



# Special Issue on Rock Fracturing and Fault Activation: Experiments and Models

Selected Papers Presented at the 13th EURO-Conference on Rock Physics and Geomechanics—The Guéguen Conference Held on 2–6 September 2019 in Potsdam, Germany

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## 1 Introduction

Since 1998, the EURO-Conference series on Rock Physics and Geomechanics is regularly held at different locations throughout Europe and beyond and is self-organized by the European Rock Mechanics community (Table 1). The conference intends to bring together rock mechanics experts from academia and industry with special emphasis on support for early career scientists. Each conference is dedicated to a topic of particular relevance to the community at the time and frequently results in special issues on these topics (Table 2). The augmentation ‘The Guéguen Conference’ was added on the occasion of the 70th birthday of Yves Guéguen, one of the main initiators and supporters of the EURO-Conference series.

The ‘13th EURO-Conference on Rock Physics and Geomechanics—The Guéguen Conference’ was held on 2–6 September 2019 in Potsdam, Germany. The overarching theme of the conference was ‘Rock fracturing and fault activation: experiments and models’. Given the increasing

relevance of fracture and fault development and associated induced and triggered seismicity in human subsurface operations such as conventional and unconventional hydrocarbon production, hydrothermal and petrothermal energy utilization, wastewater disposal, energy storage, and rad waste storage, this subject deserves and will attract special attention in the near future. The conference provided a unique opportunity for international researchers and industry experts to discuss latest results and developments on the topic of rock fracturing and fault activation, which is fundamental to safely and economically utilize the subsurface.

This special issue intends to summarize the highlights of the conference programme consisting of 8 keynote lectures, 47 oral presentations and 26 poster presentations given by rock mechanics experts and early career scientists (Fig. 1). The programme was divided into the following eight oral presentation sessions: ‘Fluid-driven fractures and seismicity’, ‘Compaction and damage of porous rock I+II’, ‘Laboratory fracture and rock characterization studies’, ‘Porosity and seismicity of reservoir rocks’, ‘Simulation of fractures and faults’, ‘Hydraulic, thermal and mechanical cyclic loading at multiple scales’ and ‘Hydraulic fracturing, hydromechanics and fracture permeability’. Abstracts of all conference contributions can be found in Hofmann and Spalek (2019).

This special issue consists of 19 scientific papers which are based on these conference contributions and all of which address different important aspects relevant to the variety of industrial applications outlined above. We want to highlight that rock fracturing and fault activation are two very different processes and that both hard data measured in experiments as well as analytical and numerical models together yield a powerful path to solve industrial and societal challenges associated with the utilization of the subsurface based on scientific evidence.

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This special issue is dedicated to our dear colleague and friend Prof. Ove Stephansson, who was not only one of Sweden’s most influential geologists, but also an enthusiastic supporter of the 13th EURO-Conference on Rock Physics and Geomechanics. Ove was actively involved in research, teaching, conferences and publications until he passed away on 19 February 2020. Lilljequist and Zang (2020) look back on his outstanding academic career with personal remarks in a dedicated remembrance article.

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**Table 1** Summary of past EURO-conferences

Year	Location	Organizer	Topic
1998	Aussois, France	Y. Guéguen, M. Boutéca	Pore pressure, scale effect, and the deformation of rocks
1999	Edinburgh, UK	G. Couples, I. Main	The relationship between damage and localization
2000	Bad Honnef, Germany	H.J. Kümpel, C. Clauser	Thermo-hydro-mechanical coupling in fractured rock
2003	Kijkduin, The Netherlands	A. Makurat	Micromechanics, flow and chemical reactions
2004	Potsdam, Germany	G. Dresen, S. Shapiro, O. Stephansson, A. Zang	Scaling laws in space and time
2005	Oléron, France	C. David, M. Le Ravalec	Rock physics and geomechanics in the study of reservoirs and repositories
2007	Erice, Italy	S. Vinciguerra, Y. Bernabé	Natural hazards: thermo-hydro-mechanical processes in rocks
2009	Ascona, Switzerland	L. Burlini, P. Baud, A. Schubnel	Thermo-hydro-chemo-mechanical coupling in rock physics and mechanics
2011	Trondheim, Norway	R. Holt, S. Johnsen	Linking laboratory, computational and field evidence
2014	Aussois, France	C. Viggiani, P. Besuelle, F. Renard	Multi-scale rock mechanics and rock physics
2015	Ambleside, UK	P. Benson, P. Rowley, P. Meredith	Holistic rock physics: integrating theory, observation and application
2017	Ma'ale HaHamisha, Israel	E. Shalev, R. Weinberger, V. Lyakhovksy, Y. Hatzor	Bridging between rock physics and structural geology
2019	Potsdam, Germany	H. Hofmann, G. Zimmermann, G. Blöcher, H. Milsch, A. Spalek, A. Zang, O. Stephansson, K.Y. Kim	Rock fracturing and fault activation: experiments and models

**Table 2** Summary of special issues on past EURO-Conferences

Year	Journal	Topic	Reference
1999	Oil & Gas Science and Technology – Rev. IFP	Pore pressure, scale effect and the deformation of rocks	Boutéca and Guéguen (1999) <a href="https://doi.org/10.2516/ogst:1999055">https://doi.org/10.2516/ogst:1999055</a>
2003	Pure and Applied Geophysics	Thermo-hydro-mechanical coupling in fractured rock	Kümpel (2003) <a href="https://doi.org/10.1007/978-3-0348-8083-1">https://doi.org/10.1007/978-3-0348-8083-1</a>
2005	International Journal of Rock Mechanics & Mining Sciences	Rock physics and geomechanics	Makurat and Zimmerman (2005) <a href="https://doi.org/10.1016/j.ijrmms.2005.05.001">https://doi.org/10.1016/j.ijrmms.2005.05.001</a>
2006	Pure and Applied Geophysics	Rock damage and fluid transport, Part I	Dresen et al. (2006) <a href="https://doi.org/10.1007/3-7643-7712-7">https://doi.org/10.1007/3-7643-7712-7</a>
2006	Pure and Applied Geophysics	Rock damage and fluid transport, Part II	Zang et al. (2006) <a href="https://doi.org/10.1007/s00024-006-0114-2">https://doi.org/10.1007/s00024-006-0114-2</a>
2007	Geological Society of London, Special Publications	Rock physics and geomechanics in the study of reservoirs and repositories	David and Le Ravalec-Dupin (2007) <a href="https://doi.org/10.1144/SP284.1">https://doi.org/10.1144/SP284.1</a>
2007	Geological Society of London, Special Publications	The relationships between damage and localization	Couples and Lewis (2007) <a href="https://doi.org/10.1144/SP289.1">https://doi.org/10.1144/SP289.1</a>
2009	Pure and Applied Geophysics	Rock physics and natural hazards	Vinciguerra and Bernabé (2009) <a href="https://doi.org/10.1007/978-3-0346-0122-1">https://doi.org/10.1007/978-3-0346-0122-1</a>
2011	Tectonophysics	Thermo-hydro-chemo-mechanical couplings in rock physics and rock mechanics	Baud and Schubnel (2011) <a href="https://doi.org/10.1016/j.tecto.2010.11.002">https://doi.org/10.1016/j.tecto.2010.11.002</a>
2021	Rock Mechanics and Rock Engineering	Rock fracturing and fault activation: experiments and models	This issue

We admit, however, that fracture mechanical principles and rock physics elements behind rock fracturing and fault activation may be similar, and that the joint discussion of fracturing and faulting, therefore, has a long tradition in the rock mechanics and rock engineering community.

## 2 Rock Fracturing

### 2.1 Laboratory Experiments

Forbes Inskip et al. (2021) measured tensile strength and fracture toughness of Nash Point limestone, a typical



**Fig. 1** Participants of the ‘13th EURO-Conference on Rock Physics and Geomechanics—The Guéguen Conference’ during the social event at the Winzerberg Potsdam

hydrocarbon reservoir rock, in three principal fracture orientations and found it to be roughly isotropic in terms of microstructure and fracture properties. Additionally, they discuss how layered sequences (i.e., limestone and shale layers) may influence vertical fracture crossing.

Meng et al. (2021) quantified the effect of bedding anisotropy and crack closure on the effective stress behaviour of clayey sandstones. Their data show that bedding anisotropy has a significant influence on the effective stress coefficient for permeability, but little effect on the effective stress coefficient for pore volume change.

Geremia et al. (2021) performed water flooding experiments of dry, critically loaded Obourg Chalk samples in a conventional triaxial test apparatus which resulted in a significant reduction in mechanical strength. They observed a brittle–ductile transition between low- to high-confining pressures and propose that the failure might be controlled by a mechanical coupling between water-invaded zone and dry zone.

Jung et al. (2021) analysed in laboratory hydraulic fracturing experiments the fatigue behaviour of cylindrical granite samples subject to different continuous and cyclic injection schemes. They found that the number of cycles to failure increases exponentially with decreasing maximum pressure and that cyclic injection led to more acoustic emissions, lower seismic energy and higher Gutenberg–Richter  $b$  values as compared to the continuous injection cases.

Kluge et al. (2021) initiated a shear zone in Flechtingen Sandstone and Odenwald Granite laboratory samples under in situ conditions using a punch-through shear test setup. They found that permeability did not significantly change in the sandstone samples while it increased by two orders of magnitude for the granite samples and that further shear displacement resulted in a further, but small permeability increase. They associated the difference in permeability evolution in the two rock types to a difference in the width of the shear zones.

Martin-Clave et al. (2021) performed cyclic mechanical (axial) loading tests on five rock samples with different types and amounts of secondary minerals under a

confining pressure of 25 MPa to improve the understanding on safe cyclic underground gas storage in salt caverns. They observed a strength weakening effect by high secondary mineral content (e.g., anhydrite layers) through larger brittle deformation and a change elastic moduli and porosity.

Fazio et al. (2021) investigated the effect of matrix permeability on hydraulic fracturing by performing injection experiments in highly permeable Bentheim Sandstone, in low-permeability Crab Orchard Sandstone, and sleeve fracturing experiments. They found that no fracture developed in the permeable Bentheim Sandstone, a hydraulic fracture propagates fast and continuously in the low permeability Crab Orchard Sandstone and a fracture is induced gradually and episodic in the sleeve fracturing experiment in Bentheim Sandstone. They attribute this behaviour to leak-off, which is dictated by the rock matrix permeability.

## 2.2 Modelling Studies

Yang et al. (2021) derived and applied an evaluation procedure for mode I fracture toughness determination from numerical models and three-point bending tests at confining pressures up to 30 MPa with different sealing methods. While the determined toughness generally increased significantly with confining pressure up to some tens of MPa, they found that the apparent toughness determined for jacketed specimens was larger than that of varnished ones. They explain their observations by micro-crack closure and suggest that non-linearity effects may not be as severe at depths beyond a few kilometres as previously thought.

Zhao et al. (2021) developed a flexible wall approach to improve the simulation of triaxial compression tests in discrete element models. They constructed their models based on CT images and validated them against triaxial compression test data. The models were then used to investigate the effect of inclusions in coal samples on strength, deformation, and damage. They found that a higher proportion of high strength inclusions increases the peak strength of a coal sample.

Jacquey et al. (2021a) review concepts of the thermo-mechanics theory and extend it by a thermodynamically consistent modelling approach that includes rate-dependent critical state-line models for porous rocks. They use their model to analyse strain localization behaviour.

Jacquey et al. (2021b) extend this theory to account for poromechanics and dissipative inelastic processes. Based on experimental data they demonstrate how their model accounts for the macroscopic response of triaxial loading experiments with focus on the transition from dilation to compression and the resulting range of localization styles from shear dilation to compaction bands.

Spetz et al. (2021) propose a modified phase-field model for simulating the evolution of mixed mode (tensile and shear) fractures in porous artificial rocks. The simulated results are compared to experimental data and to other current phase-field methods, both qualitatively and quantitatively. It is shown that the proposed model is able to capture the commonly observed propagation pattern of wing cracks followed by secondary cracks driven by compressive stresses. Additionally, the typical types of complex crack patterns observed in experimental tests are successfully reproduced.

### 3 Fault Activation

#### 3.1 Laboratory Experiments

Ji et al. (2021) investigated the fluid injection-induced slip of a critically stressed natural fracture in a granite core sample subject to different pressure-controlled and volume-controlled monotonic and cyclic water injection schemes. While they found that cyclic injection with restricted pressure could reach similar displacements with lower slip rates as compared to monotonic injection, they also observed fast unstable slip after a certain displacement was reached.

Cheng and Milsch (2021) performed an experimental study on fracture closure of aligned and displaced tensile fractures as well as saw-cut fractures of soft Flechtingen Sandstone and hard Fontainebleau sandstone under confining pressures between 5 and 30 MPa. They found that depending on fracture surface roughness, fracture displacement can significantly enhance fracture aperture, and that rough fractures, strong asperities, and a certain fracture offset are required for fractures under stress to stay open to fluid flow.

#### 3.2 Modelling Studies

Su et al. (2021) performed two-dimensional discrete element modelling of dynamic fault rupturing using Particle Flow Code 2D (PFC2D) to understand the related

spatio-temporal stress re-orientations measured by a borehole strain meter in the direct vicinity of the Ganzi–Yushu fault in the eastern Tibetan Plateau before and after the 2010 Ms 7.3 Yushu earthquake sequence. They highlight the influence of structural complexity and off-fault damage by co-seismic fault slip on the local stress field.

Lyakhovsky and Shalev (2021) performed a poro-elastic damage rheology modelling study on stable versus runaway fracture growth. They separate diffusion-controlled rupture growth, considered to be stable, from runaway fracture where the rupture propagates beyond the pore pressure front. They found that the amount of permeability increase with damage and the injection pressure are two major factors governing the stability of the modelled faults and fault branching.

Parastatidis et al. (2021) demonstrate that localized effective medium (LEM) models are an accurate and efficient method to retrieve fracture properties from inverse modelling of seismic waves in comparison to less effective explicitly modelled zero-thickness frictional slip surfaces or less accurate effective medium models. They note that the thickness of the localized effective medium layer representing the fracture becomes important when the frequency is high, and the normal stiffness is low.

Shapiro and Dinske (2021) investigated high-stress-drop earthquakes induced by underground fluid injection or production. They derived a relationship between seismogenic index and stress drop showing that the seismogenic index increases with average stress drop of induced seismic events. Additionally, they formulated a simple phenomenological model of stress drop of induced earthquakes that shows how a decrease of fault cohesion during the earthquake rupture process and larger effective stresses could lead to high-stress-drop earthquakes.

Deng et al. (2021) introduced a new methodology to determine fracture diffusivity from numerical simulations. This was done by fitting the numerically computed spatio-temporal pressure field with the solution of an equivalent parallel plate model. They used their model to investigate hydraulic diffusivity reduction caused by fracture closure and surface roughness.

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