale natural fractures. As seen in X-ray tomographic imaging, the features display localized planar zones with a density lower than the surrounding rock, and so they are locally dilational, like open fractures. In the experimentally-created examples the array of dilational features is incompletely connected through in 3D, and so any liquid (here water) movement from base to top of the cylinder must pass through some matrix. Fluid-flow experiments, observed with 4D neutron tomographic imaging, reveal complex patterns of fluid motion. During the initial water saturation of an air-filled sample, the water enters the sample initially by imbibition into the smaller pores of the undeformed rock and fracture/band system entering very thin open fractures before the wider features. As the entering fluid pressure increases fluid path lengthening, water enters the wider fracture-component network. At this stage of observation it would appear that open fractures and the undeformed rock's pore system are the two main components of the fluid movement system, and this is the normal assumption made. But post-experiment investigations, via thin sectioning and SEM images, reveal that the features are not the expected open cracks, but instead are filled with broken grains and complex arrangements of mixed particle sizes, like that typically seen in bands. Digital-rock methods, based on the SEM-observed textures, calculate flow properties that agree with the inferences from the experimental flow observations. As well as the obvious implications, in terms of processes operating during rock deformation of a transitional fracture-band feature, this study has significant implications concerning the assumptions usually made relative to the multi-phase characteristics of flow-enhancing features that are assumed to be classical 'open' fractures. The distinction – in terms of process, or in terms of flow effects – between fractures and bands, is not as clear-cut as has been assumed.

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S7.7: Full 3D investigation at microstructural scale of heterogeneous swelling strains and induced damage in anisotropic clayey rocks

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The complexity of the mechanical behavior of clayey rocks results in particular from the sensitivity to water of the constitutive clay which undergoes swelling of shrinking strains when moisture content is changed. These strains may be strongly heterogeneous, both because of macroscopic gradients of water content created during transient phenomena, and local variations of swelling properties because of the presence of non-swelling phases such as quartz and calcite grains. 2D observations with optical microscopy or in the environmental scanning electron microscope have shown that these phenomena may induce meso- or micro-cracks, the extension and location of which, either inside the clay matrix, or at particle/matrix interfaces, depend on the experimental conditions. Such experiments have been further extended to full 3D investigations, by the combination of synchrotron X-rays computed microtomography, in situ testing, digital volume correlation and associated micro-crack detection procedures.

Cylindrical samples 4mm in diameter and 6mm in length machined from Callovo-Oxfordian clayey rock cores provided by Andra were first equilibrated at either 35% or 95% relative humidity (RH), using appropriate saline solutions. Two orientations were considered, with the sample axis either in the bedding plane or perpendicular to it. The lateral surface was then made impermeable to water, so that water exchanges could only be possible from the extremal faces. Samples were then fully imaged at the Psiché beamline of Synchrotron Soleil (Saint Aubin, France) with sequences of high definition images (1,3µm voxel size, images up to 3500x3500x2048 voxels) in their equilibrated state. Relative humidity was then changed to 95% or 35% RH respectively to induce controlled humidification or desiccation, and maintained constant all along the experiment and during imaging by means of a specifically designed device compatible with synchrotron imaging and which allowed also to monitor the weight of the samples. Images at various stages of the transient water exchange phenomena were then acquired under similar conditions. Images were then compared by 3D image correlation techniques to quantify displacement and strain fields. Because of the low strain values (of the order of 10^{-3}) local strains fields were rather noisy, but complex strain profiles at mesoscale could be evidenced accurately along the sample axis, as well as their anisotropy related to bedding plane orientation. Profiles show some complex features necessarily associated with residual stress fields. The latter did however not induce any mesoscopic damage, even though strain gradients up to 0,15%/mm could be quantified. This was probably the consequence of a very thorough selection of the samples, using laboratory tomography, which did not exhibit initial mesocracks nor significant pyrite of calcite veins which are already known to be sources of crack initiation. Microcracking at a scale close to voxel size, with subvocal accuracy in terms of crack opening, has then further been investigated by means of correlation-assisted 3D image subtractions techniques.

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SESSION 8: Hydraulic fracturing, hydromechanics and fracture permeability

Keynote 8: Key implementation aspects and results from the in-situ stimulation experiment at the Grimsel test site

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The Swiss Energy Strategy 2050 (ES2050) plans to replace nuclear electricity production with an increased utilization of different sources of new renewable energy and sets a target of 7% national electricity supply from Deep Geothermal Energy (DGE) by 2050, corresponding to 4.4 TWh per year and over 500 MWe installed capacity. To reach the ES2050 target, Switzerland will need to install on average 20 MWe per year of additional capacity of electricity production from DGE between 2025 and 2050. A capacity of 20 MWe requires the circulation of over 220 l/s of water at temperatures of 170-190°C, commonly found at 4-6 km depths in Switzerland. As hydrothermal water is scarse and difficult to locate, deep reservoirs will need to be created in hot crystalline basement rock (EGS), safely and at competitive costs.

The ISC project is a decameter in-situ experiment that has been performed at the Grimsel Test Site (GTS) at a depth of approximately 480m and within crystalline rock. The ISC experiment includes controlled fault slip and hydraulic fracturing experiments at an intermediate scale (i.e.~20*20*20m), which allows high resolution monitoring of the evolution of pore pressure in the stimulated fault zone and the surrounding rock matrix, fault dislocations including shear and dilation, and micro-seismicity in an exceptionally well characterized structural setting.

From 2015 to 2017 we performed an intense characterization and preparation phase that included stress measurements using various methods such as hydraulic fracturing, overcoring and hydraulic jacking, geological characterization using borehole logging, tunnel mapping, Ground Penetration Radar and active seismic measurements, pre-stimulation hydraulic characterization, tracer tests using dyes, salt and DNA nanoparticles. Further monitoring equipment including FBG fibre optics sensors and distributed fibre optics for strain measurements, distributed fibre optics temperature measurements, tiltmeters, micro-seismic surface and borehole sensors, pore pressure sensors and surface extensometers were installed.

In February 2017 we performed a series of fault-slip experiments on interconnected faults adjacent to two injection boreholes. Subsequent to the fault-slip experiments we performed an intense phase of post-stimulation hydraulic characterization. In May 2017 we performed a series of hydraulic fracturing tests within test intervals that were free of natural fractures.

The presentation summarizes key aspects of the design and implementation of this experiment and provide selected results relevant for future research activities and enhanced geothermal system design.

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S8.1: On the anisotropy and nonlinearity of the Grimsel Granite

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The elastic deformation of many rock types is anisotropic and nonlinear due to their complex micro-structure. Taking rock anisotropy and nonlinearity into account allows accurate predictions of rock deformation under different loading types. Determination of the elasticity constants (both secant and tangent definitions) is therefore of crucial importance in a wide range of fields related to geomechanics and geophysics. An important application is related to so-called enhanced geothermal systems (EGS) or reservoirs. Previous methods to determine the elastic constants of anisotropic rocks require either multiple samples or multiple loading types. In this paper, we present a methodology to determine both secant and tangent values of elastic constants of anisotropic rocks using only a uniaxial compression test.

We developed a methodology to determine the static and dynamic values of the five elastic constants of transversely isotropic rocks from one cylindrical sample. We performed uniaxial compression tests on cylindrical specimens of granite, extracted from the underground rock laboratory in the Grimsel Test Site (GTS), Switzerland. These rock samples exhibit a clear foliation that induces anisotropy. Strains were measured at different polar angles around the circumference. Ultrasonic measurements were also conducted in order to obtain the orientation of the isotropy plane and the dynamic elastic constants.

The main conclusions of this research are as follows: 1) Not all five elastic constants can be determined exactly from one uniaxial compression test. Only the shear moduli can be determined exactly, while the rest of the elastic constant can be determined only when extra Information is provided with regard to one of Young's moduli or Poisson's ratios, or a relationship among them. 2) Using the Saint-Venant relation as an extra equation provides a simple method to efficiently determine the five elastic constants of transversely isotropic rocks. 3) The presented methodology can efficiently determine both secant and tangent values of the elastic constants in transversely isotropic rocks from a minimum four strain gauge measurements. 4) Experimental results on Grimsel granitic samples yield average anisotropy ratios of two for the Young's moduli and the Poisson's ratios and 1.4 for the shear moduli. 5) The tangent values of the elastic constants show a significant stress dependency, where the tangent moduli increase by a factor of three to four when the rock is loaded up to about 20 MPa. 6) The comparison of the static and dynamic values of the elastic constants show that the dynamic values are significantly greater than the static ones and that the anisotropy ratio of static Young's moduli is larger than that of the dynamically determined ones.

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S8.2: Hydraulic fracture growth in the heterogeneous strata of the upper carboniferous

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The carboniferous strata in the North German Basin is a potential reservoir horizon for geothermal energy production. Due to low reservoir permeabilities, stimulation will be necessary. The effectiveness of stimulation might be affected by heterogeneity and anisotropy of the reservoir. The strata is composed of alternating sequences of sandstones, conglomerates, siltstones and coal which all have different rock properties e.g. fracture toughness and Young's modulus. Due to the layered strata, the rock mass may be considered being transvers anisotropic. Heterogeneity is observed within each stratum.

In order to investigate the influence of heterogeneity and anisotropy on fractures crossing the interface between two different rock materials, stack frac experiments have been conducted. In these experiments three cuboid specimen are stacked and axially loaded. The central block consists of a different material than the two neighboring blocks. An injection borehole is located within the central block. The fracture is initiated in the center of the central block and propagates up and downwards towards the artificial joints separating the middle block from the upper and the lower block. Axial loads were varied while the injection rate was kept constant at 1 ml/min. As testing materials served two different types of sandstone, a schist, a limestone and charcoal briquettes, respectively. It has been found that conductivity and the frictional properties of the interface between different rock types in the stack determine fracture crossing. Accordingly, these properties have been estimated from lab tests.

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SESSION 8: Hydraulic fracturing, hydromechanics and fracture permeability

S8.3: Stress reorientation by earthquakes near Ganzi-Yushu strike slip fault and interpretation with discrete element modeling

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Stress and earthquakes are generally known to be interrelated that is stress triggers earthquakes and earthquakes in turn alter the shear and normal stresses on surrounding faults. The observation of in situ stress within YSH borehole near Ganzi-Yushu Fault using YRY-4-type four-gauge borehole strain meters (FGBS) shows that the orientation of the maximum horizontal stress (SHmax) changes from an angle about 40° to 65° during the time period from January 1, 2009 to December 31, 2018. In this period of time, 28 earthquakes (M≥3) occurred near the fault and the SHmax orientation show a drastic change after Yushu earthquake (Ms 7.3). We present a discrete element modeling using Particle Flow Code 2D (PFC2D) to interpret this stress reorientation phenomenon. Working hypothesis for this problem is that a fault slip releases energy that can temporally alter the local stress around the fault and form resultant force associated with the far-field tectonic stress before the co-seismic slip occurs. Using PFC2D, we investigate the effect of fault frictional properties and structural complexity on slip profiles and reorientation of the stress field near the activated fault.

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S8.4: Laboratory experiments investigating the hydro-mechanical behaviour of rocks containing a single fracture

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The majority of rock formations of the brittle upper crust contain discontinuities of various scales from micro cracks to macroscopic fractures to large faults. In tight fractured rocks, fluid flow and storage is governed to a large degree by the transport properties of their discontinuities. To fully understand transport in fractured media the hydro-mechanical coupling between the fluid flow-induced changes in stress and the mechanical deformation of the surrounding solid matrix has to be taken into account. Fluid flow in fractures is controlled by their hydraulically effective width, as for example expressed by the cubic law. The fracture width at a given stress state in turn depends on the fracture's normal stiffness. Hence variations in effective normal stress, e.g., by fluid injection, strongly influences fracture transport properties. Recent studies suggest that fracture specific stiffness is the scaling parameter linking mechanical and surface characteristics with fluid transport characteristics. We performed hydraulic measurements on single fractures in a granitic matrix oriented perpendicularly to the sample axis. A central borehole connected the fracture to the upstream fluid reservoir. Due to the simple radially symmetric geometry of the setup the dataset serves as a benchmark to test and fit numerical simulations schemes, which will be discussed in a separate EURO-presentation. We performed measurements at a range of effective stresses on three fractures with varying roughness. For the hydraulic characterization, we applied an oscillatory pressure signal through a central borehole. Effective hydraulic parameters were derived from the phase shift and amplitude ratio between the fluid pressure and the corresponding fluid flow from the borehole in and out of the fracture. Displacement transducers tracked the axial sample deformation constraining changes in mean fracture width. Measurements were simultaneously performed to investigate the interrelation between mechanical and hydraulic fracture properties.

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S8.5: Hydraulic-mechanical characterisation of microfaults in low porosity rocks – an experimental study

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Fault zones are key features in crystalline and other low permeability geothermal reservoirs, due to the fact that they serve as main fluid pathways and thereby control the mechanical stability and hydraulic sustainability of such systems. An adequate experimental description of the evolution of permeability during the generation and under varying effective stress of a realistic microscopic fault zone under in-situ reservoir and fracture parallel flow conditions is required.

We demonstrate an innovative experimental set up (Punch-Through Shear test) which is able to generate a shear zone (microfault) under in-situ reservoir conditions while simultaneously measuring permeability and aperture. Sedimentary and crystalline rock samples were installed into a MTS 815 tri-axial compression cell, where a self-designed piston assembly punched down the inner cylinder of the sample creating the desired microfault geometry with a given offset. Permeability was measured for the entire duration of the experiment and fracture aperture was inferred from an LVDT extensometer chain and the balance of fluid volume flowing in and out of the sample. After fracture generation, the shear displacement is increased to 1.2 mm and pore pressure changes of 5 or 10 MPa are applied cyclically to simulate injection and production scenarios. X-ray CT scan and thin section analysis are used to identify microstructural features and to quantify local aperture variations.

The permeability enhancement caused by the formation of a microfault in low permeability rocks varies between no enhancement (sandstone) and an increase of up to 3 orders of magnitude (granite). Further shear displacement can lead to a small increase of permeability, but reductions due to fault healing are possible. Permeability changes are elastic when varying the effective pressure and the increasing fracture normal stiffness for an increasing number of pressure cycles suggests a sufficient sustainability of microfault permeability, comparable to displaced tensile fractures. The microstructural analysis reveals a complex fault zone including mode I and II fracturing.

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S8.6: Thermo-Mechanical Investigations on the Self-propping Potential of Tensile Fractures in Sandstone

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Fracture aperture, which is determined by the fracture's geometry, the mismatch between the two adjacent fracture surfaces, and the properties of asperities, determines the hydraulic transport within a fractured rock mass of low matrix permeability. In this study the pressure and temperature dependence of fracture permeability was measured in a hydrostatic flow-through apparatus. Two types of sandstones, Fontainebleau and Flechtinger, both with a matrix permeability below 0.15 mD were selected. Artificially generated tensile fractures were introduced within otherwise intact cylindrical rock cores and the samples were tested with predefined relative fracture offsets of 0 µm, 200 µm, and 750 µm, respectively. Pore pressure (Pp) was maintained at 1 MPa throughout the experiments and confining pressure (Pc) was varied stepwise between 5 and 35 MPa. The void volume within the samples was monitored by drained compression tests during confining pressure cycling yielding the relative mechanical aperture changes. The absolute initial and final mechanical apertures were obtained by µCT-scans prior to and after the experiments, respectively, and analyses of surface scan data bridged the gap between the initial aperture under zero load and the aperture under starting pressure conditions (i.e., Pp=1 MPa and Pc=5 MPa). In addition, temperature was cycled between room temperature and 140 °C after the respective loading-unloading cycle. For all samples it showed, that the observed mechanical aperture changes were significantly larger than the corresponding hydraulic aperture changes obtained from permeability measurements applying the "cubic law". After the load cycle, the sample containing a tensile fracture with zero offset showed an irreversible permeability decrease by two orders of magnitude. The specimen with 200 µm fracture offset experienced one order of magnitude permeability decrease while the permeability of the sample with 750 µm fracture offset only slightly degraded and remained constant during subsequent pressure cycles. Moreover, a temperature increase resulted in decreasing permeability for all samples where the relative permeability changes and the amount of irreversible permeability degradation showed more pronounced for the sample with zero fracture offset as compared to the samples with relative fracture displacement. Overall, the results indicate the range of fracture offset necessary to induce sustainable self-propping in sandstones for fracture aperture being insensitive to pressure and temperature variations. Results of similar and comparative experiments on samples containing single rough saw-cut fractures, currently ongoing, will complement this contribution.

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S8.7: How to publish Open Access in earth sciences

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Open Access to scientific literature and research data has significant advantages for researchers as well as for society as a whole. Researchers might gain from increased citation rates and from higher visibility of their research outputs, while researchers as well as the public benefit from a better accessibility of scientific literature and data. Increasingly, funding organisations such as the European Commission in the context of Horizon 2020-funded projects or the 16 national and international members of "Plan S" demand that publications that result from projects funded by them are made openly accessible.

This presentation outlines the different ways of publishing text and data in Open Access. After a brief overview of reasons for publishing Open Access, it offers a practice-oriented introduction into what researchers need to do in order to publish Open Access. Topics include different routes for publishing texts in Open Access (in Open-Access-Journals or self-archiving), financing options for Open Access publication costs (such as Article Processing Charges), open licences, and strategies of how to avoid "predatory publishers". Researchers will learn how to find high quality Open-Access-Journals as well as repositories to publish research data or postprints of their research articles.

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Conference website

https://events.gfz-potsdam.de/euro-2019

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