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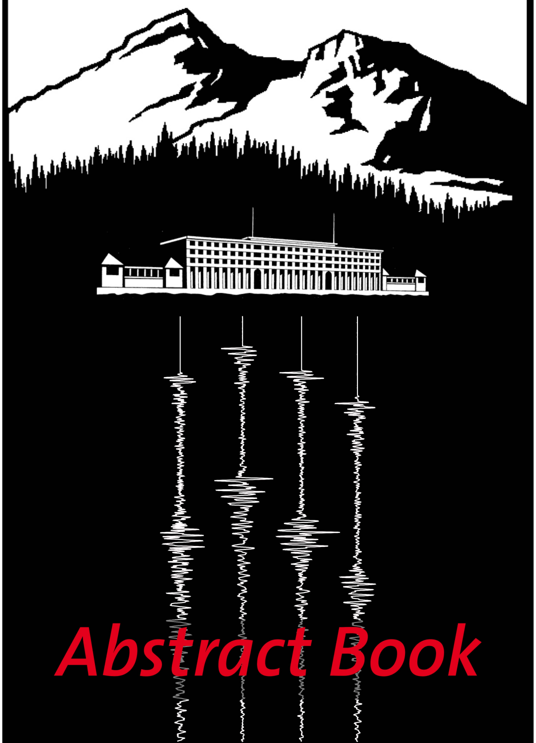

Abstract Book

5 - 8 March 2019

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SCHATZALP

3rd Induced Seismicity Workshop

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Abstracts Talks

Session 1

Case Studies I: World Tour

Induced Seismicity in the Permian Basin, USA

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The Permian Basin of west Texas and southeast New Mexico is the largest petroleum-producing basin in the U.S. The basin has been under production since the early 1920s and is currently undergoing an intense new phase of development. Almost half of the active drill rigs in the U.S. are drilling thousands of horizontal wells to tap shale oil and gas, and hundreds of thousands of additional wells may be drilled the coming decades. Because the petroleum-bearing shale rocks now under production are stacked over thousands of meters of section, thickest in the deep Delaware Basin (a sub-basin on the west side), the Permian Basin represents what some have described as an effectively unlimited hydrocarbon resource for the United States.

Induced seismicity has been known to occur in the region since the 1970s, when pioneering studies identified seismicity associated with enhanced oil recovery activities in the Cogdell Oil Field in the extreme northeast part of the basin. Natural seismicity also occurs in the region but generally locates outside of the petroleum-producing areas. Since 2015, seismicity has increased in the western Delaware Basin, with more than 30 M ≥ 3 earthquakes occurring in the past 4 years, the largest of which (Mw 3.4) occurred at the end of 2018. Following the installation by the University of Texas, Austin, of 8 regional stations as part of the Texas Seismological Network (TexNet), over 4000 smaller events have been detected. Due to the large distance between stations (Texas is a big place), there is essentially no focal depth control for most earthquakes when they are located using standard methods.

The origin of contemporary seismicity in the Delaware Basin is poorly understood due to the complex geology, long history of production and wastewater disposal, multiply-stacked production and injection horizons, extensive near-surface salt and anhydrite deposits, and lack of precision hypocenters. At the Stanford Center for Induced and Triggered Seismicity (SCITS), we are working with industry and university partners to understand where and why seismicity is occurring. A key component of our research is the development of a comprehensive stress model for the basin (see presentation by Lund Snee and Zoback), where the orientation of the maximum horizontal stress changes markedly over short spatial scales in certain areas and the faulting regime transitions gradually from normal/strike-slip in the east to normal faulting in the west. We are also using Sentinel-1A/B InSAR data to measure crustal deformation within the basin. Preliminary results reveal subsidence patterns that correlate with production, disposal and seismicity. To unravel these intriguing patterns and their relationship with seismicity, we are applying waveform-modeling methods to resolve earthquake focal depths and hypocentral fault structures. This talk will summarize our current understanding and discuss the challenges that lie ahead if we are to identify effective strategies for managing the hazard of induced earthquakes in this region of critical economic importance.

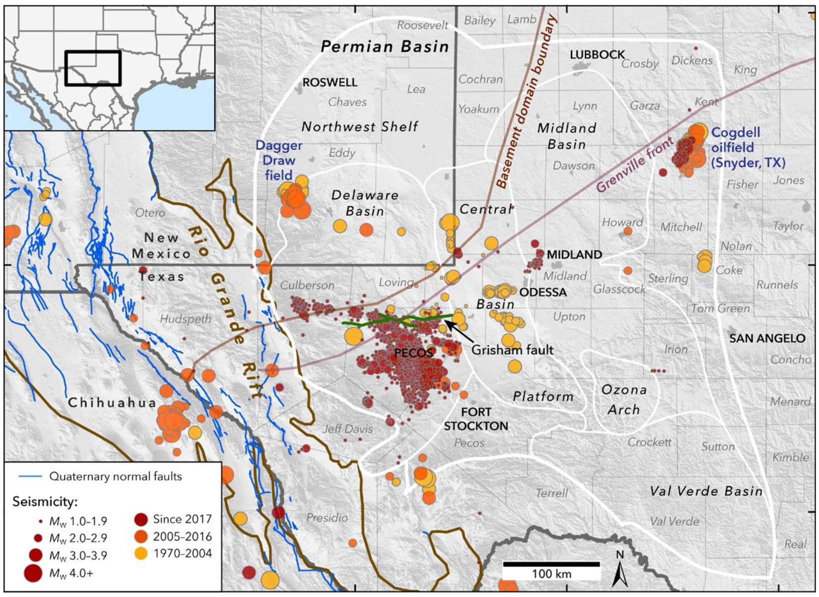

Fig. 1 Seismicity in the Permian Basin area, from the U.S. Geological Survey, Texas Seismological Network (TexNet), and W. Gan and C. Frohlich (2013, *PNAS*). Basement domain boundary from the U.S. Geological Survey and Grenville front from W.A. Thomas (2006, *GSA Today*).

Seismicity Induced by Hydraulic Fracturing Operations at Preston New Road, Lancashire, 2018.

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Hydraulic fracturing of an unconventional shale gas reservoir in northwest England began in October 2018, over seven years after induced seismicity related to the first such operations in the UK resulted in a moratorium. A dense network of surface sensors was installed to monitor any induced seismicity, partly in order to comply with regulatory requirements. We use a combination of conventional, energy transient detection algorithms along with template matching to detect seismic events with magnitudes as low as -1.0 ML using only surface sensors. We also show that the detected seismicity is strongly clustered in space and time, presumably associated with periods of injection, with only small numbers of "trailing" events. Injected volumes during the initial hydraulic fracturing stages were small and did not exceed 800 m^3. As a result, the levels of seismicity were low, but despite this a number of events exceeded the magnitude limit of 0.5 ML that is set by current regulations and requires operators to temporarily stop injection. Magnitude uncertainty creates a considerable problem for operators. We use a bootstrap approach to better quantify magnitude uncertainty, and even with a dense network of sensors, the variance in the measured magnitudes is high. The non-linear earthquake location problem also contributes to magnitude uncertainty and we show how both location uncertainties and incorrect assumptions about seismic velocities in the Earth can result in very significant changes in magnitude. These issues highlight some of the problems in the reliable characterisation of induced seismicity during operations using surface arrays.

Induced earthquakes in the Hellisheiði geothermal field, Iceland

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The 300 MW Hellisheiði, Iceland geothermal power plant was commissioned in 2006 and as of January 2018, the 63rd production well is being drilled. Additionally, there are 17 injection wells in the region. Drilling of a few of these wells has been accompanied by significant (M ~2-3) earthquakes [Vogfjord & Hjaltadóttir, 2007; Ágústsson et al., 2015], whereas no seismic events were observed during the drilling of others. Often the induced seismicity is coincident with either; 1) loss of circulation fluid, when drilling through large fractures, which absorb the drilling fluid or 2) well testing after completion of drilling, during which fluid is pushed into the hole with increasing pressure. Most of the wells are located in the highly fractured fissure swarm of the central volcano Hengill, which includes hyaloclastite ridges and lava fields and it is considered that the fluid flow is fracture dominated.

In addition to the seismicity induced in connection to drilling, the level of seismicity in the region has been highly increased by reinjection of affluent water (including two Mw 4.4 earthquakes in 2011), as well as by the production itself. In the Hverahlíð subregion, six wells have been drilled since 2006. During well testing of well HE-21, the first one drilled in the region, significant seismicity was observed [Vogfjord & Hjaltadóttir, 2007], whereas no seismicity followed the drilling and well testing of HE-53 and HE-54 (Fig. 1). However, the seismicity increased significantly when production started in 2016 and has stayed elevated since.

In this study we document the seismicity associated with the drilling of each well, and correlate that with other well parameters, for example lithology, temperature, injectivity/productivity and faults observed cutting the wells. Furthermore, we compare the seismicity during drilling with that during production/injection.

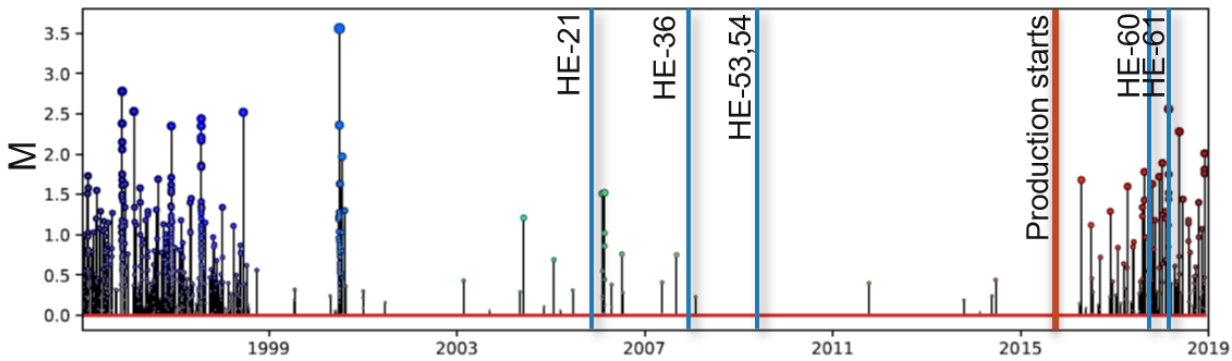

Fig. 1 Seismicity in the Hverahlíð region of the Hellisheiði geothermal field. Initiation of drilling of wells are indicated with vertical blue lines and start of production with red line.

Induced Seismicity at Thoresby Colliery, UK

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The United Kingdom has a long history of deep coal mining, with numerous cases of mining induced seismicity recorded over the past 50yrs. In this study we examine the nature and characteristics of seismicity induced by longwall mining over 9 months in 2014. During this period 305 individual seismic events were recorded on a network of seven seismometers, with their location closely tracking the position of the mining face within the Deep Soft Seam (Figure 1). Source mechanisms analysis reveals a consistent dip-slip motion along near-vertical planes that strike parallel to the orientation of the mining face, which is consistent with the expected deformation.

This dataset highlights several challenges and issues with respect to magnitudes for microseismic earthquakes. We observe inconsistent estimates of M_L, significant divergence between M_L and M_W, source spectra contrary to a Brune (1970) ω^{-2} spectrum, and event magnitudes that do not follow the expected Gutenberg-Richter distribution. This has a significant impact on the calculation of source properties, and broader implications, such as the operation of traffic light schemes for hydraulic fracturing. We seek to explain the causes of these inconsistences, and propose approaches to correctly calculate magnitudes and model source spectra.

To understand further the nature of the seismicity, we estimate the maximum rupture areas of the events through modelling both source spectra and magnitude distributions. These estimates correspond to the distances between the Deep Soft seam, and mined seams that over and underlie it. By inference these seams control the rupture area, preventing the growth of larger ruptures and limiting the maximum magnitude of the distribution. Combined this with the nature of the source mechanism, we conclude that the events are directly induced by mining.

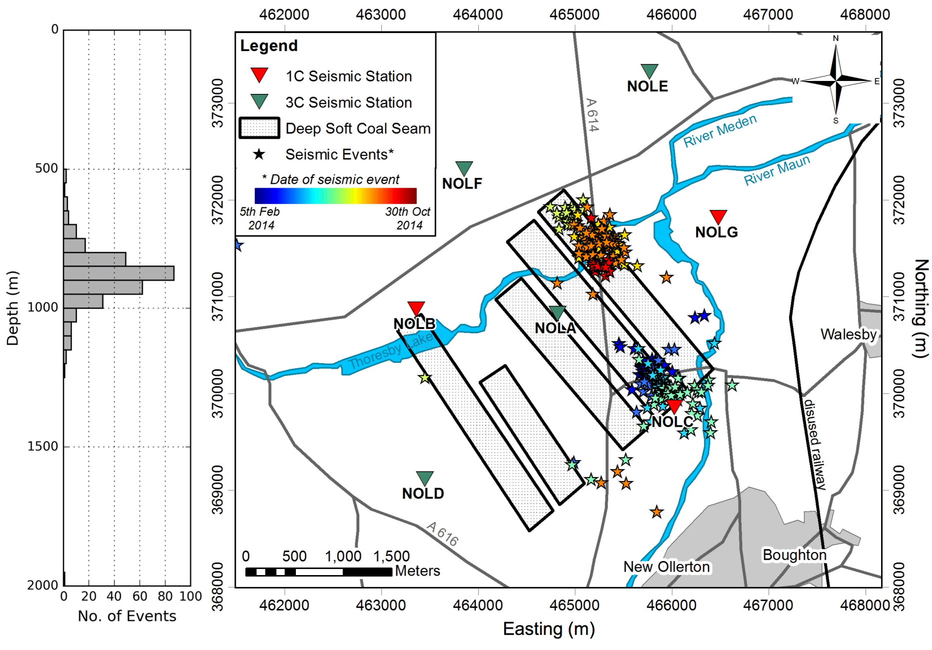

Fig. 1 Left – Depth distribution of seismic events at New Ollerton, UK. Right - Location of seismic network (inverted triangles), recorded seismic events (stars) and coal seam panels (black rectangles). Seismic events have been coloured coded to show temporal distribution. Position and depth distribution show a strong correlation with the excavated coal panels.

The 15 November 2017 Pohang Earthquake

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The Pohang area in southeastern Korea was shocked by a Mw 5.4 earthquake in 15 November 2017. It was the second largest earthquake and the most damaging earthquake during the instrumental seismic observation period in Korea. As soon as the Pohang earthquake occurred, there has been a considerable controversy over the potential for a causal connection between the destructive earthquake and industrial activities to develop enhanced geothermal system (EGS) due to its proximity (only a few hundred meters). EGS creates new fractures or expands existing fractures through the rock to improve the permeability of fluid by pumping high-pressure fluid into the rock. Some induced seismicity is inevitable and expected during the process. However, it is generally not possible to distinguish natural and induced earthquakes by their waveform characteristics. It is also difficult to assess the effect of EGS activity on seismicity. The Pohang earthquake sequence provided a unique opportunity to assess its causal relation with fluid injections. We noticed abnormal seismicity near the EGS site in 2017. A dense temporary seismic array has been installed and recorded the whole sequence of the Pohang earthquake including foreshocks, the mainshock, and aftershocks. Here, we show seismological observations suggest the M5.4 Pohang earthquake is 'almost certainly induced' by the EGS activity. Reviewed observations include (1) there were no noticeable earthquakes before the EGS activity, (2) micro-seismicity began after the completion of wells for the EGS reservoir creation at 4-5 km depths, (3) there are very high temporal correlations between micro-seismicity and fluid-injections for the geothermal reservoir creation, (4) there are high spatial correlations in locations and depths of earthquakes (foreshocks and the mainshock) and injection wells (Fig. 1), and (5) locations and depths of well-bottoms coincide with the location of the fault revealed by aftershock distributions. They also reveal well-bores for EGS are drilled to the fault zone and the fluids were injected directly into the fault zone. Immediate onsets of seismicity to fluid injections to create the EGS reservoir also suggest well-bores are drilled to the fault zone. The Pohang earthquake show very small amount of additional fluid may trigger large earthquakes in a critically stressed fault system.

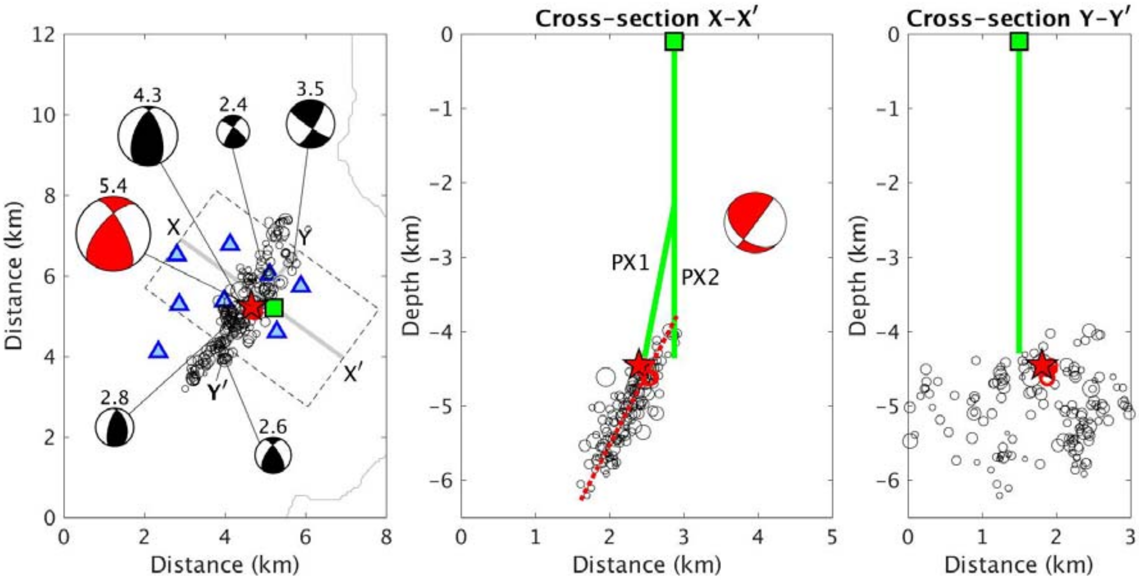

Fig. 1. Spatial distribution of epicenters and hypocenters of the 2017 Pohang earthquake sequence.

Abstracts Talks

Session 2

Social Aspects of Induced Seismicity

The Societal Role of Scientists in Induced Seismicity
Lessons Learned from Groningen (The Netherlands)

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Induced seismicity has in recent years become an issue of public concern in many countries around the world, in particular in relationship to hydrocarbon production, hydraulic fracturing and wastewater disposal. In the future, hazards emanating from induced seismicity will remain a matter of public concern, especially with further developments in e.g. geothermal energy production and carbon sequestration.

The primary cause of public concern is a fear of the unknown, because most of the people confronted with induced seismicity live in rather stable continental regions without any natural seismicity worthy of mention. This fear is, though, often out of proportion, not in the least because of the discourse used by environmentalists, protesting against the hydrocarbon industry, in recent years in particular against 'fracking' for shale gas extraction.

The issue, I would like to address in this contribution, concerns the practice of proper science communication with respect to the potential hazards related to induced seismicity. I would like to reflect on the societal role of the scientist in the communication efforts towards the public and policymakers that may be confronted with the issue of induced seismicity related to new geotechnical underground projects.

Based on my personal experiences and a proper analysis after five years involvement in the case of induced seismicity in the northern Dutch province of Groningen, I identified a number of examples that illustrate the failure of the scientific community in properly communicating, to policymakers and the general public, about the induced seismic hazards and risks caused by the gas extraction. Notwithstanding the fact that no one-size-fits-all solution for managing hazards and risks exists, I'm convinced that lessons can be learned from the Groningen case that can be inspirational for scientists involved in hazard and risk communication in other cases of induced seismicity.

The science communication failure in Groningen finds its origin in initial attempts of the operator to downplay the possible societal impact of induced earthquakes that may be felt by people or even cause damage. Remarkably, one still sees such attitude appearing in geothermal projects nowadays. In Groningen, this attitude left the scientific community off guard when an 'unexpectedly large' (M3.6) earthquake rattled the region in 2012. Ever since the scientific community has unsuccessfully tried to catch up with what is really going on in the local communities in Groningen. Moreover, scientific research has been, and still is, completely expert-led, focusing on technical and physical aspects of the induced seismicity. And finally, science communication has been a one-way transfer of scientific information, basically talking above the heads of the general public.

Another communication strategy is needed in geotechnical underground projects that potentially induce earthquakes. Such a strategy builds on a transparent and candid dialogue between scientists and public and policymakers involved, even in the preparatory stages of a project. Such dialogue should identify the matters of concern of the people that are potentially confronted with the consequences of induced seismicity. These matters of concern could subsequently even become drivers for bottom-up, community-led research, complementing expert-led research. Together with the people concerned, scientists should build a public science, of which the public can claim ownership, and the scientists guarantee the scientific validity. By strengthening the knowledge of the public and policymakers, scientists help the people involved to overcome their initial fear of the unknown, to properly assess the true hazard, and to take, if necessary, appropriate mitigation measures.

The Limits of Expert Knowledge as a Political Problem

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One of the most important and most difficult tasks of experts is to communicate the limits of their knowledge to politicians and the public. Experts who fail in this task fuel exaggerated expectations and attract scandalization. However, the way expert advice is organized and functions today in the political arena complicates communication about the limits of scientific knowledge in several respects. Thus, experts can find themselves in situations where they feel compelled to pass rather than to explain the limits of their knowledge. In my talk, I will analyze two scandals of 2009, where such situations appeared under different circumstances and with contrasting effects: the firing of David Nutt as chair of the advisory council on the misuse of drugs in Britain and the trial of the "L'Aquila seven" in Italy. The paper will also discuss possible solutions to the problem, as proposed in recent literature on the topic.

Fig. 1 For further reading (in German). Matthes & Seitz 2018.

All Shook Up: Rhetorics of Induced Seismicity

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"That was the biggest earthquake I've ever felt. Never want to experience that again."
--Cassie, tweeting about an induced earthquake in Oklahoma, 2017

This talk presents an analysis of the types of rhetoric people use to describe the effects of induced seismicity on their everyday experience. Drawing from historical and cultural analyses in the field of disaster studies, I argue that more attention should be paid to how individuals describe the experiences of living through earthquake events. The study of rhetoric allows us to understand the cultural rationales that operate for those living with induced seismicity, and highlight why they might conflict with the technical rationales offered by government and industry officials.

This talk analyzes published media interview excerpts conducted with individuals affected by induced seismicity in Oklahoma, USA, which has seen a dramatic increase in induced seismic events in the last ten years because of oil and gas operations. These individuals describe these seismic events in terms of attack—"a very large truck" hitting a building, or a "boom" like a bomb going off. They may also describe them in the terms of trauma, such as one survivor who said she didn't care what caused them, she "just wanted them to stop," or like the quote from the twitter user Cassie, who simply said she "never wanted to experience that again." Still others describe them in natural terms, as "waves" that just keep coming.

What do such metaphors and descriptions imply about the experience of these earthquakes? What do they mean for how we understand how people make sense of their world when things have literally been "shook up"? And by contrast, what does it mean when technical experts describe induced seismic events in terms of "rattles" and "swarms"? Or when they downplay the significance of such events, or focus solely on technical responses?

The work aims to fill two gaps in our understanding. First, induced seismic events are not the same as major natural disasters, such as naturally occurring earthquakes, like those that have impacted Chile, Nepal, Japan, and Haiti in recent years. Induced seismicity is frequently the result of industrial activities, and often occurs in economically developed nations. However, work on how people are affected by and attempt to recover from these earthquakes is of relevance to those trying to understand community responses to induced seismicity, especially in terms of trauma. Technical experts would benefit from understanding trauma-induced responses more clearly.

Second, much of the social science and humanities work on induced seismicity, particularly in the American context, has focused on tensions between the oil and gas industry, government officials, and communities affected by human-caused quakes. The emphasis of this work has often been on the stress, anxiety, and frayed trust experienced by communities who feel they have been misled by government and oil and gas industry officials. Power dynamics and the impacts of financial interests on the shaping of discourse are a central part of this story.

However, rhetorical analysis also allows us to identify the way cultural rationales—the sense-making individuals and communities do following a traumatic seismic event—reveal a set of facts and experiences that are no less true than technical facts. Government and industry officials, on the other hand, often use rhetorical strategies to de-emphasize trauma and lived experience. Instead, they may privilege a paradoxical mix of technical specificity and technical ambiguity, when strategically useful.

Where do energy and environmental benefits from EGS outweigh induced seismicity risk?

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Enhanced geothermal systems (EGS) harness thermal energy from the deep underground to produce renewable and low-carbon electricity and heat. The literature has repeatedly drawn attention to the dilemma of siting EGS projects in terms of induced seismicity and EGS profitability. On the one hand, siting EGS projects in remote areas, away from populated spaces and buildings, can reduce exposure and thus induced seismicity risk, but the waste heat from these projects often remains unused due to the absence of large heat consumers. On the other hand, heat sales, especially to a district heating network in densely populated areas, make EGS projects more economically viable and reduce CO_2 emissions. The induced seismicity risk is, however, higher.

Motivated by ambitious EGS targets and hence complex siting decisions in Switzerland, we use cost-benefit analysis (CBA) to quantify the trade-off of siting EGS of different capacities in remote or in densely populated areas. We conduct CBA from two perspectives: private and social CBA. Private CBA reflects the viewpoint of the EGS operator and thus includes private Net Present Value (NPV), internal rate of return (IRR), and levelized costs of electricity (LCOE). Social CBA (social) reflects costs and benefits to society as a whole, including damage risk due to induced seismicity, CO_2 savings, and heat and electricity benefits, and quantifies social NPV and benefit-to-cost ratio (B/C ratio). Among all parameters that could be varied for CBA, we put primary emphasis on the trade-off between benefits of producing electricity and supplying geothermal heat to residential buildings and avoiding CO_2 emissions from fossil fuel heating versus induced seismicity risk to the same residential buildings. For the case of Switzerland, we analyze 12 hypothetical scenarios combining different EGS capacity (water circulation rates of 50, 100, or 150 l/s) and siting (0, 1’000, 10’000, or 100’000 residents nearby). We model the EGS plant and its heat and electricity production in detail and couple it to a purposely developed model of induced seismicity hazard and risk that is adequate for first order-of-magnitude estimates, given the high uncertainties for induced seismicity.

Assuming a price of electricity that would make EGS investment in half of our scenarios worthwhile to investors, we show that large EGS (150 l/s) near large populations (10’000 or 100’000 residents), enabling high heat sales, are most profitable. The CBA from the social perspective shows that medium- or large-sized EGS (100 or 150 l/s) near some residents (1’000 or 10’000) are most beneficial due to reasonable heat sales and limited induced seismicity damage. Siting EGS in remote areas is less favorable, even if expected induced seismicity damage is zero.

Abstracts Talks

Session 3

Natural or Induced, and Beyond

Understanding the Pohang EGS reservoir and the need for advanced traffic light systems

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On November 15, 2017, a magnitude 5.4 earthquake occurred near a geothermal project under construction in Pohang, South Korea. Based on the information available and its own analysis of the situation, Geo-Energie Suisse (GES) decided to immediately inform the Government of the Canton Jura. The Government reacted on November 28, 2017, by asking Geo-Energie Suisse to provide a report on the Pohang events and their possible implications on the Haute-Sorne EGS project.

Therefore, based on information available through our participation in the DESTRESS project, we evaluated micro-seismicity and hydraulic data from the stimulation campaigns, geological well data, well logging data, information from borehole drilling and information on the regional stress field. Only by an integration of all this information, we were able to derive a plausible conceptual model for the basic understanding of the Pohang EGS reservoir and the probable triggering of the magnitude 5.4 earthquake.

The Pohang EGS project has had a well-defined traditional magnitude based traffic light system. However, our evaluation highlights the need for advanced traffic light systems taking into account the spatial distribution of seismicity and integrating continuously throughout all project stages information about fault structures. Such a procedure has been the basis for the permit by the authorities of the Canton Jura for the Haute-Sorne project and is also recommended by the “Good practice guide for managing Induced Seismicity in Deep Geothermal Energy Projects in Switzerland” published by the SED in 2017.

With our contribution we want to sensitize the geothermal community to understand seismic risk assessment as an accompanying process through all project stages and as a multidisciplinary task, and we want to stress the importance for an advanced traffic light system allowing a timely and qualitatively good localization of micro-seismic events, especially in the case that EGS projects are close or within fault structures.

Non-seismic reverberations of the M5.4 Pohang earthquake in Switzerland

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The Pohang M5.4 earthquake has affected permitting and regulatory oversight procedures as well as the perception of risk as perceived by key stakeholders involved in the exploitation of geothermal energy resources through enhanced/engineered geothermal systems (EGS). Switzerland has one permitted EGS project scheduled to commence construction in 2019 after years of legal proceedings. In the wake of the M5.4 Pohang earthquake and in line with the conditions of the permit, the permitting authority of the Canton of Jura has asked for an update of the management of the risks related to induced seismicity. The oversight of the project's compliance with regulatory guidelines (minimum 6-month baseline seismic monitoring; monitoring in real-time, automated and online with monitoring results to be published; obtaining high-quality local velocity models; adherence to state-of-the-art processes, methodologies and equipment) rests with the Swiss Seismological Service. Importantly, the M5.4 Pohang earthquake itself and the subsequent media coverage had a strong impact on perceptions of the wider stakeholder community. At the political level, parliamentarians in the Canton of Jura have used an alleged anthropogenic contribution to the M5.4 Pohang earthquake to argue for a complete ban on any deep geothermal energy exploration and development in the Canton. At the level of local and national interest groups that oppose EGS projects, the M5.4 Pohang earthquake serves to illustrate their point that risks cannot be controlled. Their point is underscored by quoting scientific publications. Scientists have contributed from very early on to the public discourse by sharing scientific information, analysis and interpretation. Yet, it is doubtful that the debate in the science and technology community around the M5.4 Pohang earthquake has matured sufficiently for us "to know the rest of the story", a quote attributable to the American broadcaster Paul Harvey. And, the "full story" is of course necessary to derive essential learnings.

Earthquakes close to anthropogenic activities – statistical discrimination without statistics ?

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On 15 November 2017 a Mw 5.5 earthquake occurred near the city Pohang, South Korea. The hypocenter was close to an Enhanced Geothermal Systems site, where high pressure hydraulic injections had been performed during the previous two years and only two month before the event. Is the closeness between the earthquake and the operation a proof of anthropogenic activity? A second Mw 5.5 event occurred ~30 km farther south about 14 month before. What if the Pohang event has the same origin as this "foreshock", and occurred only by chance close to the injection well?

The Pohang discrimination problem is typical for almost all extreme, and therefore rare and isolated earthquakes occurring close to human operations. Such single events cannot be evaluated by statistical means. However, similarly to climate and extreme event research we developed a probabilistic discrimination scheme to estimate the probability that a single earthquake has been triggered by human activity.

The discrimination is viewed as a process to evaluate the relative contributions of different causal factors to the triggering of a main shock, with an assignment of a statistical confidence. The two factors under consideration are a steady state tectonic background stressing rate, and the time dependent stress rate induced by human activity. The earthquake is attributed to the latter if the triggering is consistent with a physics-based process model of rate and state earthquake triggering, and less consistent with the tectonic background model.

The approach is simple and straightforward if parameters are reasonable well known. However, the attribution of probabilities for a causal relationship is not a unique procedure if parameter uncertainties are large. For instance, the statistical average of the best location in the model parameter space (maximum of the prior) has a tendency to become smaller with increasing uncertainties. Therefore, we suggest to include at least the maximum of the posterior distribution as a second attribution model, where the question is answered to which level of confidence a hypothesis is excluded.

We give examples where the discrimination has been applied and discuss its strength and weaknesses. The question how to weight the different statistical attribution models and how to communicate to society and lawyers is still open and should be answered by the scientific community.

Towards a More Robust and Transparent Simplified Scheme for the Discrimination of Induced from Natural Seismicity

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Regulators and operators will often need to make assessments of the likelihood of seismic activity within some proximity of industrial activities (such a hydrocarbon production or an enhanced geothermal system) having a causal relationship with the extraction or injection of fluids associated with the project. In order to inform operational decisions, as well as to communicate to the public and the media, such assessments may be required swiftly, which precludes the option of reliance on detailed modelling of fluid pressures and their interaction with geological faults. Simple schemes based on binary questions have been proposed, such as the widely used scheme of Davis and Frohlich (1993). While these proposals represent a valuable contribution to addressing this challenge, recent experience has highlighted some shortcomings and ambiguities associated with their application. This was particularly brought to light following a swarm of small earthquakes in southern England in 2018, which happened to occur in the same general area as some small oilfields. While the overwhelming view of UK scientists was that the events had no causal link to hydrocarbon production activities, and several people invoked the Davis-Frohlich criteria in support of this conclusion, the sole proponent for the view that these events were induced also made the claim that this was demonstrated by application of the same assessment scheme.

Prompted by this incongruous situation, we have developed a new framework that can still be applied swiftly but avoids the problems encountered with existing approach. This inevitably involves assigning numerical scores to responses to the questions that are posed; while there may be reservations about such subjectively-defined values, we believe that the advantages gained over qualitative schemes more than outweigh such concerns. The first benefit of assigning numerical scores is that these can be allowed to take positive or negative values, which means that questions can be asked not only along the lines of "does this evidence support an anthropogenic origin?" but also "does this evidence indicate that these events were tectonic earthquakes?" This allows a more balanced and robust assessment. Moreover, the scores can reflect the degree of certainty in the response, rather than just indicating "yes?" (which is then treated as if it were the same as "yes"). For example, in response to a question regarding whether there has been previous seismicity in the same area, -2 might be assigned if epicenters were present, -3 if hypocenters also matched the recent events, and -5 for re-located focal depths similar to the events under examination. Another advantage of the numerical scheme is that the absolute value of the scores can reflect the relative influence of the factors in determining whether or not the events were induced; in the Davis-Frohlich scheme, all questions effectively the same weight.

A score of zero may be assigned because the response is ambiguous in the light of the available data. In the existing scheme a question may remain unanswered either for this reason or simply because there are no data available to answer the question. This ambiguity is avoided in the new framework because the final score is reported as a proportion of the maximum score attainable with the data available for the assessment. This is reported together with a second number that expresses the proportion of data available to the full dataset that would ideally be used for the assessment. This second score may increase over time and qualifies the degree of reliance that can be assigned to the positive or negative score regarding the more likely origin of the observed seismicity.

The implementation of framework is illustrated by application to UK and other case histories using data available shortly after the events and subsequently updated with more complete datasets.

Human-induced or Natural? – Some Philosophical Considerations and Concepts

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Was the Pohang earthquake human-induced or was it a natural event? Questions like this have recently become virulent, not at least because their answers have serious and wide-ranging ethical and legal implications. However, before considering such implications it is important to engage in some theoretical and conceptual reflections. That is, before deciding about legal consequences, we must get clear on what counts as human-induced in the first place and what does not.

Without doubt, the impact of human intervention on our environment has increased in many respects. But how to distinguish what is manmade from "what would have happened anyway"? Did a certain intervention "induce" an event or merely "trigger" it? Is this distinction the same as that between a so-called necessary and a sufficient cause? Or what kind of reasoning and what kind of data count as good evidence for or against a hypothesis in this context? What counts as an explanation, as a prediction, etc.? These and similar questions are the topic of the present keynote.

I will provide a brief outline of some concepts and distinctions from philosophy of science which I take to be particularly relevant in the context of induced seismicity. Hence, I will say something on different types of scientific interferences, different types of causation, causal explanations, and different concepts of probability. Moreover, I will have a quick and critical look at the concept of a "paradigm shift" since this is something several seismologists have recently asked for with respect to their own discipline.

Notably, this talk will not result in a specific answer to the question raised at the beginning about the Pohang earthquake. (In fact, to provide such an answer would go far beyond the speaker's competences.) However, what the keynote aims at and hopefully opens up is a fruitful discourse among different disciplines. The common ground for such a discourse, I take it, is given by a broad interest in better understanding our own scientific practices. On the one hand, philosophy of science is exactly that discipline which tackles such general questions. On the other hand, philosophy of science is a purely reflective enterprise which depends crucially on learning about the actual practices and concerns from single disciplines. Hence, broad conceptual questions about induced seismicity seem to form both an interesting and an important area of research where science and philosophy can meet in a constructive (not a nitpicking) way.

Abstracts Talks

Session 4

Induced Seismicity in the Dutch Gas Fields

New developments in monitoring seismicity in the Groningen gas field

Bernard Dost[1], Elmer Ruigrok[1,2], Jesper Spetzler[1,3], Annemijn van Stiphout[2], Daniela Kuehn[4,5]

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The installation of a dense seismic network consisting of borehole sensors over the Groningen gas field, one of the largest onshore gas fields in the world, enabled the application of new techniques to improve imaging of the location and mechanism of seismicity in the field. Average station separation was reduced from 20 km to 5 km over the field. The aim of continued research is to reduce uncertainties, required to gain more insight in the earthquake generation process.

We will show new results from the application of the EDT location method combined with a 3D raytracer and a new (2017) version of the velocity model for Groningen. Seismicity follows closely existing faults on top of the reservoir. In addition we show results of moment tensor inversion using a full waveform probabilistic optimization method (Grond). Double couple solutions are in general in agreement with known fault characteristics. Some events show a large isotropic component. Finally, we will present a rupture analysis for the M 3.4, January 8, 2018 Zeerijp event

Physics-based, operational forecasting of productioninduced seismicity within the Groningen gas field

Stephen Bourne[1], Steve Oates[1], and Jan van Elk[2]

1 Shell Global Solutions International B.V., The Netherlands; **2** Nederlandse Aardolie Maatschappij B.V., The Netherlands

The possibility of fault reactivation under stresses induced by hydrocarbon recovery or CO2 storage operations represents a risk. Within the Groningen field this process induces earthquakes of sufficient frequency and magnitude to raise significant concern about the risks to building integrity and public safety. Mitigating these risks to acceptable levels requires a combination of gas production controls and building strengthening informed by a probabilistic seismic hazard and risk analysis (PSHRA). A critical element of PSHRA is a data-driven, physics-based, stochastic model to forecast the space, time, and size evolution of induced seismicity according to changing pore-pressure. This probabilistic seismological model represents intra-reservoir stress changes using a simple analytic poro-elastic thin-sheet model that incorporates the heterogeneous distribution of geometric and elastic properties observed via seismic and geodetic imaging respectively. Initial reactivations of the previously stable trans-reservoir fault systems are represented by Coulomb fault friction and the tail of an inferred initial stress probability distribution described in a general manner according to Extreme Threshold Theory (ETF) in statistics. Magnitudes are modelled with an exponential probability distribution where b-values vary as an inverse power-law (IPL) of Coulomb stress. Similarly, we include aftershocks as Epidemic Type Aftershock Sequences (ETAS). We infer the joint posterior distribution of the ETF, IPL and ETAS parameter values given the thin-sheet Coulomb stress model and the observed catalogue of Mw ≥ 1.5 events.

The performance of this seismological model in out-of-sample likelihood tests exceeds a wide range of alternatives from purely data-driven to purely physics-based models. We attribute this to model simplification which allows rapid computation of large ensembles of physically-possible model realizations for statistical optimization and forecasting to characterise the full range of variability and uncertainty. This operational seismological model enables Groningen PSHRA and the evaluaton of alternative control options to better inform future risk management decisions.

Insights from a closed-form solution for injection- and production-induced stresses in vertical displaced faults

Jan-Dirk Jansen[1] , Pranshu Singhal[1] and Femke Vossepoel[1]

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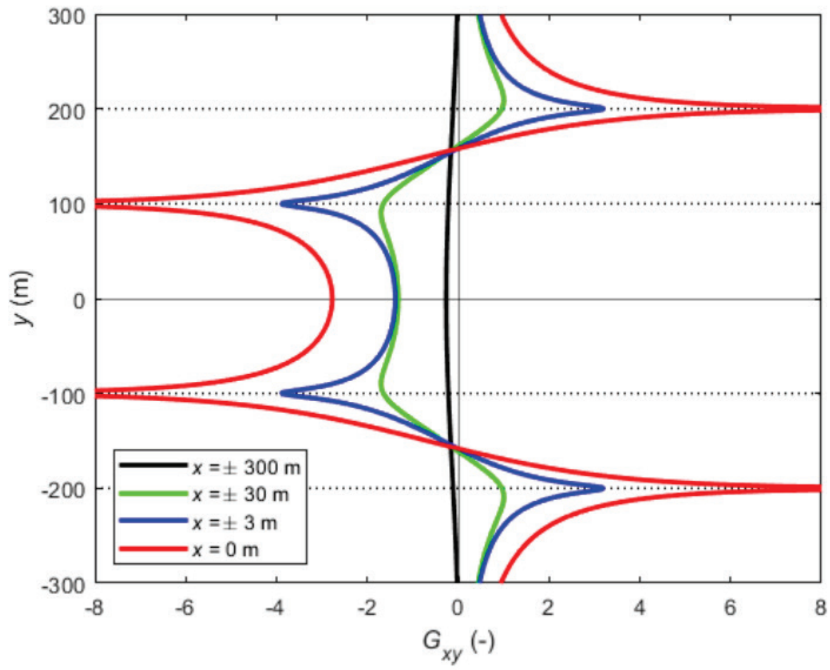
We present closed-form expressions for the elastic displacements, strains and stresses resulting from the injection into or production from a reservoir with displaced normal faults, which are a likely cause for induced seismicity. We use a fault model that has been stripped to the bare minimum while still maintaining the essential features. In particular we model a vertical fault in a homogeneous two-dimensional reservoir in an infinite domain using classic inclusion theory. We confirm and sharpen various findings from earlier numerical studies and we give expressions for several quantities such as seismic moment and excess shear stress. In particular the incremental shear stress in the fault can be expressed as $\sigma_{xy} = \ln\{[(y-a)^2(y+a)^2]/[(y-b)^2(y+b)^2]\}/2$ where $a=(h-t)/2$ and $b=(h+t)/2$ with h representing the reservoir height and t the fault throw. Application of these expressions to a simple model leads to several conclusions, including the insight that the development of infinitely large shear stresses in a displaced fault, at the internal and external reservoir/fault corners, implies that even the smallest amount of injection or production will result in some amount of slip. Another finding is that there is a marked difference between the shear stress patterns resulting from injection and production in a reservoir with a displaced fault. In both situations two slip patches emerge but at the start of injection slip occurs immediately in the overburden and underburden, whereas during production the slip remains inside the reservoir region.



Scaled shear stresses $G_{xy} = \sigma_{xy}/C$ at constant horizontal distance x from the fault.

A Framework for Training and Testing Induced Seismicity Forecasting Models: the Groningen Case Study

Sander Osinga[1], Thibault Candela[1], Dirk Kraaijpoel[1], Maarten Pluymaekers[2], Jan-Diederik van Wees[1,3]

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Since the start of gas production in 1963, over 2200 bcm of natural gas has been produced from the Groningen field. In the early 1990's, the first induced seismic events were recorded in the field. As of yet, over 300 events with local magnitudes ranging between 1.5 and 3.6 have been recorded in the Groningen field (Fig 1.). Although of relatively small magnitude, the damage and societal unrest caused by these events have led to the government's decision to drastically reduce production rates and shut down the field by 2030 with approximately 500 bcm of natural gas remaining in the field.

Gas production is widely believed to be the driver of the seismicity in the Groningen field and different models have been proposed to forecast seismicity based on forecasted gas production (e.g. Bourne and Oates, Dempsey and Suckale, Hagoort, Hettema). With another decade of gas production ahead, accurate forecasting of induced seismicity remains an important topic for hazard and risk assessment and the strengthening of buildings and infrastructure in the affected area.

We have conceptualized and developed a software framework in which different models for induced seismicity can be (1) trained with historical seismicity data, (2) tested against seismicity data that the model has not been trained on, (3) be compared in terms of forecasting performance to other models, (4) provide induced seismicity forecasts based on the full posterior distribution of forecasts.

This framework provides the means to quickly implement new models or combine already existing models. The implementation of any specific model is mostly unconstrained, as long as it predicts earthquake density on a grid in time and space (and optionally magnitudes). It allows model parameters to be defined as prior distributions and obtains a posterior distribution of model parameters by evaluating spatio-temporal(-magnitude) forecasts through a likelihood function. A range of statistical tests from CSEP (Collaboratory for the Study of Earthquake Predictability) are implemented to assess whether models are consistent with the observed data. Although the current focus is on the Groningen case, this framework is general in its formulation and can be used for case studies around the world.

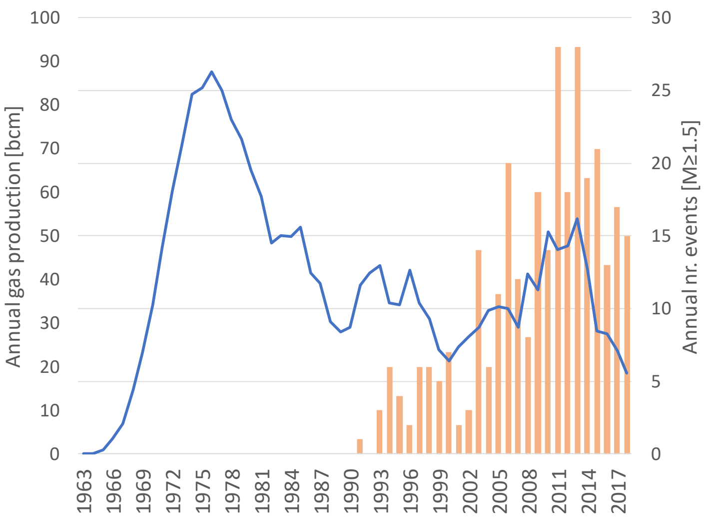

Fig. 1 Annual gas production from the Groningen gas field. The bars represent the number of earthquakes (M_L1.5 and higher).

Abstracts Talks

Session 5

Physics of Induced Earthquakes I

Laboratory Earthquake Precursors and Prediction

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Efforts to forecast and predict earthquakes are hampered by a lack of reliable lab and field observations. Even for the somewhat rare cases when changes in rock properties prior to failure (precursors) are observed reliably in the lab we generally lack sufficient information on the underlying physics to rationally extrapolate results to other conditions and, ultimately, tectonic faults. However, recent advances show: 1) clear and consistent precursors prior to earthquake-like failure in the lab and 2) that lab earthquakes can be predicted using machine learning. These works show that stick-slip failure events –the lab equivalent of earthquakes– are preceded by reduction in elastic wave speed across the fault, changes in elastic wave attenuation, and acoustic emission events (AE). The labquakes are preceded by a cascade of micro-failure events that radiate elastic energy in a manner that foretells catastrophic failure. These data exist for the complete spectrum of faulting modes observed in nature, from slow earthquakes to elastodynamic rupture. The results are sufficiently robust that it is possible to investigate the micromechanics of precursors and prediction in relation to frictional slip and fault constitutive properties.

Our results, and those of others, indicate that faults begin to weaken via creep slip and nucleation of microfractures that grow until the damaged region reaches a critical size. Remarkably, microfracture formation and growth can be tracked via AE with machine learning, which predicts the failure time and in some cases the magnitude of lab earthquakes. These predictions demonstrate a mapping between fault strength and statistical attributes of the fault zone elastic radiation that it is valid throughout the duration of the lab seismic cycle. Laboratory earthquakes can be predicted via supervised machine learning, for which an algorithm is trained using known events. This approach is successful for both dynamic rupture and slow slip events. Our works are now focused on questions such as: do micro-failure events define a geometric structure that evolves into catastrophic fault failure and if so can machine learning be used to identify similar features in tectonic fault zones? We are also addressing the use of unsupervised ML to identify precursors in the lab and on tectonic faults. Induced seismicity offers unique possibilities for testing the application of the lab results on tectonic faults, and my goal for this talk is to stimulate that discussion.

Fluid-injection and the mechanics of frictional stability of shale-bearing faults

Marco M. Scuderi[1] and Cristiano Collettini[1,2]

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Fluid overpressure is one of the primary mechanisms for triggering tectonic fault slip and human-induced seismicity. This mechanism is appealing because fluid overpressure reduces the effective normal stress, hence favoring fault reactivation. However, upon fault reactivation models of earthquake nucleation suggest that increased fluid pressure should favor stable sliding rather than dynamic failure. Here, we describe laboratory experiments on shale fault gouge, conducted in the double direct shear configuration in a true-triaxial machine. To characterize frictional stability and hydrological properties we performed three types of experiments: 1) stable sliding shear experiments to determine the material failure envelope and permeability; 2) velocity step experiments to determine the rate- and state-frictional properties; 3) creep experiments to study fault slip evolution with increasing pore fluid pressure. The shale gouge shows low frictional strength, μ=0.28, and permeability, $k \sim 10^{-19}m^2$ together with a velocity strengthening behavior indicative of aseismic slip. During fault pressurization, we document that upon failure slip velocity remains slow (i.e. v~200 μm/s), not approaching dynamic slip rates. We relate this fault slip behaviour to the interplay between the fault weakening induced by fluid pressurization, the strong rate-strengthening behaviour of shales, and the evolution of fault zone structure. Our data show that fault rheology and fault stability is controlled by the coupling between fluid pressure and rate- and state- friction parameters.

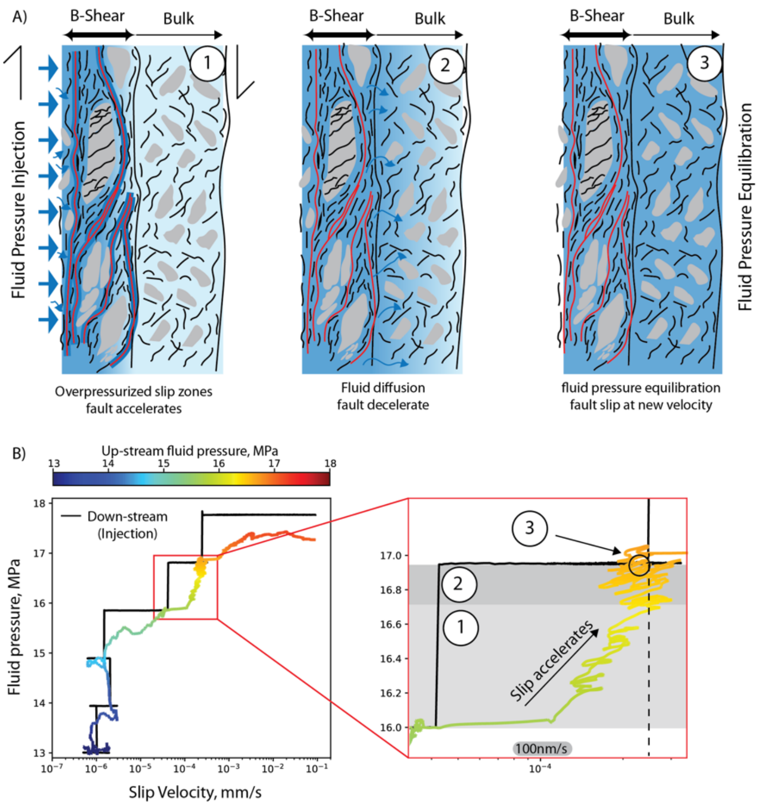

Fig. 1 A) conceptual micromechanical model describing the evolution of fault zone deformation for shale bearing fault gouge under fluid pressurization conditions. B) relation between fluid pressure and slip velocity. In black is reported the fluid pressure at injection and the fluid pressure at equilibrium is color coded by the pressure recorded at the up-stream intensifier (equilibration). The inset represents a typical fluid pressure step where all the three stages of the proposed model can be individuated, see text for details.

Seismic and Aseismic Response to Fluid Injection

Art McGarr and Andrew J. Barbour[1]

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The science of fluid-injection induced seismicity began more than 50 years ago when it became clear that the injection of liquid into formations at depth could cause earthquakes. Early investigations confirmed the idea that the earthquake activity was the result of fault reactivation due to the increase in pore pressure within the fault zone owing to injection activity. This finding raised numerous questions that remain unresolved, at least to some extent, including: 1) Is the maximum magnitude controlled by the injection activity or by tectonic factors? and 2) How much of an increase in pore pressure within a faulted seismogenic crust is required to cause earthquakes that are large enough to be felt or damaging?

McGarr and Barbour (Geophys. Res. Lett., 2018) argued that the upper bound on the deformation response to injection is given by

$$\sum M_0 \leq 2G\Delta V, \qquad (1)$$

where G is the shear modulus, ΔV is the total volume of injected liquid, and $\sum M_0$ is the moment release, which may be either seismic or aseismic. Equation (1) implies that the maximum moment earthquake in response to an injection activity is limited according to

$$M_0(\max) \leq 2G\Delta V \qquad (2)$$

which would be the case if the total moment release is due to a single earthquake; the earthquake sequence that included the M5.8 Pawnee, Oklahoma mainshock of 2016 is an example of this inasmuch as the main shock accounted for essentially all of the moment release and was consistent with equation (2) (McGarr and Barbour, 2018).

Although results from numerous case histories entailing injected volumes ranging from 1 ml up to more than 10 million m^3 are consistent with equations (1) and (2), there appears to be no consensus as to whether these equations can be considered useful upper bounds, partly because several outliers have been reported (Atkinson et al., Seism. Res. Lett., 2016; Diehl et al., J. Geophys. Res., 2018; Grigoli et al., Science, 2018). The alternate hypothesis is that magnitudes or moments of injection induced earthquakes are bounded in the same way as for natural earthquakes, for which the upper bounds tend to be higher (e.g., van der Elst et al., J. Geophys. Res., 2016). The question of how much pore pressure increase is required to reactivate a pre-existing fault prone to failure in the contemporaneous state of crustal stress is key to deciding whether equations (2) and (3) provide reliable limits inasmuch as these equations are based on the premise that the pore pressure increase required to induce fault slip is approximately the same as a seismic stress drop, of the order of 5 MPa, or so. On the one hand, direct measurements of pore pressure changes needed for fault reactivation (e.g., Raleigh et al., Science, 1976; Guglielmi et al., Science, 2015) support this premise, but, on the other hand, reported estimates based on hydrological modeling indicate that pore pressure increases several orders of magnitude lower are sufficient (e.g., Keranen et al., Science, 2014). If the direct measurements of pore pressure at depth are more reliable indicators of what is needed for fault reactivation, then it is likely that equations (1) and (2) are useful indicators of either the maximum moment release (seismic or aseismic) or the maximum seismic moment.

Induced seismic and aseismic slip in EGS reservoir: Case studies from Alsace, France

Jean Schmittbuhl[1], Olivier Lengliné[1], Léna Cauchie[1], François Cornet[1]

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The injection of fluid in the upper crust, notably for the development or exploitation of deep geothermal reservoirs, is often associated with the rise of induced seismicity. The occurrence of large seismic events during such operations needs to be reduced in order to preserve infrastructures and population nearby the injection site. However it is not clear how the injected fluid influences the characteristics of the induced events. Here we investigate the micro-earthquakes that occurred during one of the hydraulic stimulation in Soultz-sous-Forêts, France in 1993 and study the link between the injected fluid and the source properties of the induced earthquakes when aseismic slip is known to occur. We take advantage of the deep borehole accelerometers that were running during this experiment in the vicinity of the injection zone. We estimated the moments and radii of all recorded events using a spectral analysis and classified them into 663 repeating sequences. We show that events follow the typical scaling law between radius and moment but fluctuations of moments are important while the radius of the events remain similar. Repeating events on a given asperity with a well-defined radius, are shown to experience very different stress drops questioning the involved mechanisms. We also evidence an increase of the average event radius (and moments) over the course of the injection that follows the increase of the wellhead pressure but also an evolving access to preexisting fault zones of the reservoir (see Figure). Two different populations of events are characterized. These observations suggest that the fluid pressure has both a direct and an indirect control on the rupture size of the induced events. We also compare this behavior with those of other deep geothermal circulations in Northern Alsace, France (Soultz-sous-Forêts and Rittershoffen).

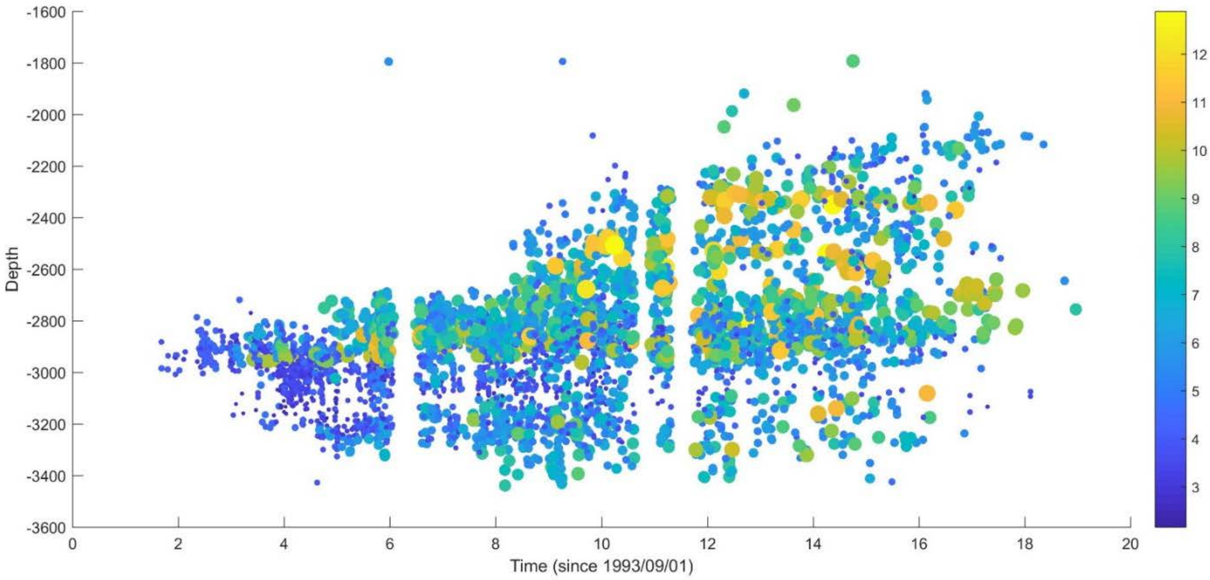

Figure 1: Time evolution (in day) of the source radius as a function of the depth during the 1993 stimulation of GPK1 (Soultz-sous-Forêts). The colorbar corresponds to the size of the radius in meter.

This work was supported by the EGS Alsace project funded by ADEME in the framework of the LabEx G-eau-thermie Profonde (Investissements d'Avenir).

Energy budget during laboratory earthquakes

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During an earthquake, part of the released elastic strain energy is dissipated within the slip zone by frictional and fracturing processes, the rest being radiated away via elastic waves. While frictional heating plays a key role in the energy budget of earthquakes, it could not be resolved by seismological data up to now. Here we investigate the dynamics of laboratory earthquakes by measuring frictional heat dissipated during the propagation of shear instabilities at stress conditions typical of seismogenic depths. We estimate the complete energy budget of earthquake rupture and demonstrate that the radiation efficiency increases with thermal-frictional weakening. Using carbon properties and Raman spectroscopy, we map spatial heat heterogeneities on the fault surface. We show that an increase in fault strength corresponds to a transition from a weak fault with multiple strong asperities and little overall radiation, to a highly radiative fault behaving as a single strong asperity.

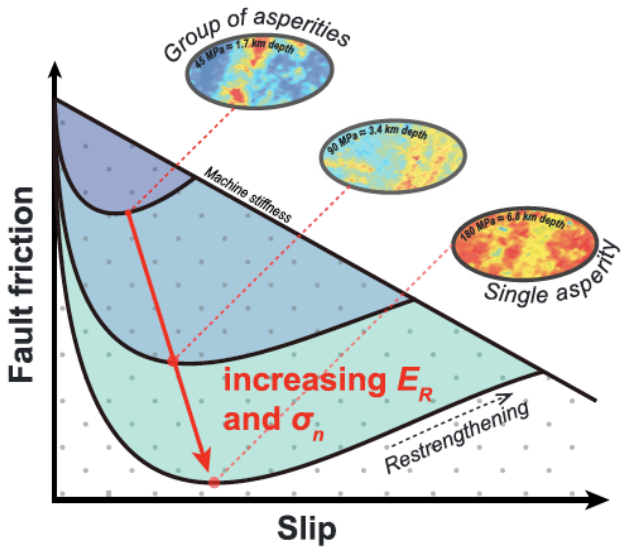

Fig. 1 Schematic of friction evolution by combining thermocouple temperature measurements, heat distribution from carbon method, and energy budget. With increasing confining pressure, the mechanical behavior evolves from that of a group of asperities to that of a single asperity. When the fault surface is entirely molten, heat generation by frictional processes and fracture energy become low and radiated energy increases. Colored regions correspond to the radiated energy, ER. From Aubry et al. GRL 2018

Abstracts Talks

Session 6

Physics of Induced Earthquakes II

Seismicity in Central Oklahoma shows features of reservoir-induced seismicity

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The recent surge of seismicity in Oklahoma and Kansas, U.S., is clearly related to the disposal of waste water. Starting in 2009, the number of earthquakes in the central U.S. strongly increased. The saline water is injected directly into the permeable Arbuckle aquifer which is in hydraulic communication with the underlying crystalline basement where most of the seismicity occurs. Many works have been published, focusing on the mechanisms linked to the seismicity. However, the assessment of governing physical processes remains a challenging task as they deviate from the ones leading to high-pressure reservoir stimulations. In Oklahoma, events occur in the basement, not in the injection formation and do not follow a classic time-distance behavior as obtained by the triggering front approach. Since the seismicity poses a risk to infrastructure and humans, a model capable of explaining the spatio-temporal evolution of the events is fundamental for seismic hazard mitigation and future research.

In this work, we consider the scenario of large-volume waste-water disposal, using the concept of seismicity induced by the filling of large surface reservoirs known as reservoir-induced seismicity, RIS. We developed a new model called underground reservoir-induced seismicity, URIS (Fig. 1a). To draw the connection between URIS and RIS, we assume that the strong increase of fluid injections into the Arbuckle formation corresponds to the filling of a large subsurface reservoir. This leads to pore pressure and stress changes in the poroelastic basement, caused by the added fluid mass in the injection formation, pore-fluid pressure diffusion in the basement, as well as poroelastic couplig effects.

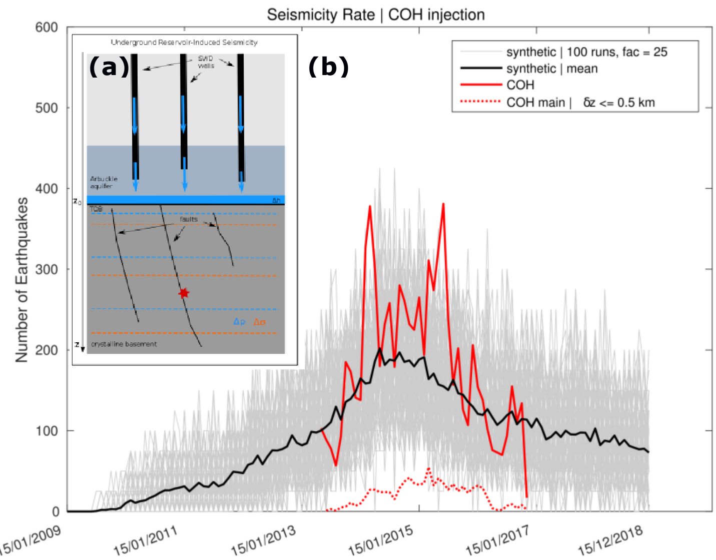

Fig. 1 (a) URIS conceptual model, (b) Synthetic seismicity rates for 100 realizations oft he criticality field (grey), the meand (black) and the observed rate in Central Oklahoma (red)

We derived modified analytic solutions based on analytic solutions for RIS. Additionally we developed a numerical finite element model. Using elastic and hydraulic parameters from literature, we analytically and numerically solved for pressure and stress changes. These were used to calculate the failure criterion stress for different tectonic stress regimes. With the obtained values for a strike slip regime, as prevalent in Oklahoma, and with the assumption that optimally oriented, critically stressed faults exist in the basement, synthetic events were generated.

Our studies demonstrate that the evolution of Central Oklahoma seismicity in time and space can be well explained by the URIS model: 1) Seismicity occurs below the injection formation in the crystalline basement, caused by the instantaneous elastic response of the rock matrix. 2) With time, events migrate to greater depths which might be attributable to pore-fluid pressure diffusion. 3) For declining injection volumes, observed seismicity rates are also captured by the URIS model (Fig. 1b).

Examining the distance decay and effects of active mitigation on injection induced seismicity

T.H.W. Goebel, X. Chen, J. Haffener, J. Walter, Z. Rosson, M. Weingarten & E.E. Brodsky

Induced earthquakes provide a rare opportunity to study the connection between stress perturbations and resulting seismic activity. Much of the recent increase in induced earthquakes has been linked to injection induced pressure changes on pre-stressed faults. This process requires a direct hydraulic connection between injection wells and faults, which is complicated for earthquakes at large distances and depths from injection wells. We study induced earthquake sequences associated with field-wide injection in central and northern Oklahoma and single injection wells in a global dataset. In northern Oklahoma densely spaced high-rate injection wells created a relatively cohesive zone of high-pressure perturbations between 0.1 and 1 MPa. This zone has a diameter of ~15 km and produced much seismicity potentially due to direct pressure effects. Outside of the high-pressure zone, we observed two remarkably detached, linear seismicity clusters at 30 to 50 km distance. Poroelastic models suggest that elastic stress changes in the rock matrix surpass direct fluid pressure effects at these distances, providing a plausible triggering mechanism at large distances.

Expanding on these observations in Oklahoma, we examine the spatial seismicity decay from 18 individual wells in the context of scientific, geothermal and wastewater injection. All sequences show a spatial gap between well locations and the location of highest seismicity density. Moreover, we observe two different types of decay behavior: 1) Sequences with a near-well density plateau followed by rapid decay. These sequences also show a systematic r~t^1/2 migration which is characteristic for a diffusive process. 2) 11 out of the 18 sequences show a gradual decay that extends out to ~10 km. The distant seismicity decays as r^-1.8+/-0.2 which is significantly slower that expected for pressure-driven seismicity and even slower than spatial aftershock decay. This gradual decay may be indicative of elastic stresses in the far-field of fluid injection wells which lack the commonly expected rapid spatial decay and gradual spatial-temporal expansion of fluid-pressure-driven induced seismicity clouds.

Beyond earthquakes associated with increasing injection rates, we examine the influence of targeted injection rate reductions after notable mainshocks on ensuing aftershock sequences. In comparing aftershock productivity between California and Oklahoma up to magnitude ~6, we find similar power-law scaling behavior between mainshock magnitude and average number of aftershocks with an exponent close to 1. However, several events above M4.4 in Oklahoma appear significantly deficient in number of aftershocks compared to the overall trend. All of the mainshock with low aftershock productivity also sparked rapid mitigation in form of reduced injection rates. We quantify the expected poroelastic stress perturbations and find stresses to be lowered by 10s to 100s kPa. The observations and modeling results suggest that targeted injection rate decrease may lower fault stresses below triggering stresses from preceding mainshocks.

Our results indicate that both fluid pressure and elastic stress changes can play a significant role in triggering deep and distant earthquakes by fluid injection and should be considered for seismic hazard assessment beyond the targeted reservoir.

Connecting physics-based models of natural and induced seismicity

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Injection-induced seismicity is a hazard of increasing concern in the energy industry, but also an opportunity to gain fundamental insights on earthquake processes in general and on the role of fluids in crustal mechanics. Provocative as this may sound, induced earthquakes are the closest we currently have to a natural-scale earthquake physics experiment. By exploiting common features of anthropogenic and natural earthquakes we can try to achieve insight on the latter from observations of the former. In turn, a body of concepts and models developed to understand natural earthquakes may be exploited to advance our understanding of induced earthquakes and their practical risk management. In particular, in both contexts rupture nucleation can be driven by a concentrated load: induced earthquakes can start in a confined area of a fault that has been weakened by increased fluid-pressure, whereas natural earthquakes can nucleate along the base of the seismogenic zone where stresses are concentrated due to deeper steady creep. Also, in both contexts ruptures can develop elongated shapes (large aspect ratio) due to vertical confinement: by the finite seismogenic depth or heterogeneous fault stresses in natural earthquakes, and by reservoir thickness or material layering in injection-induced earthquakes. Moreover, an interplay between seismic and aseismic slip can be involved in the genesis of both natural and induced earthquakes. Here, we review theoretical and simulation results for ruptures nucleated by localized loads, ruptures with elongated shape, and interacting seismic and aseismic slip. We discuss the potential implications of these models on induced seismicity.

On a fault broadly pre-stressed by long-term loading, an earthquake nucleated at a localized stress perturbation can grow dynamically beyond the perturbed area. Depending on the background prestress, the rupture can be either self-arrested (stop spontaneously) or runaway (stop only when it reaches the ends of the fault). Theoretical estimates, validated by simulations, of the size of self-arrested ruptures as a function of the size and amplitude of the stress perturbation, applied to various scenarios of induced seismicity, yield a non-linear relation between the seismic moment of the largest arrested earthquakes and the net injected volume. The relation is consistent with maximum magnitudes of induced earthquakes observed across a wide range of injected volumes, from laboratory to field scales. The result suggests that most injection-induced events so far have been self-arrested ruptures, and a few notable cases have been runaway ruptures.

The model features a tendency for larger magnitude earthquakes to be induced later during injection. This tendency is also found in rate-and-state models of earthquake sequences and may be observable in properly declustered catalogs. If the stress perturbation is elongated, the model predicts that in some situations a runaway rupture can be triggered without substantial foreshock activity, which could be challenging for Traffic Light Systems. Efforts to model underground field experiments of injection-induced slip demonstrate the challenges to anticipate the partitioning between seismic and aseismic slip based on in situ monitoring.

Applied to natural earthquakes nucleating near transitions between locked and creeping parts of a fault, the models produce accelerating moment release by intermediate-size earthquakes, foreshocks and slow slip. They also provide insight on supercycles, in which intermediate-size earthquake confined near the bottom of the seismogenic zone occur in between mega-earthquakes breaking the whole seismogenic width. The process of nucleation at the edges of seismically coupled zones contributes to the observation that mature faults operate at low average fault stress (low long-term apparent friction).

On the nature of induced seismicity: control from pore pressure distribution

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An increase in pore pressure along crustal fault is known to contribute to earthquake nucleation. From a theoretical point of view, faults are expected to reactivate when the effective friction coefficient, which increases with increasing fluid pressure, achieves the static friction of the fault. However, while the static reactivation of the fault is well established, the influence of the state of stress and of the pore pressure level on the nature of the induced seismicity remains poorly constrained.

Here, we conducted laboratory injection experiments on saw-cut sample of andesite coming from geothermal reservoirs. Fluids were injected directly along the fault through a borehole located at a fault edge, and fluid pressure was continuously measured during injection at the two edges of the fault. In addition to regular mechanical measurements and acoustic emissions monitoring, we used eight strain gages located at different along the fault to monitor the onset of fault reactivation and the propagation of dynamic instabilities.

Injections were conducted at three different effective confining pressure (30, 60 and 95 MPa with an initial pore pressure of 10 MPa), and along fault loaded at 90 percent of the peak shear stress. Independently to the confining pressure, injections induced all dynamic instabilities, episodic slow slip and stable slip events. Our experimental results highlight that dynamic instabilities rupturing the entire fault occur when only a small portion of the fault is affected by the fluid pressure perturbation. In these conditions, a slip front propagates far behind the fluid pressure front. When the slip front outgrows the fault, dynamic instability occurs, inducing fault dilatancy and shear-induced fluid flow. Increasing cumulative slip leads to the progressive homogenization of the fluid pressure along the fault. This homogenization promotes the transition from dynamic instabilities to episodic slow slip events, and to stable reactivation when the fluid pressure is almost homogeneous along the entire fault. Our experimental results are supported by numerical modelling coupling Dieterich-Ruina rate-and-state friction law and poroelastic interaction. Our results suggest that the distribution of the fluid pressure at the onset of the instability, and its degree of heterogeneity, could control the nature of the induced-seismicity.

Seismic rupture caused by merging of two slip patches

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The seismic events recorded in the depleting Groningen gas field in The Netherlands are mapped on known fault with increasing confidence. The Groningen field is in a normally stressed environment where the reservoir offset is less than half the reservoir thickness over more than 80% of the length of known faults (Figure 1a). The offset of the depleted reservoir causes a concentration of shear stress at the top of the hanging wall and at the bottom of the foot wall reservoir. Fault reactivation and the development of aseismic slip patches is expected to start at these locations (Figure 1b). Aseismic slip patches may become seismic if their length exceeds the critical slip length L_c as defined by Uenishi and Rice (2003) when using a linear fault slip-weakening relationship. Typically, this occurs at the most shallow aseismic slip patch at the top of the hanging wall.

Two cases with the same reservoir-fault configuration are presented in which seismic rupture occurs by merging of two a-seismic slip patches. In the first case, slip patch 1 and slip patch 2 develop a-seismically with increasing reservoir depletion, until they merge at elevated reservoir depletion pressure (Figure 1b/c). The residual friction coefficient is reached before the size of the slip patches reaches the critical size L_c. This suppresses seismic rupture. Instead, seismic rupture occurs at elevated depletion pressure when the a-seismic slip patches are about to merge. In a second case, with slightly lower residual friction coefficient, merging of slip patch 1 and 2 is preceded by a relatively small seismic rupture at slip patch 1. In this case, the critical slip length *is* reached at slip patch 1 before the residual friction coefficient is reached. However, rupture is arrested before merging with slip patch 2 occurs. Incremental reservoir depletion is required cause seismic merging of the two slip patches.

The two case demonstrate that seismic rupture may occur by coalescence of previously seismic or a-seismic slip patches. It is found that merging of two slip patches tends to cause larger seismic events compared to seismic rupture of a single a-seismic slip patch. It is shown how the parameters of a linear slip-weakening relationship influence the occurrence of the type of seismic rupture, and at what depletion level.

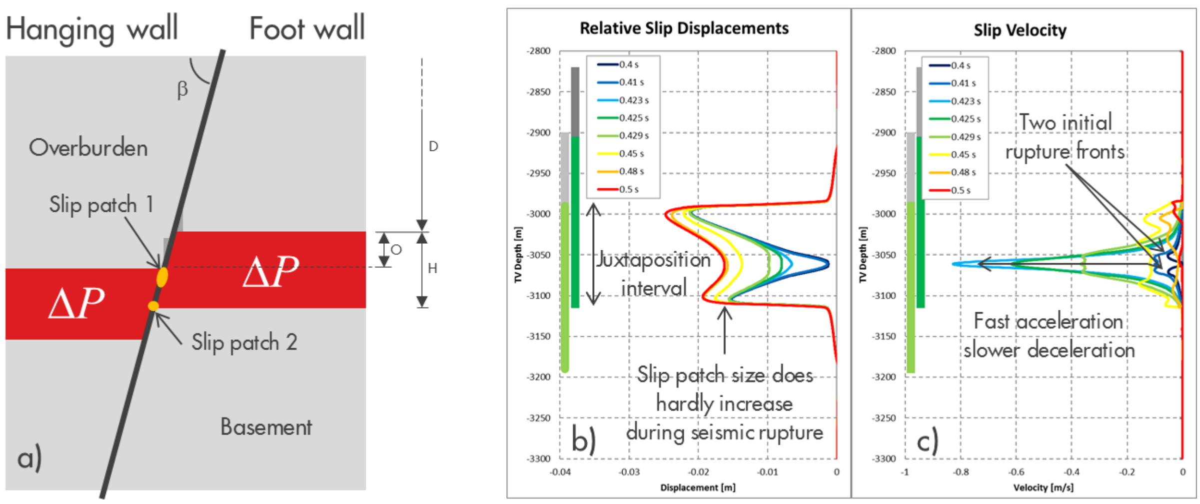

Figure 1 a) Typical reservoir-fault configuration in the Groningen field, b) The Relative Slip Displacement, and b) the relative slip velocity as a function of depth along the fault plane at various moments during the merging of two aseismic slip patches in a depleting reservoir with offset.

Uenishi, K. and Rice, J. R. (2003), Universal nucleation length for slip-weakening rupture instability under nonuniform fault loading, J. Geophys. Res., 108(B1), 2042, doi:10.1029/2001JB00168.

Abstracts Talks

Session 7

Modelling Induced Seismicity

Hydroshearing and permeability enhancement: Revisiting a fracture zone stimulation at Fenton Hill

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In this study, we analyze a deep hydraulic stimulation of a fracture zone that was conducted as part of the classical Fenton Hill Hot Dry Rock Program in the 1970s. At the time, it was suggested that a pre-existing fracture or multiple fractures within the fracture zone were jacked open aseismically by injection-induced increase in pressure. In this study, we analyze the same stimulation experiment, but investigate the possibility of an alternative mechanism of aseismic shear reactivation of pre-existing fractures.

We conduct modeling that accounts for both jacking (or elastic-fracture opening) and shear-slip dilation and demonstrate that injection-induced shear reactivation (or hydroshearing) could have occurred simultaneously with seismic events of magnitudes lower than what can be felt by humans. In fact, simulations considering shear reactivation seem to better match observed fluid recovery after multiple injection cycles. Shear reactivation and shear dilation results in locked-open fractures, especially near the injection well that provides permeability enabling higher flow recovery. We then investigate the sensitivity of the proposed model by varying some of the critical parameters such as maximum aperture, dilation angle, as well as fracture density.

Interestingly, none of the simulated cases resulted in a large event that could have been felt by humans, but did result in a cumulative seismic magnitude of less than 1 for each given stimulation step. These results suggest that a permanent irreversible permeability increase of several orders of magnitude can be obtained by hydroshearing in a "seismically" safe manner.

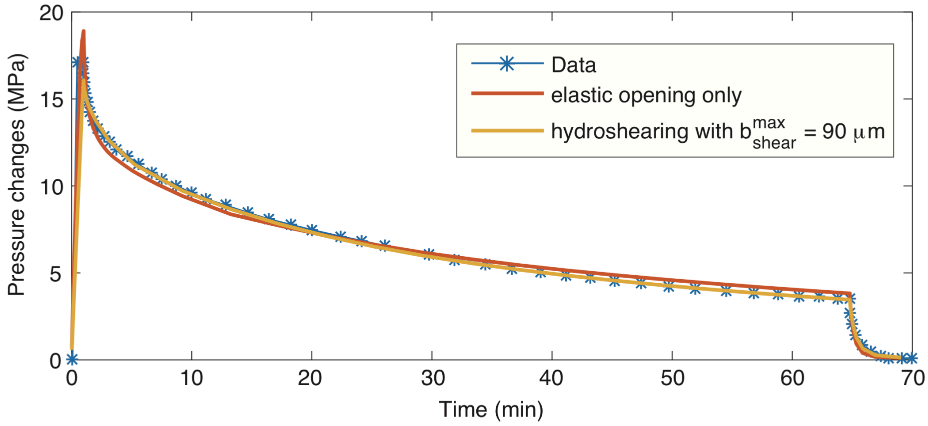

Fig. 1 Comparison of elastic opening only model (red line) and hydroshearing model with 90 μm maximum aperture (yellow line) with data from Fenton Hill, Test 1 (blue line).

Multi-physics earthquake simulations on complex fault networks across scales

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Earthquakes are highly non-linear multi-scale problems, encapsulating the geometry and rheology of propagating shear fractures that render the Earth's crust on a variety of length-scales. Numerical models solving for the non-linear interaction of seismic wave propagation and frictional failure shed light on the dynamics, and severity, of earthquake behaviour. Using modern numerical methods and hardware specific software optimisation such dynamic rupture scenarios can account for increasingly complex physics on and off faults motivating their application to reservoir scales towards physics-based seismic hazard assessment in the joint KAUST-LMU "FRAGEN" project.

Recent large-scale earthquake scenarios aim to understand the physical conditions that allow rupture cascades on complex fault systems. A "reloaded" scenario of the 1992 Mw7.3 Landers, California event (Wollherr et al., 2018, https://eartharxiv.org/kh6j9/) reveals complex interplay of triggering and branching rupture transfer mechanisms, geometric fault complexity, initial regional stress, viscoelastic attenuation, and off-fault plasticity. Modeling the arguably most complex rupture observed to date, the 2016 Mw7.8 Kaikōura, New Zealand earthquake (Fig. 1, Ulrich et al., 2018) provides insights on the mechanical viability of a complex rupture cascade linking the crustal fault system only when operating at low apparent friction due to over-pressurised fluids, low dynamic friction and stress concentrations induced by deep fault creep.

Fault networks at geo-reservoir scales are inherently geometrically complex; the dynamic stress released during the rupture process interacts with multiple adjacent fractures and 3D Earth structure acting as interdependent reinforcing and inhibiting factors for rupture cascading. We aim to explore the richness of the dynamic response of such a geo-reservoir for the example of the 2017 Pohang ML5.4 earthquake, specifically focusing on geometrical and structural complexity, as a potentially segmented rupture plane and mixed faulting mechanisms (Kim et al., 2018).

Our models use the open-source software SeisSol (www.seissol.org) that combines high-order accuracy in space and time (minimal dispersion errors) with unstructured tetrahedral meshes to account for complex geometries. The achieved degree of realism and accuracy is enabled by computational optimisations targeting strong scalability on many-core CPUs and a ten-fold speedup owing to an efficient local time-stepping algorithm (Uphoff et al., SC'17).

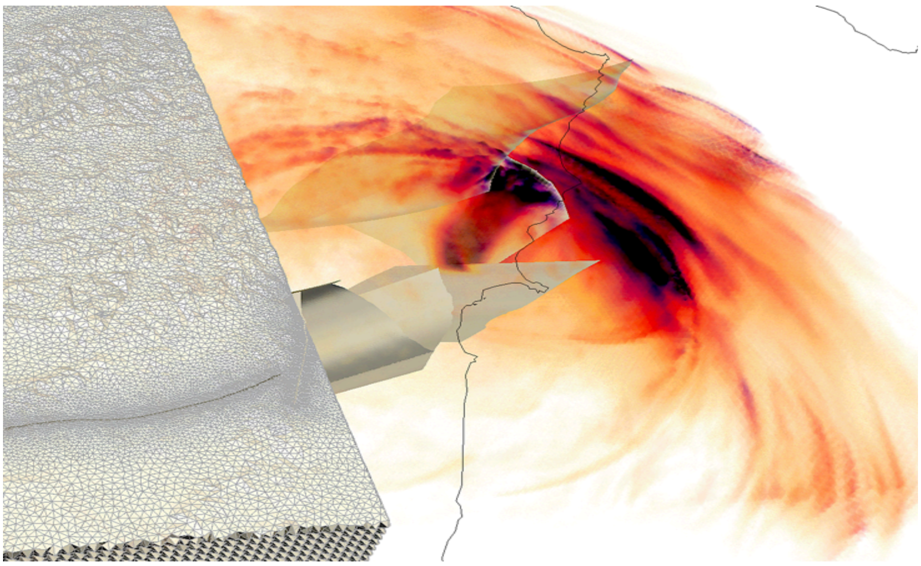

Fig. 1 Physics-based rupture model of the 2016 Kaikōura, New Zealand earthquake. 3D dynamic rupture cascade across eight weak crustal fault segments interacting non-linearly with off-fault plasticity and wave propagation throughout subsurface structure and topography. Snapshot of the seismic wavefield (Ulrich, et al., 2018, accepted at Nature Communications, **https://eartharxiv.org/aed4b/**).

Induced seismicity during the St. Gallen deep geothermal project, Switzerland: insights from numerical modeling

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The St. Gallen deep geothermal project conducted in 2013 targeted a fractured carbonate reservoir in about 4 km depth. After an injectivity test and two acid jobs that induced only minor seismicity, the operators were forced to inject water and heavy mud to fight a gas kick. These well control measures induced multiple earthquakes including a M_L 3.5 event that was felt by the nearby living population. The seismicity in St. Gallen is remarkable in two ways: (i) Despite the almost immediate seismic response, the events are all located hundreds of meters away and deeper relative to the open-hole section of the borehole (Fig. 1), and (ii) the spatio-temporal evolution of the main sequence is complex, likely because of the potential multi-phase fluid interaction during the gas kick and the subsequent injection. Recent studies have suggested that the seismicity on distant fault planes may only be explained by changes in poroelastic stress, since the direct influence of pore pressure is too slow to account for an immediate seismic response. In St. Gallen however, the fractured nature of the reservoir and the possible location of the gas source raise the question whether there may exist a hydraulic connection to greater depth (Fig. 1). The geothermal project was later suspended because of insufficient reservoir permeability and a too high gas content as would be required to maintain flow rates adequate for hydrothermal utilization. Still, the project represents an interesting case to study possible physical mechanisms that lead to induced seismicity.

Here, we use TOUGH2-based numerical simulators to test two endmember models that may explain the seismicity: (i) A model with a distinct fracture zone that acts as a hydraulic conduit between the borehole and the reactivated fault, and (ii) a model without a connection where stress changes on the fault are purely governed by poroelasticity. The results show that the pore pressure front may propagate fast enough if a highly permeable fracture zone is present. Stress changes on the fault may be 2 to 3 orders of magnitude larger, while in case of no connection, the stress changes are much less than 1 bar, which implies a highly critically stressed fault. We use the first model to simulate the gas kick assuming an overpressurized gas source at depth. We obtain a reasonable timing and strength of the gas kick at the borehole, which supports the hypothesis of a hydraulic connection to greater depth.

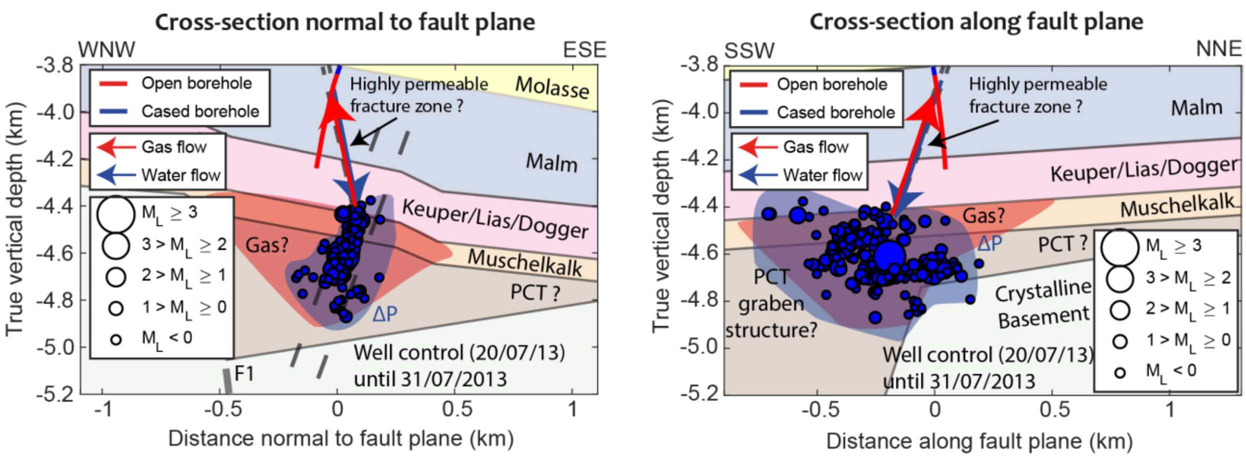

Fig. 1 Conceptual model of the gas kick and the well control measures: the seismicity is either induced directly by pore pressure increase through a fracture zone or due to poroelastic stress change without any hydraulic connection. The gas kick suggests a hydraulic connection to a source at greater depth.

Inferring in situ Reservoir Pressure From Induced Earthquakes

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Knowledge of *in situ* hydraulic pressure is of primary importance for managing geothermal and hydrocarbon reservoirs. Reservoir models typically rely on a limited number of pressure measurements at wellbore locations, whereas hydraulic pressure away from wells is a modelled parameter and inherently ambiguous.

We have developed a new approach to infer *in situ* reservoir pore pressure from induced seismicity observations. The approach is based on fracture patches slipping repeatedly during fluid injection operations. Sequences of repeated slip bear the information of stress-strength conditions being in exact equilibrium at the time of seismic activation. The co-seismic stress changes associated with each individual slip can be deduced from seismogram recordings. Therefore, the amount of additional stress required to re-activate the fracture, the stress deficit, becomes a known parameter. We resolve to what extend pore pressure compensates the stress deficit while explicitly accounting for inter-earthquake stress interferences.

We demonstrate the performance of the proposed methodology using a data set of seismicity induced during hydraulic stimulation of a geothermal reservoir in the Cooper Basin, Australia. The spatio-temporal evolution of *in situ* pressure is resolved over the entire reservoir. Despite some data scattering, we observe the following: (i) the maximum pore pressure is obtained near the injection well and tends to decrease with distance from the well; (ii) the magnitude of pore pressure is consistent with the injection pressure; (iii) the temporal evolution of pressure increase generally follows the signature of the injection pressure; (iv) the delay of the pressure signal increases with distance from the injection well; (v) the reservoir is dominated by (previously unknown) pressure channels. The latter observation is crucial for the development strategy of a geothermal reservoir in order to reach economic scale.

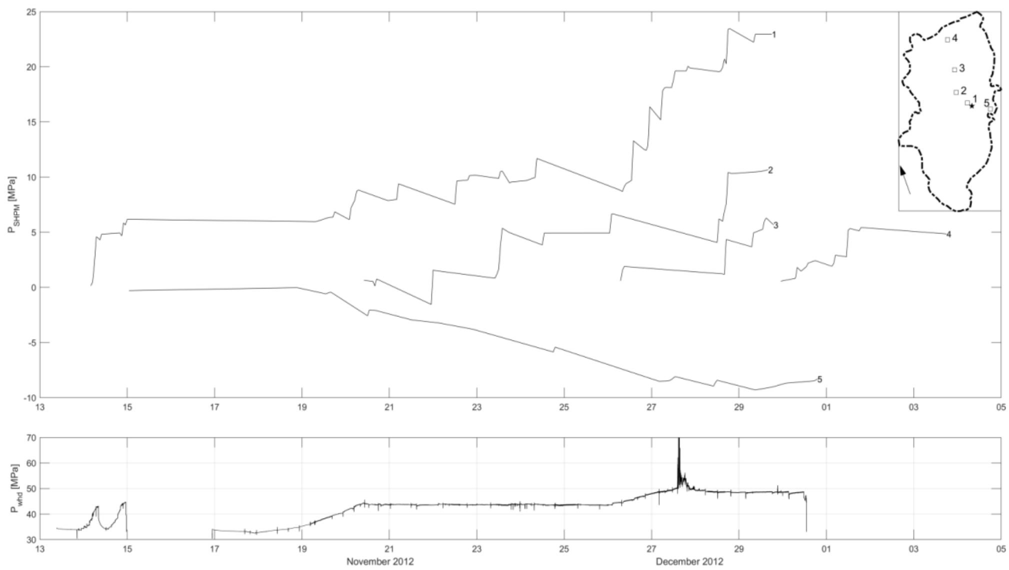

Fig. 1 Temporal evolution of fluid pressure determined from repeated slip at different locations in the reservoir (top) and well head pressure during stimulation (bottom).

Abstracts Talks

Session 8

Deep Underground Laboratories

Induced Seismicity and CCS at Scale: Understanding Caprock Integrity Impacts Based on Mesoscale Experiments

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Understanding fault reactivation as a result of subsurface fluid injection is critical in geologic carbon capture and sequestration (CCS) projects because it may result in enhanced fault permeability, potentially inducing CO_2 leakage from the injection zone through the overlying caprock layer, often a low-permeability shale. This is in particular true when considering future CCS scenarios where CO_2 storage is implemented at the grand scale necessary to be effective as a climate mitigation methodology. Faults are complex three-dimensional features that may consist of multiple cores where gouge may accommodate most of the strain surrounded by fractured damage zones made of secondary faults or fractures, some of them displaying significantly different orientations compared to the average orientation of the fault zone. In hard rocks, fault zone models are widely accepted that associate gouge or core zones with very low permeability while assuming relatively higher permeability for the damage zones. Fault zones in shales are different due to their high clay content, often displaying very low permeability both in the core *and* damage zones similar to the low permeability of the intact rock. Predicting the short-term and long-term evolution of such initially low-permeability fault zones during and in particular after CO_2 injection is a key challenge for large-scale CO_2 sequestration, and a very complex one. This is due to (1) the complexity of fault slip processes in heterogeneous media where injection pressure triggers stress and strain variations that can locally create and destroy porosity and permeability, (2) the complex sealing and healing behavior of clay-based fault materials driving the long-term permeability evolution, and (3) the difficulty of measuring relevant properties and processes in situ and at scale at sufficient spatial and temporal resolution. As a result, constitutive laws relating permeability changes with evolving fault structure, stress, and strain remain poorly constrained.

This presentation introduces a controlled fault stimulation experiment conducted in 2015 in a clay formation in the Mont Terri Underground Research Laboratory (Switzerland), which addresses some of the key questions discussed above: whether reactivation of a fault in a clay formation typical of a caprock layer creates a permeable flow path in previously low-permeability rock, and how the permeability of this path will evolve as a function of time and as repeated fault injections are conducted in sequence. The Mont Terri fault zone, a perfect analog to a minor fault zone that would hardly be detectable from surface seismic surveys during the initial characterization of a CCS site, is a few meters thick and, under the ambient stress state, has a very low static permeability (on the order of 10^{-13} m/s). To estimate the potential of a dynamic permeability variation of the fault upon reactivation, we actively repeated high-pressure fluid injections cycles about 30 minutes long intercalated with rest periods of the same duration. Stimulations were conducted between two packed-off sections of two vertical boreholes intersecting the fault and 3 m spaced. In each section, the three-component displacement of the fault, the pore pressure, and the injection flowrate were continuously monitored at a 1 kHz sampling frequency. A third borehole was used to synchronously monitor induced seismicity with two three components accelerometers respectively set in the hanging wall and in the footwall of the fault, while three more boreholes were used to monitor the pore pressures in the intact hanging wall close to the fault zone.

Our presentation discusses results from the meso-scale experiment at Mont Terri in the context of understanding caprock integrity and evaluating the feasibility of CCS at scale. We explore what is known today and what research gaps still exist, and we introduce a planned follow-up experiment at Mont Terri that specifically looks into long-term leakage behavior in the reactivated fault. We also present some ongoing work using our experimental findings in quantitative risk assessment studies for CCS projects.

Seismic Monitoring at the Utah Frontier Observatory for Research in Geothermal Energy

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The U.S. Department of Energy is building a Frontier Observatory for Research in Geothermal Energy (FORGE) in the eastern Basin and Range, ~340 km south of Salt Lake City, Utah. "FORGE's mission is to enable cutting-edge research and drilling and technology testing, as well as to allow scientists to identify a replicable, commercial pathway to enhanced geothermal systems." The plan for the facility is to drill two highly deviated wells into granitic rock where temperatures exceed ~175 ºC. The two wells will be hydraulically stimulated to create an Enhanced Geothermal System (EGS) reservoir. Seismic monitoring is required for: 1) seismic hazard and risk assessment and mitigation; and 2) monitoring of fracture growth and reservoir development. Pre-development seismic monitoring has found that the immediate footprint of the FORGE facility is aseismic—no earthquakes have been detected in this area since at least 1981. To the east of the FORGE site, in the Mineral Mountains, there is a region of small magnitude (M<2.5) natural tectonic activity and possibly seismicity related to injection at the Roosevelt Hot Springs geothermal system.

In the spring of 2019, well 58-32, a 2297 m vertical well drilled in 2017, will be stimulated to inform the future seismic monitoring system. The stimulations will be performed below 1920 m in rocks with temperatures between 175 and 199 ^{o}C. They will include the firing of check shots, injection into the open hole section of the well below 2256 m and hydraulic stimulation of the granite behind casing at shallower depth. For hazard related seismic monitoring, a local array of broadband seismometers has been installed. In the current configuration, the magnitude of completeness for the area approaches M 0. Fracture growth for the small-scale injection tests will be monitored using a Distributed Acoustic Sensing (DAS) fiber optic cable and a downhole string of three-component sondes deployed in an ~1000 m deep well. The seismic signals from these tests will be used to measure detection levels upward from the top of the granite basement and to characterize the attenuation structure in the overlying alluvial deposits. In addition, a dense array of three-component geophones will be installed on the surface to analyze the detection threshold and to characterize the local velocity structure. Using the data collected during this experiment, a borehole seismic monitoring program will be designed that will be deployed in advance of the drilling and stimulation of the deep production and injection wells.

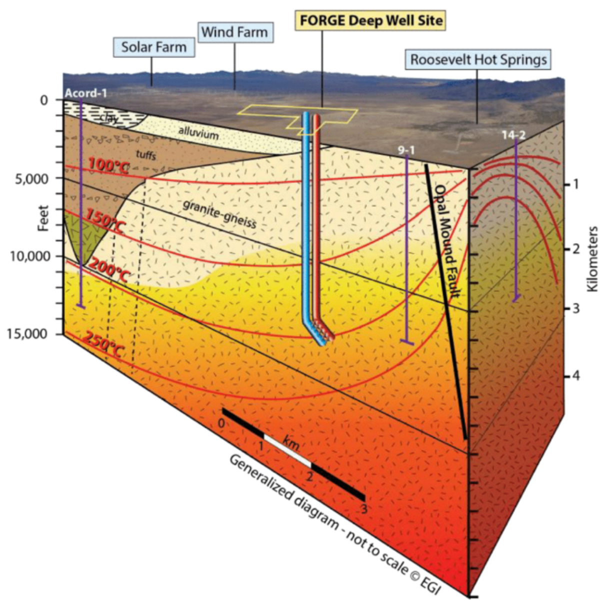

Fig. 1 Schematic diagram showing the proposed plan for the FORGE site.

STIMTEC-a mine-back experiment in the Reiche Zeche underground laboratory

Joerg Renner[1]; Georg Dresen[2,3]; Marco Bohnhoff[2,5]; Heinz Konietzky[4]; Grzegorz Kwiatek[2,5]; Katrin Plenckers[6]; Gerd Klee[7]; Tobias Backers[8]; and STIMTEC team

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The STIMTEC underground experiment was designed to investigate stimulation processes involved in hydrofrac and hydroshear activation aiming at a permeability enhancement in deep geothermal projects. We combined periodic pumping tests, high resolution seismic monitoring, structural analysis and drilling into stimulated volumes in an effort to improve near-real-time monitoring, phenomenological models of the hydrofrac/hydroshear process, and prognosis strategies. The ongoing experiment is located at the Reiche Zeche underground laboratory below Freiberg in Saxony/Germany at a depth of about 130 m below surface in metamorphic gneisses. A structural analysis of the test volume enclosed by tunnels preceded the experimental program. The massive gneiss was found to be strongly foliated and three steeply dipping shear zones were identified that cut across the test volume between the access tunnels. Subsequently, a combined seismic network consisted of 12 broad-band acoustic emission sensors (sensitivity 1-100 kHz) and three 1-component Wilcoxon accelerometers (sensitivity 50 Hz-25 kHz). These sensors were installed in boreholes drilled into the test volume, surrounding the stimulation site, and providing optimum spatial coverage. A stimulation borehole with 63 m length was drilled with 15° northward inclination. Analysis of the core material, and borehole logs were used to identify potential intervals for hydraulic tests and stimulation. With a maximum horizontal stress direction striking 10°W from N, as typical for Germany, stimulation-induced fractures were expected to form NNW-SSE striking tensile hydrofractures and NNE-SSW striking hydroshears. We performed a series of laboratory tests on core samples to estimate fracture toughness and elastic properties of the gneiss. A strong elastic wave anisotropy was found with fast and slow propagation parallel and perpendicular to the foliation, respectively. The laboratory measurements were found to be in good agreement with an extensive series of active ultrasound measurements performed in the mine to establish a velocity model of the test volume. In addition to a strong effect of metamorphic foliation on the elastic properties, the field measurements revealed significant local velocity variations possibly related to damage/fault zones. After an extended campaign characterizing the hydraulics of the test volume, a series of ten stimulation tests were performed in the injection borehole. Each stimulation stage consisted of a frac stage, several refracs, and a subsequent hydraulic testing period. A total of > 5000 high frequency events were induced. Currently, analyses of the induced microseismicity and the hydraulic measurements are performed. In Spring 2019, a series of boreholes will be drilled into the stimulated volume as identified by the spatial distribution of detected seismicity. These boreholes will be fully cored to retrieve samples for structural analysis and testing. A series of hydraulic tests using the mine-back boreholes will conclude the experiment.

Injection-Induced Seismicity and Aseismic Fault Slip in Laboratory and In-Situ Experiments and Hydromechanical Models

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Injection of fluid into the deep subsurface can at times generate measurable or even damaging earthquakes, but often they only produce aseismic deformations along faults and fractures. The relationship between injected pressure and these aseismic deformations is a fundamental point in the estimation of how the crust responds to fluid injection and the associated induced seismic hazard.

In this study, we present laboratory and in-situ measurements of fault-parallel ('slip') and fault-perpendicular ('opening') displacement during controlled fluid injection experiments. We also use laboratory experiments to characterize the fault frictional properties with increasing fluid pressure and a three-dimensional hydromechanical model to test if these properties are consistent with the in-situ observations and shed light on the origin of aseismic deformation and seismicity.

Through our multiscale investigations, we demonstrate that fault slip induced by fluid injection in a natural fault at the decametric scale is quantitatively consistent with fault slip and frictional properties measured in the laboratory. The increase in fluid pressure first induces accelerating aseismic creep and fault opening. As the fluid pressure increases further, friction becomes significantly rate-strengthening favoring aseismic slip. Our study reveals how coupling between fault slip and fluid flow promotes stable fault creep during fluid injection. Seismicity is most probably triggered indirectly by the fluid injection due to loading of non-pressurized fault patches by aseismic creep.

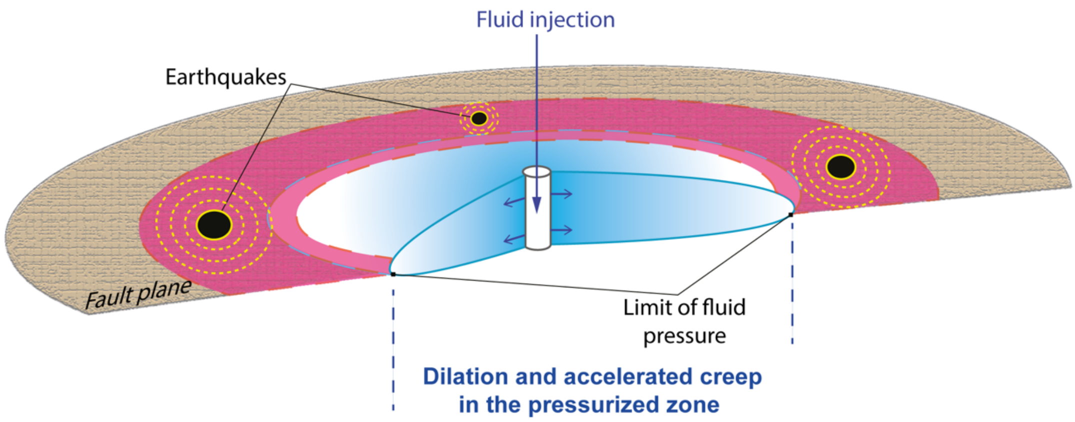

Figure: Conceptual illustration of evolution of fault stability during fluid injection derived from experimental evidence and numerical modeling. Fault opening and accelerating creep occur in the pressurized area, whereas, at its limit and beyond, the fault accumulates shear stress caused by propagating creep, which, at least, helps to trigger seismic slip.

Abstracts Talks

Session 9

Advances in Monitoring Induced Seismicity

The Grimsel in-situ stimulation project – on the seismo-hydro-mechanical response during hydraulic stimulation tests

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A decameter-scale in-situ stimulation and circulation (ISC) experiment has recently been conducted at the Grimsel Test Site in Switzerland (Fig. 1a,b) with the objective of improving our understanding of key seismo-hydro-mechanical coupled processes associated with high-pressure fluid injections in a moderately fractured crystalline rock mass. The ISC experiment activities aim to support the development of EGS technology by 1) advancing the understanding of fundamental processes that occur within the rock mass in response to relatively large-volume fluid injections at high pressures, 2) improving the ability to estimate and model induced seismic hazard and risks, 3) assessing the potential of different injection protocols to keep seismic event magnitudes below an acceptable threshold, 4) developing novel monitoring and imaging techniques for pressure, temperature, stress, strain and displacement as well as geophysical methods such as ground penetration radar, passive and active seismic and 5) generating a high-quality benchmark datasets that facilitates the development and validation of numerical modelling tools.

The ISC experiment includes six fault slip and six hydraulic fracturing experiments at an intermediate scale (i.e. ~20*20*20m) at 480m depth, 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.

In February and May 2017, we performed the fault-slip experiments (Fig. 1c) on interconnected faults and the hydraulic fracturing tests within test intervals that were free of natural fractures. Data processing is ongoing, but current results already show the exceptional scientific value of the acquired data. Amongst other observations, pressure data show indications of both non-linear pressure diffusion and heterogeneous flow channeling, and rock deformation data clearly show slip on some pre-existing structures and opening of new fractures during the experiments.

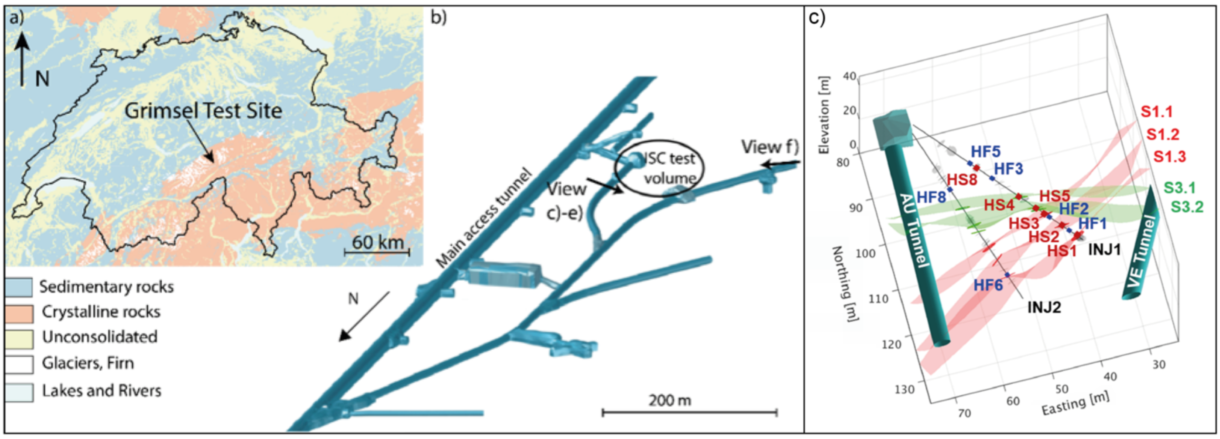

Fig. 1 Location of the GTS in Switzerland indicated in the geological map (a), and location of the test volume within the GTS (b). The injection intervals are marked together with the target shear zones (c).

Understanding reservoir processes in injection operations from advanced microseismic analysis

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Better characterization of induced microseismic events can reveal important geomechanical parameters for fluid injection operations. The spatio-temporal evolution of seismicity in conjunction with source parameter analysis can provide more detailed insight into reservoir behavior, such as for example the assessment of seal integrity. Especially the depth resolution of microseismicity is critical to support reservoir characterization. In this direction, exploiting information contained in later arrivals/multipathing as well as full-waveform modelling for hypothesis testing and confirmation can be very valuable. We present data from several case studies (Decatur, In Salah, Oseberg) where detailed microseismic analysis led to improved understanding of the reservoir geomechanics. At the Illinois Basin - Decatur Project (IBDP), for example, about 4800 microseismic events were located with deep borehole sensors during the injection of 1 Mio tons of CO_2 over 3 years. Using a waveform cross-correlation method, we can distinguish between events occurring in the sandstone reservoir and events only some tens of meters deeper in the adjacent uppermost crystalline basement. We find that events of selected clusters migrate from the reservoir into the basement over time. Furthermore, relative event relocation using a modified double difference method shows the importance of precise event locations on microseismic interpretation. The relocated event cloud appears to show a planar feature with a change in strike and dip compared to the original locations. We employ full-waveform modeling to identify observations of different phase arrivals and to confirm the interpretations of event locations around the reservoir/basement interface. To this end, two different waveform modelling methodologies are applied. The analysis of the wavefield reveals onsets of head waves, converted waves and turning/diving waves in addition to direct waves. Such wavefield characteristics can be employed e.g., to differentiate between events originating in the basement and reservoir. Focal mechanisms are estimated to confirm identified structures for selected events by combining recordings from surface and downhole sensors. In addition, temporal changes in attenuation as measured from microseismic waveforms may also carry information about the progression of the CO_2 plume.

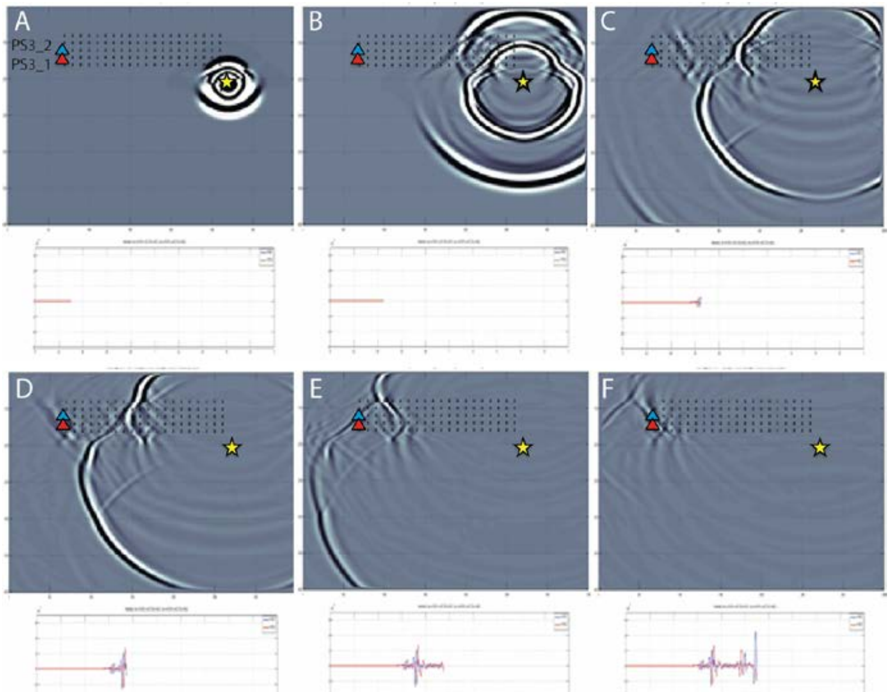

Fig. 1 Sequential snap-shots of full waveform modelling (from A to D). The yellow star denotes the source location. The two receivers are marked by the red and blue triangle, respectively. The black dots indicate an artificial set of receivers. The seismograms show the waveform arrivals at the two sensors.

Statistical and Phenomenological Analysis of a High-resolution Catalog of Induced Seismicity in Basel

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Seismic monitoring at the site of the Basel Enhanced Geothermal System (EGS) has been running for more than a decade, but the details of the long-term behavior of Basel's induced seismicity has remained unexplored. Based on sensitive matched filter detection, we have created a seismic event catalog that contains 280 000 events down to $M_w -1.5$ covering the pre-, co-, and post-operational phase of the Basel project (12 years). The majority of events occurred during the six-day stimulation in December 2006. We put particular care on creating consistency in terms of magnitude estimation and detection sensitivity, and apply a machine learning method to remove false detections.

Compared to previous catalogs, our higher temporal resolution allows us to analyze the induced seismicity in greater detail and reveals patterns that have not been identified before. For instance, we resolve temporal variations of seismicity parameters (e. g., the *b*-value of the Gutenberg–Richter relation) and observe a dominating temporal clustering of events in the post-operational phase. During the stimulation phase, we find a breakdown in the Gutenberg–Richter scaling of the event size distribution. This scaling break results in an overestimation of the seismic hazard if the occurrence of large events is inferred from small events.

We further investigated statistically the temporal behavior of event clusters as well as the influence of remote dynamic triggering on the induced seismicity in the Basel geothermal reservoir. In our catalog, we also found short-term incompleteness (see Fig. 1) despite our sensitive detection method. This incompleteness effect is typically observed in regional or global seismic networks (known as aftershock incompleteness), but apparently also applies to this smaller and spatially restricted scale. We quantify this detection limitation and its influence on the frequency magnitude statistics.

Our findings have implications for the development of guidelines and mitigation procedures on how to safely operate and terminate geotechnical operations that involve fluid injections.

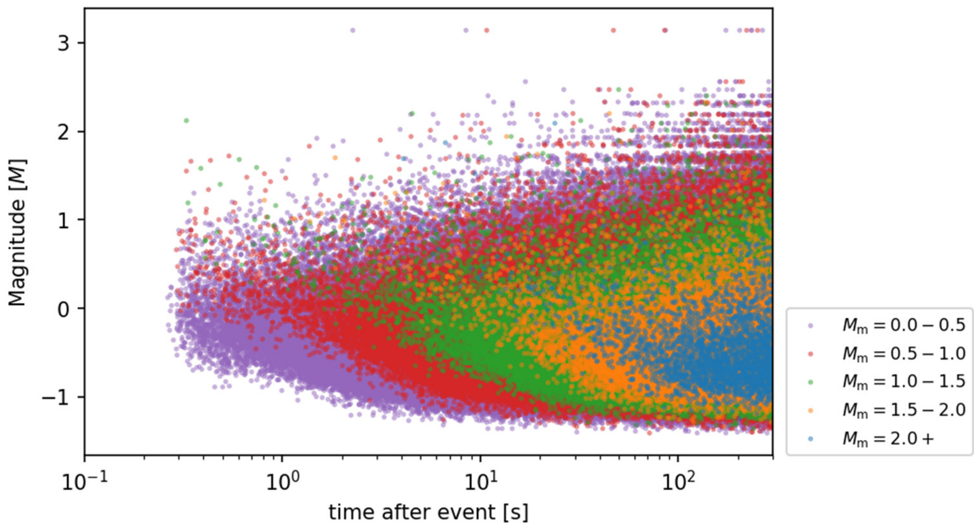

Fig. 1 Scatter plot of stacked detections that occur in the five minutes after larger events, revealing a magnitude- and time-dependent detection blindness. Colors represent the magnitude class of the larger events, M_m (see legend).

Monitoring induced seismicity with a single seismic station by combining coda wave interferometry with distance geometry solvers

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Microseismic monitoring networks are nowadays extensively used, in combination with risk analysis tools, to ensure the safety of the industrial operations which may trigger or induce earthquakes. However, in many cases the lack of dense enough microseismic monitoring networks affects the performance of the routine data analysis procedures limiting the application of adequate risk mitigation strategies. In this work we propose a novel approach based on the combination of Coda Wave Interferometry (CWI) and Distance Geometry Solvers (DGS) that allow to locate microseismic events by using a single seismic station. The use of CWI allows to determine, for pairs of earthquakes characterized by high similarity of waveforms (i.e. with similar location and focal mechanism), the absolute inter-event distance of each pair (Snieder and Vrijlandt, 2005), while DGS allow to determine their location based only on the given values of the distances between member pairs. Microseismic events can be classified in different families by combining a waveform correlation analysis and a clustering technique. Clustered events are characterized by a high similarity of waveforms, which implies a similarity in both source mechanism and location. In these conditions, the analysis of seismic coda recorded at a single receiver can be used to infer a measure of the spatial separation between two seismic sources. Coda waves are radiated in all directions with a radiation pattern determined by the source mechanism and a small change in the source position affects the interference pattern of the scattered waves that constitute the coda. This change in the coda waves is used to constrain the inter-event distance for each events pair. Absolute locations can be then retrieved by using DGS and considering all inter-event distances, a procedure which requires at least four reference locations. In order to show the potential of this approach we firstly validated the method with a synthetic dataset, then we applied it to the September-October 2013 induced seismicity sequence associated to the underground gas storage operations performed in the offshore Spain. The largest event of the sequence, a magnitude Mw 4.3 earthquake occurred on 2013 October 4th, was preceded by about 1000 seismic events, mostly with magnitude below 2. However, the poor monitoring network in the area (the closest seismic station was located at about ~20 km distance from the platform) did not allow to properly locate these small events. In this work we relocate these low magnitude events, showing that our approach provides better results than those obtained by using standard location methods, making this method particularly useful in poorly monitored areas where only a limited number of stations is available.

References:

Snieder, R., and Vrijlandt, M., 2005. Constraining the source separation with coda wave interferometry: Theory and application to earthquake doublets in the Hayward fault, California, J. Geophys. Res., doi:10.1029/2004JB003317

Quantification of location errors for mining induced seismicity in New Ollerton, UK, using 3D Monte Carlo body wave tomography

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Industrial activities like mining, hydrofracturing and the subsurface disposal of waste fluid can cause felt earthquakes. Sufficiently large earthquakes may cause damage to buildings and infrastructure, therefore, regulations often require operations to cease if an earthquake above a certain magnitude occurs. The location and magnitude of an earthquake determine its ability to cause damage, but these parameters are inherently uncertain and biased, because of imperfect knowledge of the seismic velocity structure of the subsurface, which most crucially controls the inferred location and magnitude of micro-earthquakes.

To overcome this problem, we have developed a fully non-linearised tomographic method using Monte Carlo sampling to invert jointly for event locations and 3D velocity structure using body wave travel times. (Zhang et al. 2018). Our Bayesian approach allows for the calculation of realistic probabilities for the velocity structure of the Earth beneath a set of seismic stations, and for earthquake locations that occur in that space.

We applied the algorithm to a synthetic model with two velocity perturbations as a testbed to explore its main characteristics and abilities. The source locations and travel times were perturbed with 2% gaussian noise. We are able to recover the true velocity model with errors much smaller than one standard deviation and we are also able to find the true source locations, in latitude and longitude, with larger errors in depth as expected. We show that we can find true source locations and velocity model even with randomly initialized source locations.

After the successful synthetic test, we applied this new inversion technique to the mining-induced events at New Ollerton in Leicestershire, UK from 2014. We find a fast velocity anomaly south-east of the coal seams, where the majority of the seismic events occur. Additionally, we observe a tradeoff between fast shear wave velocity and source locations in this fast velocity region, which emphasizes the interlinkage between subsurface velocity model and earthquake locations. The new velocity model can be used to locate new seismic events, and we can compare the source locations with those obtained with classical location methods.

Finally, we include local magnitude estimations in the Monte Carlo sampling, which allows the direct assessment of their uncertainties.

Abstracts Talks

Session 10

Case studies II: panta rhei

What Triggers Seasonal Earthquakes in South Iceland?

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A surprisingly large portion of large historical earthquakes in south Iceland have occurred in May and June. This indicates that some seasonal process is influencing the timing of the earthquakes. We explore three possible triggering mechanisms for the seasonal activity: seasonal loading/unloading, seasonal pore-pressure variations, and upward migration of near-lithostatically-pressured fluids. GPS stations in south Iceland show seasonal ~5-10 mm vertical displacement variations that we model as due to periodic snow, glacier, atmospheric and ocean loading. Both the magnitude and phase of the vertical GPS signals is well matched by the modeling, showing that snow loading is the largest contributor. The seasonal loading peaks in April with unloading throughout the summer, which means that the early summer occurrence of historical earthquakes correlates better with maximum unloading rate rather than the peak of the unloading. The periodic load-induced stresses on seismogenic faults in South Iceland are however small (~1 kPa), dominated by normal stress variations, and appear to only mildly modulate the rapid tectonic stressing rate in the area of ~20 kPa/year. Another possible triggering mechanism is periodic upward migration of high-pressure fluids, perhaps in response to the seasonal loading variations. Such migration has been suggested as a trigger for earthquakes in South Iceland and elsewhere. For example, foreshocks before the M6.5 17 June 2000 earthquake in south Iceland appear to show some upward migration. However, as the fluid properties and their possible response to seasonal loading are uncertain, it is difficult to assess the significance of this possible triggering mechanism. Yet another possibility is pore pressure increase due to spring snow melting which occurs somewhat before the peak occurrence of the earthquakes. Highland snow melting leads to a large surge in river flow and about 1-5 meter water level increase in many shallow water wells. For this transient groundwater level increase to have a significant effect on pore-pressures at seismogenic depths, very high vertical diffusivities are required. Such high diffusivities might be maintained by repeated fracturing of reoccurring earthquakes during past centuries and are supported by effective convection of hydrothermal systems in the area and rapid poro-elastic postseismic transients observed after recent major earthquakes. In this presentation, I will compare these different triggering mechanisms and discuss the pros and cons of each of them.

Controlling induced seismicity during hydraulic stimulation of a 6 km deep Enhanced Geothermal System 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, OTN3, was drilled down to 6.1 km-depth into Precambrian crystalline rocks. Well OTN3 was deviated 45° from vertical and an open hole section at the bottom was divided into several injection intervals. A total of 18,159 m^3 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 induced-earthquake rates, locations, magnitudes, and evolution of seismic and hydraulic energy, pumping 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 stimulation resulted in detection of >43,000 earthquakes with -1.2<ML<1.9. The original catalog was relocated using double-difference technique to improve hypocenter precision. The 4032 relocated earthquakes (Fig. 1) were used to investigate the spatio-temporal evolution of seismicity, seismic energy release, and maximum magnitude in response to injection. 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 G-R 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 observed magnitudes scale with stored elastic energy (~hydraulic energy), following a fracture-mechanics based model of Galis et al. (2017). Our results suggest a possible physics-based approach to controlling stimulation induced seismicity in geothermal projects.

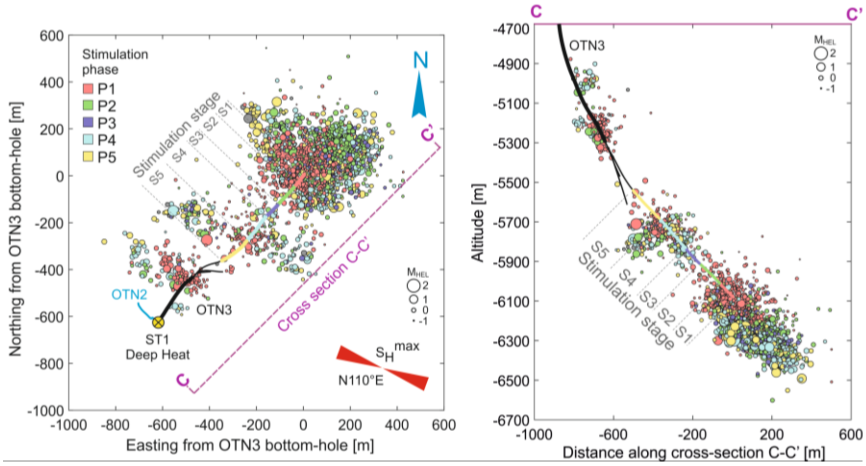

Fig. 1 Map view and SW-NE depth section showing double-difference relocated catalog, color coded with stimulation phase into corresponding stimulation stage.

Slow Deformation and Rapid Seismicity-Rate Changes Triggered by Geothermal Fluid Redistribution

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The Heber Geothermal Field (HGF) in southern California, United States, has utilized both dual-flash and binary power generation technology since 1985 and 1993, respectively, to produce around 90 MWe annually (net). Although the aggregate reinjection history suggests that very little deformation may be expected from reservoir depletion, geodetic data from InSAR and leveling surveys capture long-term, localized surface deformation, with subsidence rates in excess of 20 mm/yr (Figure 1A). Additionally, the same geodetic data capture a multi-year deformation transient (Figure 1B) that initiates between 2004 and 2005, at the time of major changes in fluid injection and production rates, ending in 2011. Low levels of seismicity at HGF were first detected around 1993, but a series of rapid increases in seismicity rate occur from the initiation of the transient deformation in 2004 through 2007 (Figure 1C) on structures flanking the geothermal wells (Figure 1D).

Here we consider a few hypothetical scenarios to understand the potential source(s) of the rapid changes in seismicity rate and the slow deformation: (1) triggered slow slip on reservoir bounding faults, including a previously imaged "feeder fault", and (2) a poroelastic response to changes in fluid injection and production. Slow slip on the feeder fault – the principal conduit used to extract hot geothermal brine – does not appear to be supported by the data at hand; rather, our simulations favor a scenario where fluid redistribution induces both a poroelastic response in the reservoir and seismicity on reservoir bounding faults.

The deformation and seismicity observed at HGF represent perhaps the first unambiguous demonstration of induced, multi-modal moment release at a geothermal field. The changes in seismicity rate are nearly instantaneous, which suggests that reservoir bounding faults are critically loaded and thus sensitive to small perturbations in stressing rates. We note that the induced seismicity occurs on a blind extension of the Coyote Creek fault in the San Jacinto fault system, which recent studies suggest is accommodating a significant proportion of strain associated with relative plate motion. Our observations highlight the inherent feedback between the dominant modes of moment release, dynamic permeability and structural complexity, while suggesting a non-stationary seismic hazard potential on a plate-boundary fault.

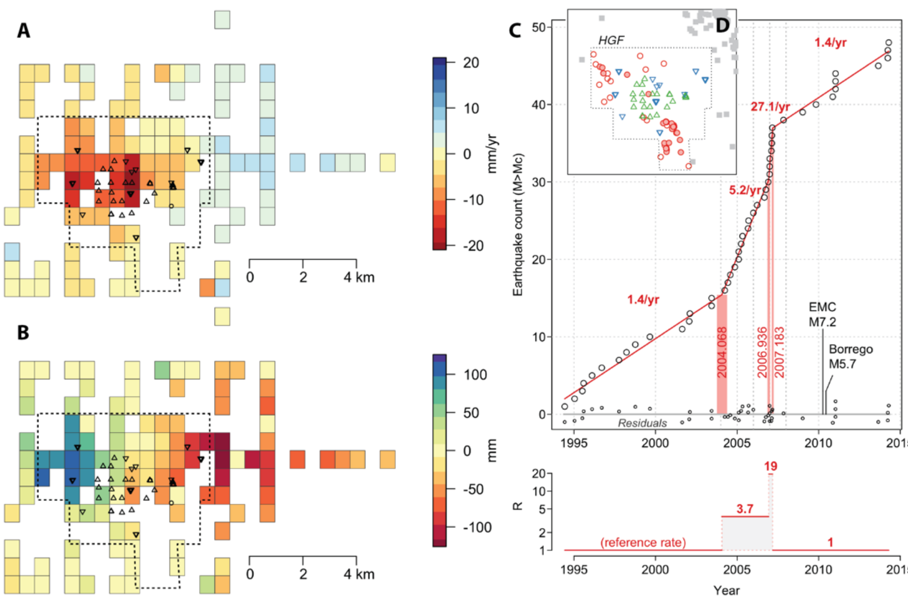

Fig. 1 Deformation and seismicity at the Heber Geothermal Field (HGF) in southern California, United States. A: Spatially-averaged rates of vertical surface motion prior to the multi-year deformation transient that began in 2004, with locations of injection wells (▽) and production wells (△). B: Relative vertical position at the end of deformation transient. C & D: Seismicity rates and locations of induced seismicity at HGF.

Repeating Earthquakes and Shear Wave Anisotropy Measurements from an Induced Seismicity Case Study, Wattenberg Disposal Zone

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Since June of 2014, a network of seismometers has been operating to monitor wastewater injection and the evolution of induced seismicity near Greeley, Colorado, USA. A seismic catalog collected between 2014 and 2018 features more than 1000 manually detected local earthquakes within the upper 10 km of Earth's crust. We use a selection of these events as templates in a waveform cross-correlation procedure to expand the catalog, and to screen for clusters of repeating or near-repeating events. We also use the differential arrival times, derived from the correlation procedure, to relocate the existing catalog more precisely. The seismograms often exhibit shear wave anisotropy, as indicated by shear wave splitting measurements collected at one station in the network. We expand on these measurements and analyze temporal changes in the splitting parameters within the context of path-dependent anisotropy, inter-event timing, regional stress, monthly injection rates and down-well pressure measurements. We find several clusters of earthquakes with highly correlated waveforms and similar locations. Some of these events exhibit apparent changes in splitting through time. We investigate methods for independently verifying that changes in the splitting parameters are related to pore pressure diffusion and wastewater injection, rather than changes in the path between source and receiver.

Fluid diffusion and the resultant dilation of grain boundaries and microfractures is one potential mechanism for shear wave anisotropy in the Wattenberg Disposal Zone. In the presence of a changing pressure gradient, a succession of shear waves may exhibit varying degrees of anisotropy as they propagate through fluid-saturated, stress-aligned pore spaces. In an effort to discriminate between static path effects and pressure-induced anisotropy, we focus on clusters of repeating and near-repeating events with long inter-event times. That is, places along a resolved dipping structure where seismicity returns throughout the course of the experiment. Perturbations in pore fluid pressure from high-rate wastewater injection is a key mechanism in many documented cases of anthropogenic induced seismicity. Seismic observations of shear wave anisotropy could lead to an improved understanding of the link between earthquake triggering and pore pressure evolution during wastewater injection.

Fault reactivation by fluid injection considering permeability evolution in damage zones: a case study of Guy-Greenbrier sequence

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Injection-induced seismicity is thought to be due primarily to increase in fluid pore pressure along existing faults and fractures, which reduces their frictional strength. In the Guy-Greenbrier area in Arkansas, USA, wastewater has been injected into the subsurface through several disposal wells since April 2009. Seismicity in the surrounding area has increased sharply and 98% of the earthquakes, following the injection, are located within 6 km of three wastewater disposal wells by Horton (2012) who related the increase in seismicity to wastewater injection. We address the modeling and prediction of the hydro-mechanical response due to fluid injection in the Guy-Greenbrier earthquake sequence. We consider the full poroelastic effects and also the changes in porosity and permeability of the rock matrix due to changes in local volumetric strains. Our results reveal that the overall trend of the Guy-Greenbrier earthquake sequence is consistent with our assumption of an anisotropic permeability structure of fault damage zones, such that they can act as barriers to flow across faults, and as conduits to diffuse pore pressure changes to deeper levels and greater distances. What's more, we validate our model against two seismic observables. First, we measure time-dependent changes in seismic velocities using auto and cross correlations of seismic ambient-noise and compare with the evolution of effective elastic properties. Second, we couple to our results the seismicity rate production model of Dieterich (1994) and compare with seismicity. We use the earthquake catalog based on template matching from Huang and Beroza (2015). Combining these theoretical and observational approaches, we aim to gain more insights in the interaction between fluid injection, structural evolution, and seismicity production for induced earthquake hazard mitigation. (supported by NSF-EAR 91315447 and NSF-DMR 90820484)

Abstracts Posters, Part A

Session 1

Case Studies I: World Tour

Seismicity rate and earthquake source mechanisms in the Hengill and Hverahlíð geothermal fields, SW-Iceland, October 2016-2018.

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The Hellisheiði power plant has been in operation since 2006, currently producing 300MWe and 133 MWt. It is located at the Hengill triple junction in SW-Iceland, where the Reykjanes ridge meets the western volcanic zone and the south Iceland transform zone. In October 2016, Iceland GeoSurvey installed a semi-permanent seismic network on Hellisheiði for the power plant operator Reykjavik Energy. From September 2018 the density of the seismic network was tripled under the 3-year long COSEISMIQ project. This study investigates the earthquake rate and earthquake source mechanisms in Hengill and Hverahlíð geothermal fields (located on Hellisheið) form October 2016 to September 2018.

Relative earthquake locations outline surface faults and show that earthquakes are mainly shallower than 4 km depth below the surface, whereas the the extraction and injection wells in the area have feed zones at depths of 1.5 - 2 km. The earthquake are primarily of magnitudes smaller than 2, while earthquakes of magnitudes between 2 and 4 are only about 5% of the earthquake catalogue.

Earthquake source mechanisms show mainly strike-slip faulting, sub-parallel to surface fractures and the tectonic trend. This finding is of interest for the geothermal industry as it points towards a very high permeability along strike-slip faults in this area, where some of the power plant's most powerful wells are located.

Benefits of Non-Damaging, Publicly-Acceptable, Geothermal Induced Micro-Seismicity in New Zealand

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Micro-seismic monitoring of operating geothermal fields complements other geophysical monitoring tools, such as micro-gravity, ground deformation, and repeat downhole surveys, to provide geothermal reservoir modelers and resource managers with improved information on geothermal reservoir behavior. Consequently, operational scenarios (production and reinjection strategies) can be fine-tuned to improve utilization sustainability. The knowledge gained can also help develop better strategies for resource expansion and choose targets for make-up drilling.

In the seismically active Taupo Volcanic Zone of New Zealand, there are five operating geothermal fields with a history of more than 10 years of micro-seismic monitoring using local network arrays. Numerous induced events have been documented, several per year in the magnitude range of 3 to 4, but there have been no cases of significant damage, and perhaps consequently, no public opposition to ongoing geothermal development. Information on all felt events (above magnitude 2), whether induced or natural, is almost immediately available through a well-known website (www.geonet.co.nz). This openness appears to provide a sense of public reassurance. An example is given from the 60 years old producing Wairakei Geothermal Field in New Zealand (Figure 1).

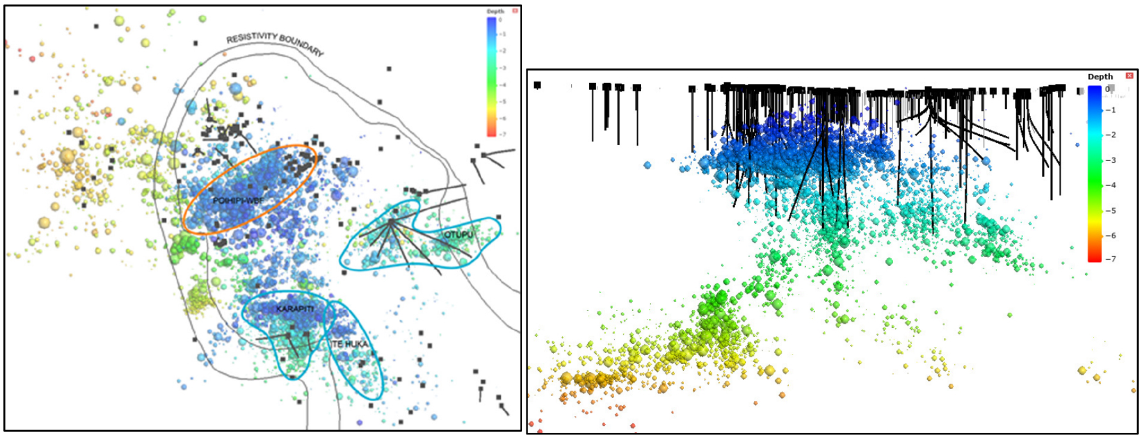

Fig. 1A) Wairakei seismicity map (period 2009-2017) showing clustered seismicity B) View from the south. Size of dot proportional to magnitude and color proportional to depth.

Seismicity Induced by Hydraulic Fracturing in Ohio in 2016: Case study of the Conotton sequence in Harrison County

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In November of 2016, a sequence of hydraulic fracturing induced seismicity was observed in Harrison County, Ohio. The events in this sequence were ≤ M 2.7 and were spatiotemporally correlated with hydraulic pumping stages from the Conotton horizontal wells. A series of adjacent wells to the west of the Conotton wells also induced seismicity when stimulated in 2013 to 2015. These western well's seismicity illuminated an east-west trending basement fault system. Kozlowska(2018) found that the seismicity induced in these wells fell into two populations, a shallow one, just below the Utica formation, and a deeper one in the crystalline basement. The two populations had b-values above and below 1, respectively. The fault's east-west trend extended beneath the Conotton horizontals based on seismicity observed in 2015, and the seismicity from the Conotton stimulation is an extension of the same fault system.

Using a 5 station seismic network, 129 earthquakes were picked and located using Hypoinverse. Relative locations were obtained using HypoDD and demonstrate that the activity was 800 to 1200 meters below the Utica formation being stimulated and related to the crystalline basement fault system. In addition, cross-correlation template matching techniques were used to observe some ~1200 detections of earthquakes with M > -0.85. Interestingly, the b-value evolved from values > 1 early in the sequence to < 1 when the larger events started happening. During the sequence, the operator took mitigation actions by skipping stages and reduced volume across stages that were closer to the fault. Pressure and volume data were investigated to assess if there was any relationship with specific stimulation parameters to the earthquake rate. Production data from the wells are also examined to investigate how interactions with a fault influence produced oil, gas, and brine.

Reinvestigating the earthquake size distribution of induced seismicity at the Groningen gas field

Laura Gulia and Stefan Wiemer

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We re-investigate the relative earthquake size distribution (b-value), activity rates (a-value), magnitude of completeness (Mc) of induced earthquakes related to production from the Groningen gas field. Thanks to continues upgrading of the seismic network, there are now about 1400 events recorded in the study region since 1990, a sufficient number for analyzing the space- and time variability of the earthquake-size distribution. The b-value is an important statistical parameter influencing greatly probabilistic seismic hazard and risk assessments. Because b-value are related to differential stress and thus also pore-pressures, the analysis can potentially also help to unravel the seismotectonic framework and geo-mechanical evolution of the system. Our analysis is builds and in parts extends similar analyses by Bourne et al. (2015) as well as Muntendam-Bos et al. (2017).

Our preliminary analysis shows consistent with previous finding that Mc remained steady at about 1.3-1.2 until 2014, improving afterwards to value of 0.8 – 0.6. However, there are also a strong spatial difference in Mc values, with higher values to the North. The overall b-value of about 0.9 (using magnitudes reported in ML scale) has remained quite stable with time, with highest values observed around 2012 (b = 1.0 - 1.1) and lowest value observed 2015 (b = 0.7 – 0.8). We also observe a strong and persistent spatial pattern of b-values, with lowest (thus most hazardous) values of b = 0.7 at the northern and southern edges of the field, while b-values exceed b = 1.1 for the central part. The observed temporal changes in b-value could thus also result from changes in activity areas. In a next step, we will try to further unravel the spatio-temporal variations of the b-values and attempt to related them to observed subsidence values as well as production parameters, analyze the local recurrence time of Magnitude 3 or larger events and develop a conceptual, predicative framework for the evaluation of b-values.

The 2018 Newdigate, Surrey, UK earthquake sequence: induced by nearby oilfield activities, or not?

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In the UK, earthquakes induced and triggered by hydrocarbon extraction are fast becoming an increasingly important issue. Starting in April 2018, a sequence of small earthquakes (max. M_L = 3.0) occurred in the county of Surrey, close to Gatwick Airport. Initial hypocentre estimates showed that these events occurred at a very shallow depth (<3 km) and within 8 km and 3 km of oilfield production and development wells, respectively. As a result, the sequence attracted attention from the public and media, making it important to characterise this sequence in detail to help understand whether the earthquakes were induced or natural. In July-August, the British Geological Survey installed five temporary broadband seismic stations in in the area to better constrain the earthquake locations and other seismic characteristics. We also used seismic data from nearby stations of the citizen seismology RaspberryShake network.

We applied a template-matching technique to detect ~40 earthquakes in the sequence (min. M_L=-1.4), revealing a mean depth of 2.3 km, which is below the oil target formations at ~1 km depth. Using 2-D seismic profiles, we identified the causative fault with a normal sense of offset within sedimentary rocks at the base of the Weald Basin. We computed moment tensors using local seismic data, which show a right-lateral faulting mechanism, consistent with the regional state of the stress in the British Isles. The best-fitting centroid depths agree with the hypocentre depths. We also compute stress drops and inter-event static stress changes to help discriminate between natural and induced causes. Although there is a strong temporal correlation with extraction and injection at the nearby production well, there is no plausible mechanism for net fluid extraction to have triggered seismicity across several fault blocks over the observed short time period (i.e., <10 days). Our interpretation is that the Newdigate sequence was very unlikely to have been induced. Nevertheless, the Newdigate seismic sequence emphasises the need to further monitor and understand baseline seismicity at shallow depths close to hydrocarbon operations.

Data features from a network around the 2018 EGS stimulation in Espoo/Helsinki, Finland

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We discuss several data features and observations associated with a stimulation experiment in the Helsinki, Finland, area. In June and July 2018 the St1 Deep Heat company stimulated a rock mass between 6 km and 7 km depth beneath the Aalto University campus in Otaniemi/Espoo, Finland, to establish an Enhanced Geothermal System (EGS) to support district heating. The relatively large depth compared to other geothermal systems is attributed to the shallow gradient of the stable Fennoscandian shield.

The St1 Deep Heat company installed 12 semi-permanent 3-component, 800 Hz borehole instruments between 238 m and 1620 m depth to monitor the induced seismicity. The Institute of Seismology from the University of Helsinki (ISUH) has been operating 7 semi-permanent broadband stations in the area. ISUH also installed a temporary network around the wellhead consisting of 100 4.5-Hz 3-component geophones that were connected to DATA-CUBE3 recorders. The sampling rate was 400 Hz. The cube-stations operated for 106 days between the day of year (doy) 127 and doy 233. The stimulation took place between doy 155 and doy 203. The 100 stations were organized in 3 large arrays consisting of 25 stations, 3 small 4-station arrays, and 8 single stations. The 100 m x 100 m large-array size and the average 25 m inter-station distance were intended to resolve propagation properties of body waves excited by earthquakes in the M~0.5 to M~2.5 range with beamforming techniques.

We report on the response to the induced seismicity (Mmax 1.7/1.9) that we received from the population in the neighborhoods around the borehole site. We present initial results from the seismic data analysis and discuss basic data features in the records to demonstrate the diverse range of studies and processing techniques facilitated by the network. We compare noise levels, signal-to-noise ratios, and detection thresholds using data from a 260 m deep borehole sensor and from a co-located 25-station surface array. Source mechanisms from selected large (M>1), manually-picked events are investigated as a function of sensor- and array-configuration. We evaluate hypocenter locations using travel times and array- or beamforming-based backprojection methods. We compare location estimates obtained with a regional velocity model to solutions based on a 1-D model obtained from surface wave inversion. These surface waves are reconstructed from ambient noise correlations in the 0.5 to 5 Hz range. We apply double-beamforming to this noise correlation database to analyze properties of P waves propagating between arrays and to evaluate the potential for monitoring the rock properties above the stimulated volume. We show time series of seismic velocity changes dv/v obtained with noise-based or passive monitoring techniques and compare them to stimulation parameters and properties of the induced seismicity. The diverse range of approaches demonstrates the versatility of the network configuration and has thus important implications for future deployments for studying EGS responses in hard-rock environments.

Ground Expansion and Seismic Hazard Induced by the Hutubi Natural Gas Repository, Xinjiang, China

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Although increasing seismologic observations reveal numerous earthquake hazards linked to anthropogenic activities, ground displacements were only detected in several induced seismicity regions. Geodetic observations of ground deformation have been demonstrated effective in assessing the natural seismic hazards, whereas very preliminary attempts were conducted for induced earthquakes. Previous studies always focused on surface uplift or subsidence induced by fluid injection/extraction, with limited attentions on the horizontal deformation. To date, the Hutubi natural gas repository (HNGR), located near the boundary between Tien Shan and Junggar Basin, Xinjiang Province, is the largest underground gas storage facility in China. Two seismologic and geodetic studies reveal that the operation of the HNGR has induced both seismicity and ground displacements. The seismologic study found that five $M_L \geq 3.0$ earthquakes occurred only 52 days after the operation on 9 June 2013 with distances of only 2.2-3.0 km from the HNGR. The geodetic study only investigated the vertical displacements measured by GPS and InSAR and found they were contaminated by groundwater extraction. Therefore, the HNGR is a unique case with both induced earthquakes and ground displacements, due to cyclic gas injection and extraction.

Here, we focus on horizontal GPS observations and make efforts to extract robust displacement signals linked to the cyclic gas injection and extraction of the HNGR. In addition, a hydrogeologic model for the HNGR is built up by combined use of seismic profiles, drilling data, a refined local velocity model, well logging data, and rock physics experiments. Fully-coupled poroelastic simulation based on the hydrogeologic model is conducted to investigate the physical mechanisms of ground displacements and induced seismicity, and also to assess the induced seismic hazard. Our research contents can be divided into two parts: (1) detecting robust horizontal displacements and unveiling its physical mechanism, and (2) determining the physical mechanism of induced seismicity and assessing its hazard.

13 campaign GPS stations measured horizontal ground expansion symmetrically distributed away from the center of the HNGR with a maximum magnitude of 1.57 cm from the 2^{nd} to 5^{th} injection phase over 3.5 years. Position time series of 6 continuous GPS stations reveal little influence of groundwater extraction on the horizontal displacements. The observed ground expansion associated with wellhead pressure data are used to characterize the hydraulic properties of the reservoir layer for model calibration, which are important parameters to investigate subsurface fluid flow and stress perturbation, further for assessing seismic hazard. Our poroelastic simulation based on the calibrated hydrogeologic model reveals that the horizontal ground expansion is induced by dilation of the gas reservoir, with magnitudes larger than ground uplift.

The simulation results also reveal that Coulomb stress increasing in the regions surrounding the HNGR attributes to the reservoir dilation, which induces local crustal compression. Therefore, the seismicity occurred in the surrounding regions is due to poroelastic loading. The 3D seismic survey of the study area imaged five primary faults with lengths over 10 km and several secondary faults with lengths around 1 km. However, the relocated seismicity occurred on the secondary faults rather than the primary faults. Moreover, the occurrence time of sharp seismicity increase is almost equal to the time of 0.1-bar boundaries of Coulomb stress increasing lobes reaching the secondary faults, indicating that dramatic increases of induced seismicity depend on the distances of secondary faults off the HNGR.

Lastly, we are attempting to evaluate the induced seismic hazard including the occurrence range of induced seismicity and the maximum potential earthquake with location based on the poroelastic simulation, the 3D seismic survey data, and dynamic rupture modeling with the rate- and state-variable friction law.

Seismic monitoring at the United Downs Deep Geothermal Project (UDDGP), Cornwall, United Kingdom

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Geothermal Engineering Limited (GEL) has secured funding of £10.6 million from the European Regional Development Fund (ERDF) to explore the geothermal resources deep beneath Cornwall, United Kingdom. With £2.4 million from Cornwall Council and £5 million from private investors, the funding is enabling GEL to drill two deep geothermal wells, build a 1MW - 3MW pilot power plant and to demonstrate the viability of supplying both electricity and heat.

The delivery partners collaborating in the UDDGP are GEL, GeoScience Limited, the British Geological Survey (BGS) and Plymouth University. The seismic monitoring programme started in May 2018 and the first well was spud in November 2018.

Unlike the previous Hot Dry Rock research project carried out in the 1980's at Rosemanowes, Cornwall, UDDGP plans to target a permeable geological structure called the Porthtowan Fault Zone. This lies approximately 800m to the west of the drill site. Two deep boreholes will be drilled to intersect the fault zone; one for injection at around 2,500m depth and one for production at 4,500m. The temperature at the bottom of the production well is expected to be about 190°C. Water will be pumped from the production well, fed through a surface heat exchanger and then re-injected at around 2.5km depth. The extracted heat will be used to supply a demonstration power plant.

The project team have deployed an integrated seismic system comprising:

- A microseismic monitoring system (MMS) in order to establish the background level of natural seismicity and to monitor induced seismicity during the operational phase of the project.
- A ground vibration monitoring system (GVMS) to accurately measure ground vibrations at a number of locations near the project site.

The performance requirements for the MMS are that it must be able to detect and locate all events down to at least a magnitude of 0.0 within a 10km by 10km area centred on the zone of interest. Location accuracy (95% confidence) must be better than 150m both horizontally and vertically, assuming a well-constrained velocity model.

The GVMS must be able to detect minimum ground velocity movements to at least 1mm/sec, ground acceleration of 1%g and minimum frequency of 1Hz.

This paper describes the MMS and GVMS, presents some preliminary results and describes the seismicity monitoring and control protocol deployed in accordance with the Cornwall Council Renewable Energy Planning Advice (2016).

The paper also outlines the role that Raspberry Shake personal seismographs are playing in the public outreach programme and also within the integrated monitoring system.

Fig. 1 HAS Innovarig during assembly at the United Downs Deep Geothermal Project site, Cornwall, UK (Image after **www.uniteddownsgeothermal.co.uk**)

COSEISMIQ Project: Control Seismicity and Mange Induced Earthquakes

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Over the last decade induced seismicity has become an important topic of discussion, especially owing to the concern that industrial activities could cause damaging earthquakes. Large magnitude induced seismic events are a risk for the population and structures, as well as an obstacle for the development of new techniques for the exploitation of underground georesources. The problem of induced seismicity is particularly important for the future development of geothermal energy in Europe, as deep geothermal energy exploitation projects such as Basel (2006) and St Gallen (2013) have been aborted due to the felt induced earthquakes they created and an increasing risk aversion of the general population. Induced seismicity is thus an unwanted product of such industrial operations but, at the same time, induced earthquakes are also a required mechanism to increase the permeability of rocks, enhancing reservoir performances. Analysis of induced microseismicity allows to obtain the spatial distribution of fractures within the reservoir, which can help, not only to identify active faults that may trigger large induced seismic events, but also to optimize hydraulic stimulation operations and to locate the regions with higher permeability, enhancing energy production. The project COSEISMIQ integrates seismic monitoring and imaging techniques, geomechanical models and risk analysis methods with the ultimate goal of implementing innovative tools for the management of the risks posed by induced seismicity and demonstrate their usefulness in a commercial scale application in Iceland.

As a demonstration site, we selected the Hengill region in Iceland (Figure 1). The Hengill volcanic complex is located in SW Iceland on the plate boundary between the North American and Eurasian plates. In this region, the two largest geothermal power plants of Iceland are currently in operation, the Nesjavellir (120MW electricity) and the Hellisheidi (303MW electiricty) power stations. In October 2018, we densified the permanent seismic network run by ISOR and IMO in this area (14 stations) with 23 broadband seismic stations.

During the meeting, we will present the project and show some first results of observed seismicity.

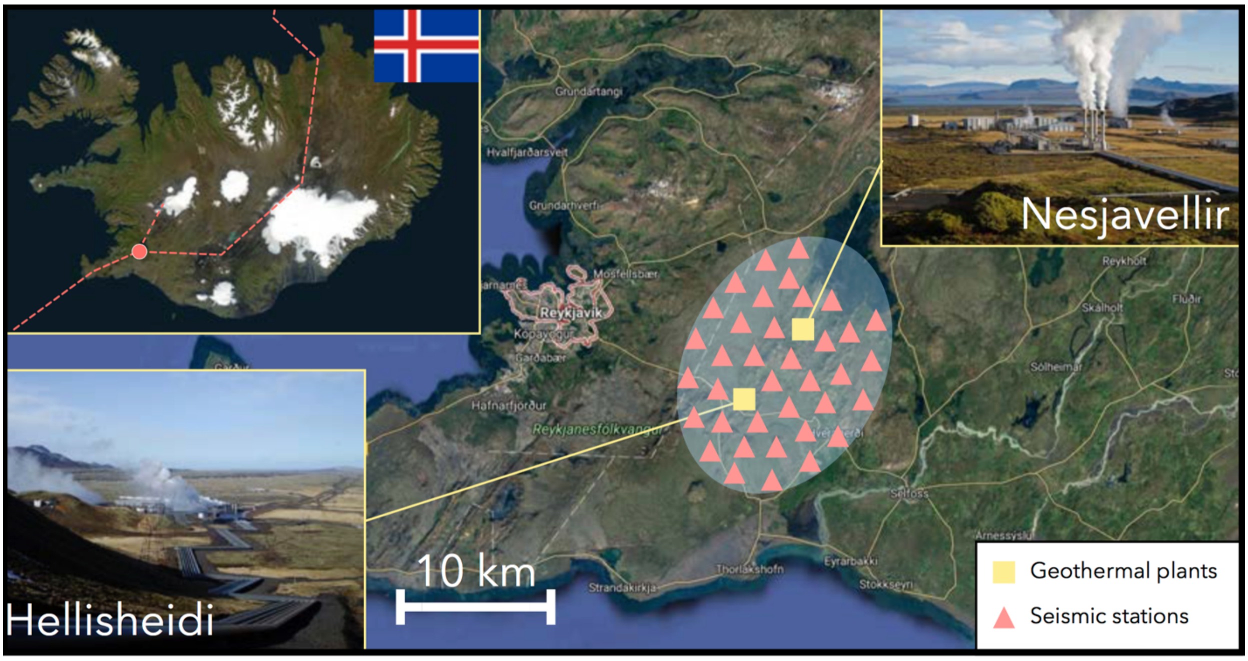

Figure 1 Map of Island showing the demonstration site of COSEISMIQ. The red dot is the location of the Hengill geothermal area, which is a triple junction between the Reykjanes Peninsula oblique rift (RP), the Western Volcanic Zone (WVZ), and the transform-type South Iceland Seismic Zone (SISZ).

Studying induced seismicity within the EPOS Thematic Core Service on Anthropogenic Hazards (TCS-AH)

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The EPOS TCS-AH brings together a broad community interested in Anthropogenic Hazards (AH) related to induced seismicity. It is designed as a functional e-research infrastructure that provides access to a large set of relevant data and allows free experimentations in a virtual laboratory, promoting interdisciplinary collaborations between stakeholders (the scientific community, industrial partners and society).

The platform provides datasets as Episodes, which comprehensively describe AH cases for infrastructures, people and/or environment. They are grouped in several categories of subsurface exploitations: CO2 sequestration, conventional hydrocarbon extraction, geothermal energy production, reservoir impoundment, unconventional hydrocarbon extraction, underground gas storage, underground mining, and wastewater injection. They gather datasets relevant for the considered hazards (e.g. seismic, air/water quality), industrial data (e.g. well path, injection rates, mining front advance, gas production, water level), and other geodata (e.g. geological section, velocity model, faults, shear wave velocity, bathymetric map). Two local data centers (eNodes: IG-PAS/Poland and CDGP-EOST/France) provide metadata and data to the TCS-AH platform in commonly used standards and formats (e.g. miniSEED, GeoTIFF, and .mat). A registration/authorization is mandatory to access some data covered by restriction imposed by data industry providers or shared data embargoed by running projects.

The platform grants access to an application portfolio, designed for the AH area, and addressing: (1) basic services for data integration and handling; (2) services for physical models of stress/strain changes over time and space as driven by geo-resource production; (3) services for analyses of geophysical signals; (4) services to extract the relation between technological operations and observed induced seismic/deformation; (5) services to quantitative probabilistic assessments of anthropogenic seismic hazard - statistical properties of anthropogenic seismic series and their dependence on time-varying anthropogenesis; ground motion prediction equations; stationary and time-dependent probabilistic seismic hazard estimates, related to time-changeable technological factors inducing the seismic process; (6) simulator for multi-hazard/multi-risk assessment in exploration/exploitation of georesources (MERGER) - numerical estimate of the occurrence probability of chains of events or processes impacting the environment.

TCS-AH is one of the 10 TCS forming the EPOS infrastructure. It is part of the IS-EPOS and EPOS-IP project. It is the ideally place for sharing and studying AH datasets, respecting the owners' intellectual property rights, for a common benefit for Science, Industry and Society. The TCS-AH web-platform is available at https://tcs.ah-epos.eu/

Characterizing seismogenic faults and discerning hydraulic fracturing induced earthquakes in Oklahoma

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Oklahoma is one of the most seismically active places in the United States as a result of industry activities. While wastewater disposal is generally accepted to be the primary cause of the increased seismicity rate in Oklahoma within the past decade, no statewide analysis had previously investigated the contribution of hydraulic fracturing (HF) to the observed seismicity or the seismic hazard. Here, we identified 274 HF wells that are spatiotemporally correlated with bursts of seismicity (Figure 1a). The majority of HF-induced seismicity cases occurred in the SCOOP/STACK plays, but we also identified prominent cases in the Arkoma Basin and some more complex potential cases along the edge of the Anadarko Platform. For HF treatments where we have access to injection parameters, modeling suggests that poroelastic stresses are likely responsible for seismicity, but we cannot rule out direct pore pressure effects as a contributing factor. In all of the 16 regions we identified, ≥75% of the seismicity correlated with reported HF wells. In some regions, >95% of seismicity correlated with HF wells and >50% of the HF wells correlated with seismicity. Overall, we found ~700 HF-induced earthquakes with M ≥ 2.0, including 12 events with M 3.0–3.5. These findings suggest state regulations implemented in 2018 that require operators in the SCOOP/STACK plays to take action if a M > 2 earthquake could have a significant impact on future operations.

Nearly all of these induced earthquakes in Oklahoma have occurred along previously unmapped faults. Earthquake locations can illuminate dense fault fabrics previously unbeknownst to seismologists, provide insight into the rupture process, and inform the regional seismic hazard analyses. In order to characterize these fault networks in Oklahoma, we relocated a large-scale template matching catalog between 2010-2016 using GrowClust. This relocated catalog is currently the most complete statewide catalog for Oklahoma during this seven-year window. Using this relocated catalog, we identified seismogenic fault segments by developing an algorithm that clusters earthquakes and then identifies linear trends within each cluster (Figure 1b). Considering the large number of earthquakes in Oklahoma, this algorithm made the process of identifying previously unmapped seismogenic faults more approachable and objective. We identified approximately 2500 seismogenic fault segments which agreed with focal mechanisms and optimally oriented relative to maximum principle stress direction.

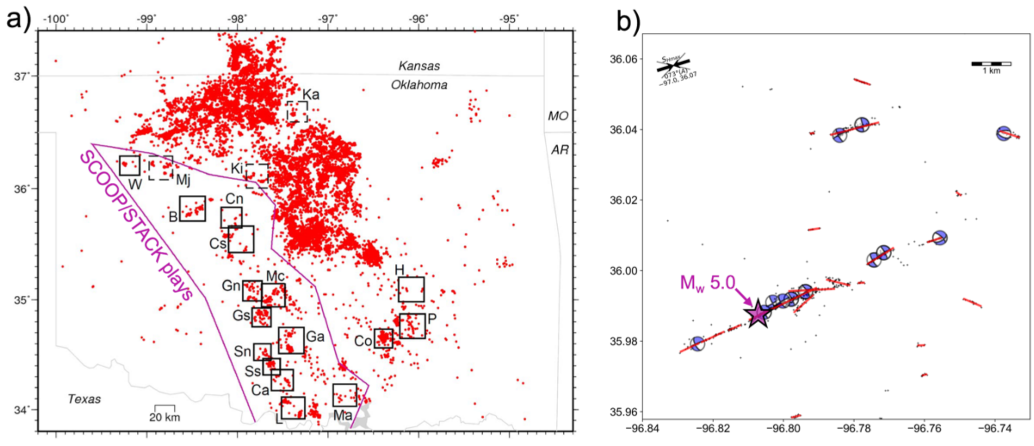

Fig. 1 a) Earthquakes in the Oklahoma area (red dots) and the regions dominated by hydraulic fracturing induced earthquakes (black squares). b) Example of the relocated catalog (black crosses), algorithmically identified faults (red lines), and computed focal mechanisms in the area around the 2016 Mw 5.0 Cushing, Oklahoma, earthquake.

Abstracts Posters, Part A

Session 2

Social Aspects of Induced Seismicity

Views of the informed citizen panel to EGS and other electricity generation alternatives in Switzerland

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Decision science literature argues that conventional opinion surveys are limited for making strategic decisions because the elicited opinions may be distorted by misconceptions and awareness gaps that prevail in the public. Such distortions are in particular expected for new technologies and phenomena, such as Enhanced Geothermal Systems (EGS) and their induced seismicity risk. We created an informed citizen panel (N=46) for understanding the preferred Swiss electricity mix in 2035, given the information about environmental, health, economic impacts as well as accident risks of various electricity generation alternatives. We used technology factsheets, an interactive web-tool Riskmeter, and group discussions for informing the opinions of participating citizens. We then measured the evolution of the panel's knowledge and preferences from initial (uninformed) to informed and longer-term views four weeks after. For EGS, we found that the participants were in particular sensitive to new information as they did not yet have a stable opinion formed and, in fact, with more information the opinion worsened. Induced seismicity risk was one of the elements that was used by our participants in their opinion formation, but high technology costs of EGS was another important element. We also found structurally different pattern in the evolution of opinion for EGS and other renewable electricity generation alternatives. We thus conclude with implications of these findings for understanding the public preferences for EGS and for communicating about it.

Abstracts Posters, Part A

Session 3

Natural or Induced, and Beyond

Hydromechanical modelling of the hydraulic stimulation PX2-1 in Pohang (South Korea)

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Between January 2016 and September 2017, a sequence of five hydraulic stimulations were carried out in the two wells of the Pohang EGS project. In the well PX2, the first stimulation campaign was done by injecting cyclically during about two weeks a total volume of about 1970 m^3 with flow rates of up to 47 l/s and with very high well head pressures of up to 90 MPa (900 bar). The equivalent downhole pressure at the injection interval below the casing shoe (4208 m) is about 132 MPa, which is higher than both the vertical principle stress (rock overburden, ~109 MPa) and the minimum horizontal stress, which is smaller than the vertical principle stress if a strike-slip stress regime is assumed. Analysis of the micro-seismicity during the injections shows that the seismic events during the stimulation fall on a plane at several hundreds of meters away from the injection interval. This plane could be part of the fault system of the M5.4 earthquake.

We present first results from an ongoing modelling work to investigate the hydromechanical impact of the high pressures applied in PX2 on the observed plane of seismicity assuming that there is no direct highly conductive pathway connecting the inflow point and the supposed rupture plane. We use the numerical code CODE_BRIGHT, developed at UPC, to account for poroelastic hydromechanical effects in a 2-D vertical plane containing the supposed low permeable rupture plane (RP; Figure 1) and the source fault (SF) where water is injected in the PX2 well below 4208 m. For simplicity and because we have no data on the orientation of the different rock materials discerned by well logging along PX2, we assume that the different materials and also the source fault extend parallel to the rupture plane. We argue that these simplified assumptions are justifiable because many structures of fault zones found in the literature are highly anisotropic with alternating high conductivity disturbed zones and low permeable fault gouge zones parallel to the fault planes. Finally, we want to investigate a case with a direct high conductive pathway from the injection point into the assumed rupture plane.

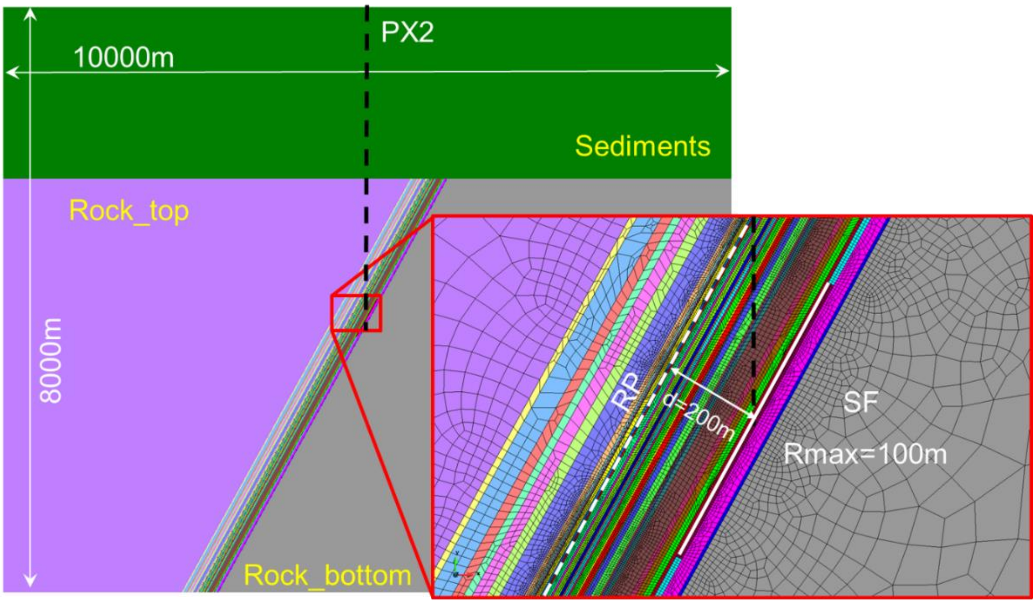

Fig. 1 2D vertical domain for poroelastic hydromechanical modelling of the first stimulation in the PX2 well. RP denotes the supposed rupture plane where micro-seismicity has been observed with assumed hydromechanical properties of a fault core zone, water is injected into the source fault SF within the open borehole section of PX2. The hydromechanical parameters of the different fault sections are derived from well logging data.

Seismic moment tensor analysis for the 2016 Gyeongju and 2017 Pohang earthquakes

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Seismic full moment tensors are valuable for discriminating among seismic sources such as earthquakes and collapses. We present seismic moment tensor analyses for two of the largest earthquakes in South Korea. The first event occurred on 12 September 2016 in the city of Gyeongju, and is considered the largest earthquake (Mw 5.5) since instrumental recording in South Korea started in the early 1900s. Another event on 15 November 2017 that struck near Pohang is the second largest (Mw 5.4) and most damaging. This latter event occurred at an Enhanced Geothermal System (EGS) site where recent hydraulic estimulation operations are believed to have had a role inducing the earthquake.

We estimate moment tensors for these earthquakes using regional and teleseismic waveforms from all available seismic broadband stations within a radius of 2000 km. Our moment tensor inversion method involves performing a full grid search over the 6D space of moment tensor parameters (including magnitude), generating synthetic waveforms at each moment tensor grid point, and then minimizing a misfit function between the observed and synthetic waveforms. We characterize the moment tensor uncertainty in terms of the variation in waveform misfit on the eigenvalue lune, a probability density function for moment tensor source type, and a confidence curve for the probability that the true moment tensor lies within the neighborhood of the best-fitting moment tensor.

We apply the methodology to the two earthquakes, and for the six declared nuclear tests and a collapse in North Korea. We present our analyses of the two earthquakes in comparison with our estimates for the six declared nuclear tests and a collapse in North Korea. In terms of the moment tensor source types (e.g. tensile, shear, explosions, collapses) our results show clear separation among the earthquakes, the explosions, and a collapse. Our results for the Gyeongju event (Fig.1a) show a clear double-couple whose mechanism (and source type) is stable over a range of depths. Our results for the Pohang event (Fig.1b) show large variability in moment tensor over a range of depths; its source type shows a range of similar-fitting solutions with negative isotropic (e.g. collapse) components.

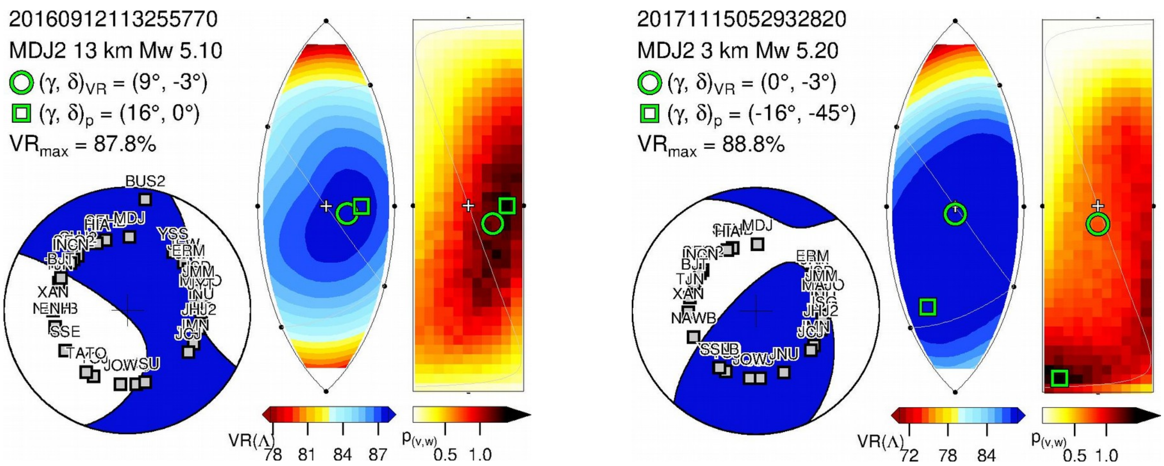

Fig. 1 Moment tensor uncertainty analysis for the Gyeongju (left) and Pohang (right) earthquakes. (See: Full Moment Tensor Analysis of Nuclear Explosions in North Korea; Alvizuri and Tape, 2018)

Seismicity analysis with spatial or temporal relation to the deep geothermal project in Pohang

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We investigate seismic events between January 2016 and November 2017 that occurred in close vicinity of the deep geothermal project in Pohang, Korea. Our aim is to understand the structure of the reservoir created by high pressure water injections during five individual stimulation campaigns. Further objectives are to determine whether the epicenter of the M5.4 event is located within the stimulated reservoir and whether the location of the epicenter can be attributed to the rock volume stimulated by specific high-pressure injection campaigns.

For our analysis we use data from locally installed networks (0-150m depth) and a deep borehole sensor (2.3 km). The dataset has many issues, such as changing network geometries, data gaps, timing issues, inter-channel time shifts and complex velocity structure. However, with careful step by step processing and manual quality control we were able to propose a reservoir structure and to investigate the possible link to the magnitude 5.4 earthquake that happened two months after the last stimulation.

In this talk we explain the issues of the Pohang dataset and how we tackled each problem. We show the sensitivity and potential bias caused by varying network geometry and velocity model. We then interpret seismicity by fitting planes to localized events of each stimulation in order to identify planar reservoir structures. Using waveform similarity analysis, we derive dependencies between each of the five individual stimulations. Waveform data of the foreshocks of the magnitude 5.4 earthquake are compared to the waveform data of induced seismicity caused by the stimulations. Linking waveforms of foreshocks to reservoir events gives an approximate indication where the M5.4 event originated. The depth of the M5.4 event is checked independently by modelling InSAR displacement observations.

The November 15, 2017, Pohang earthquake: A potential anthropogenic event of Mw 5.5 in South Korea

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On 15 November 2017 a Mw 5.5 earthquake struck the southeast part of the Republic of Korea (South Korea), injuring many people and causing extensive damage in and around the city of Pohang. This event was preceded by the September 2016 Mw 5.5 Gyeonju earthquake, occurred ~30 km farther south on one of the largest fault of the region, the Yangsan Fault. These two earthquake were the largest earthquake ever recorded since the last century in Korea. The November 2017 earthquake has triggered intense public debate in South Korea about its potential link with geothermal stimulation operations at a nearby EGS site. The proximity of this industrial facility with the epicentre of the earthquake has raised public concerns in South Korea, reflected by the sharp increase of web searches using the keywords "geothermal" and "geothermal power plant" in Korea in the days following the Pohang earthquake. In the absence of data from a local seismic network, we use advanced full-waveform seismological techniques, applied to regional and teleseismic network data, to locate the Pohang earthquake sequence and determine the source parameters of the largest events. We also use geodetic data to quantify the coseismic deformation and obtain an independent estimate of the mainshock source parameters. Seismicity and geodetic results are in agreement regarding location, depth and fault geometry. In addition, another interesting feature of this event is the large non double-couple component associated to its source mechanism. Moment tensor inversion in fact indicated that the mainshock is composed by a reverse-faulting to oblique double couple (DC) mechanism and a large non-DC term (~50%). Based on first analyses (e.g. Grigoli et al. 2018), we inferred that the non-DC component is caused by a complex rupture process that includes the simultaneous activation of different faults patches. The main findings of our work are: 1) hypocentral depths are shallower than the characteristic background seismicity of the area and mainly in the range 3-7 km, similar to the depth of injection (~4 km); 2) The mainshock and most of the aftershocks occurred within 2 km of the EGS site 2) The mainshock occurred within 1.5 km from a Ml 3,1 induced event occurred in April 2017, during hydraulic stimulation operations. 3) Our seismological and geodetic analysis rules out a re-activation of the Yangsan fault, but we found that the earthquake transferred static stress to its northern branch, potentially increasing the seismic hazard in the area. 4) Our full-waveform techniques (using regional and teleseismic data publicly available) demonstrates the extent to which a suspected case of induced seismicity can be investigated without local data from site operators.Finally, according to our analysis it seems possible that the occurrence of this earthquake was influenced by these industrial activities.

Reactivation of Unfavorably-oriented Faults for the 2017 Pohang Earthquake Sequence: Driven by Fluid Overpressure?

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The 2017 *Mw* 5.4 Pohang earthquake has been suggested to be induced by fluid injection from the nearby Pohang enhanced geothermal system (EGS). The temporal and spatial distribution of hypocenters (depth range: 2.5–7 km) including 6 foreshocks and 3,240 aftershocks as well as the mainshock recorded by our local seismic array for 340 days suggests a complex geometry and evolution of rupture segments. The initial rupture, based on 3-hour seismic data after the mainshock, consists of a main segment (N30E (strike)/51NW (dip), 3.5 km long; MS) and a subsidiary one (N10E/47NW, 1.5 km long; SS1) extending from the northeastern tip of MS. The fault slip of MS and SS1 is dominated by reverse and strike slips, respectively. The second subsidiary segment (N8E/58NW, 2 km long; SS2) has propagated from the northern tip of SS1. Toward southwest, the main segment (MS) has propagated further (~ 1.4 km more) from the first 3-hour configuration. Then, the third subsidiary segment (N67W/83SW, 1 km long; SS3) has developed at the southwestern tip of MS, almost perpendicular to MS. The fourth subsidiary segment (N13E/55NW, 2 km long; SS4), subparallel to MS, crosscuts SS3.

The aftershock sequence shows that the frequency decreases with the reciprocal of time, following Omori's law, until 83 days after the mainshock and then there was a sudden surge of aftershock frequency with an M_L 4.6 event (2018.02.11), followed by another Omori's-law decay. The timing of SS3 development corresponds to the aftershock surge with the M_L 4.6 event. The calculation of Coulomb stress change caused by the mainshock shows that there is a significant increase in stress (~ 1 bar) around SS3. All these suggest that SS3 is an independent rupture triggered by the mainshock.

Focal mechanism solutions of the Pohang earthquake sequence show strike-, reverse-, or oblique-slip faultings without any normal-slip component. Stress inversion of these focal mechanism solutions generates nearly horizontal σ_1 (109(trend)/8(plunge)) and σ_2 (18/6) with subvertical σ_3 (252/81), indicating a compressional regime. The stress ratio, $R = (\sigma_1 - \sigma_2)/(\sigma_1 - \sigma_3) = 0.89$, is rather high, suggesting a permutation of σ_2 and σ_3 is highly likely. Using orientations of these principal stresses and rupture segments, and assuming a frictional coefficient of 0.85 (based on Byerlee's law for $\sigma_n < 200$ MPa since the lithostatic pressure at the hypocentral depth of the mainshock is *ca.* 113 MPa), Sibson's (1985, https://doi.org/10.1016/0191-8141(85)90150-6) reactivation criterion shows that the angle between σ_1 and rupture segments on $\sigma_1\sigma_3$ plane (55-67°) is all higher than the frictional lockup angle (~50°). This requires an abnormaly low static friction or high fluid pressure for slip reactivation of the rupture planes of the Pohang earthquake. The development of ubiquitous sand blows with fluid discharge around the epicenter during the mainshock and its hypocenter in the immediate vicinity of the injection well suggest that overpressurized fluid should have played an important role in the 2017 Pohang earthquake event.

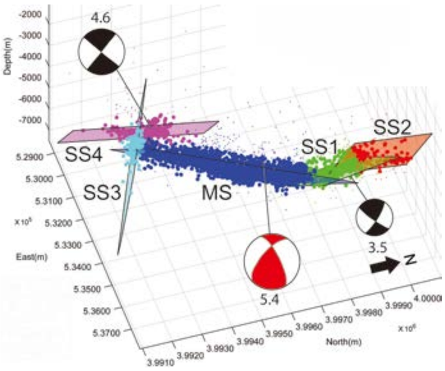

Fig. 1 Rupture segmentation of the 2017 Pohang earthquake sequence.

Abstracts Posters, Part A

Session 8

Deep Underground Laboratories

Design of the seismic monitoring network for the stimulation experiments in the Bedretto Deep Underground Rock Laboratory

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Induced seismicity associated with hydraulic stimulation of geothermal reservoirs has been studied at decameter-scale in several deep underground rock laboratories. Monitoring induced seismicity at these small scales is challenging but remains key to gain insights into stimulation processes. Comprehensive investigations were conducted at the Grimsel Test Site (Switzerland, results are presented by Linus Villiger). Similar experiments have been undertaken by the GFZ Potsdam in the Äspö Rock Laboratory (Sweden) and in the Sanford Underground Research Facility (USA). In addition to the stimulation experiments at Grimsel, a similar monitoring concept is currently applied in an experiment focusing on CO2-saturated brine injection into the Main Fault at the Mont Terri Rock laboratory (Switzerland).

To investigate processes related to geo-energies on the hectometer scale, a new deep Underground Laboratory for Geoenergy research (BULG, Bedretto, Switzerland) is being set up within the framework of the "Deep Underground Laboratory" initiative at the Department of Earth Sciences at ETH Zurich. With the objective to capture an extended magnitude range of induced seismic events a comprehensive seismic monitoring network will be installed.

The planned hydraulic stimulation experiments at BULG aim at closing the gap between the decameter-scale of the previous experiments at Grimsel, Äspö and Mont Terri and the field-scale application in geothermal wells of several kilometer depth. The laboratory is situated in an abandoned access tunnel to the Furka railway base tunnel at about 2km distance from the tunnel portal. It has an overburden of more than 1000m and is situated in a large homogenous, granitic rock volume with a minimum disturbance by only the access tunnel. While this situation provides excellent conditions for the planned stimulation experiments, it also poses large challenges for the seismic monitoring network. Firstly, accessing the rock volume is only possible from a single tunnel, which means all instrumentation has to be implemented through boreholes from this tunnel. But, for minimizing the disturbance of the hydraulic equilibrium in the rock volume the number of possible boreholes is limited. Also, due to the high pore pressures at the given overburden, the boreholes need to be of minimal diameter and all instrumentation needs to be cemented back immediately after installation. The minimal borehole diameter also limits the amount of cable connections in boreholes. Beyond uncalibrated piezo-electric sensors, which provide the highest sensitivity, also 3-component calibrated accelerometer sensors covering different frequency ranges and sensitivities, as well as broad band seismometers are being evaluated. In addition to this variety of sensing elements, down hole sources for tomographic purposes are assessed.

Finally, the seismic network shall allow a balanced spatial sensitivity and coverage in a volume of some 100mx100mx100m. For an optimum sensor network design, we need to optimize the sensor density, but limit the disturbance of the rock volume, the operational effort and cost.

Additionally, a new recording scheme, real-time signal processing and event localization is implemented and refined. This allows an immediate intervention when events at critically large magnitudes or in unexpectedly high numbers occur.

In our presentation we will explain the objectives of the seismic monitoring network for different aspects of the stimulation experiments and present candidate designs based on different borehole geometries and sensor combinations.

In situ stress characterization in the Bedretto Underground Laboratory: implications for induced slip of existing fractures

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ETH Zürich and the Swiss Competence Center for Energy Research – Supply of Energy (SCCER-SoE) is establishing a Deep Underground Geoscience Laboratory (DUGLab) in the Swiss Central Alps. The laboratory is located in the Bedretto tunnel (a branch of the Furka railway tunnel). The Bedretto Underground Laboratory (BUL) sits in an enlarged section of the tunnel (between TM2000-2100) from its south entrance. The tunnel axis trends ~N43°W, generally along the mountain ridge line above. The altitude at the tunnel entrance is ~1480.5m a.s.l. The overburden gradually increases to a maximum of 1650m at Pizzo Rotondo (TM3100). The overburden directly above the BUL is between 1000 and 1030 m.

For the main experiments planned to begin in 2019, a detailed in situ stress characterization is currently underway. Such information is critical to the experimental design and later appropriate interpretation of the experimental observations. To do so, we plan our site characterization according to the following questions:

What are the in situ stress conditions (principal stress directions and magnitudes) and how significant are the stress variations at the BUL?

What are the geometries and the distributions of the pre-existing fractures at the BUL? Are they natural fractures or induced due to tunnel excavation (blasting) and later perturbation?

What are the slip tendencies of these pre-existing fractures under the prevailing in situ stress conditions, given increased pore pressure during stimulation?

To answer these questions, we plan to drill several pilot boreholes to inspect the rock mass around the BUL and to conduct hydraulic fracturing stress measurements. As these activities are currently ongoing, the available fracture mapping and stress indicators associated with the local geology have been compiled to faciliate a preliminary study.

Our current knowledge on the stress field in the region partially comes from the World Stress Map. It indicates that a NW-SE direction of the maximum horizontal stress S_{Hmax} is expected, which would be sub-parallel to the tunnel. A predominant strike-slip regime throughout the Swiss Alps with some normal faulting towards southern Switzerland implies that thrust faulting is unlikely at the site. Nonetheless, rotation of the stress tensor is possible. Given the depth of the BUL, the local topographic effect can be superimposed onto the tectonic-controlled first-order stress pattern to cause the stress regime to vary between strike-slip and normal faulting. Thus, S_{Hmax} is expected to correspond to either the intermediate principal stress S_2 (i.e., normal faulting, $S_1 = S_v$), or the major principal stress S_1 (i.e., strike slip, $S_2 = S_v$).

Along the Bedretto tunnel, stress-induced failure (e.g., spalling and kinking) is observed on the sidewalls at certain sections where cross-cutting fractures are rare. If not associated with tunnel excavation, it indicates that the horizontal stress perpendicular to the tunnel is smaller than the vertical stress. Therefore, we presume that the local stress regime is strike-slip and/or normal faulting. Thus, the N-S striking and steeply-dipping fractures can potentially be activated with elevated pore pressure perturbation. These serve as important constraints to our experimental design.

CS-D experiment: CO_2 injection and mobility within a fault zone in tight caprock at Mont Terri

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Permeable faults represent one of the possible leakage pathways for CO_2 to migrate out of the storage reservoir through the caprock. It is widely recognized that this pathway plays a key role for the safe, long-term containment of a CO_2 storage site, as well as for the phenomenon of induced seismicity. Thus, the presence faults in caprocks will greatly affect the site characterization process in terms of the safety assessment, and consequently the monitoring, verification, and risk management plan (prevention, mitigation, remediation measures).

The CS-D experiment (August 2018 - July 2020) at the Mont Terri Lab, aims to investigate caprock integrity by determining CO_2-rich water mobility in a fault zone. We monitor for geochemical and geomechanical changes induced by CO_2 saturated fluid injection for prolonged time (approximately eight months), with the aim to better understand mechanisms of CO_2 leakage, and develop strategies to detect/monitor/predict it. Moreover, we focus on understanding the relative contribution of aseismic vs seismic slip associated with the fluid leakage in the fault zone.

The experiment offers a unique opportunity to develop improved, and more integrated monitoring technologies. One of the primary goal of the seismic instrument is to monitor for the occurrence of seismic events caused by the pressure increase may lead to the creation of preferential pathway, easily observable in close-up configuration as the one designed for CS-D (Fig. 1). The monitoring program will be continued after the end of injection (Fall 2019) in order to allow for studying not only the short-term poro-visco-elastic response, but also the geochemical and mineralogical changes within the damaged zone. This experiment will help improving the methods for monitoring and imaging fluid flow.

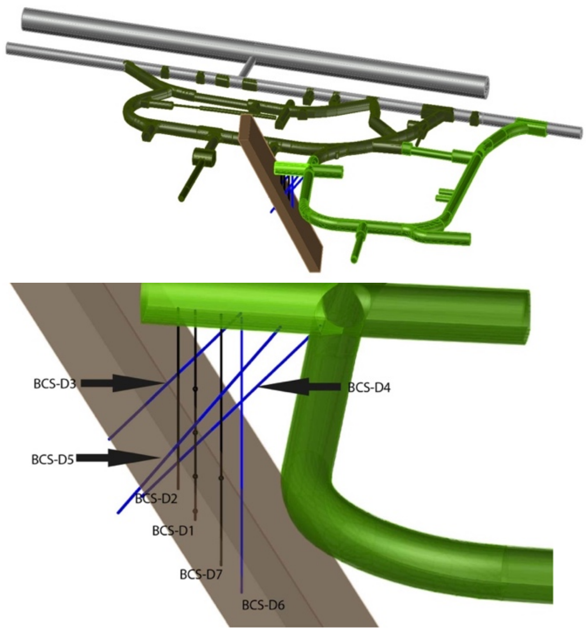

Figure 1 *(top) The Mont Terri Underground laboratory and the fault zone (brown). Niche 8, hosting the CS-D experiment, is in yellow-green. (bottom) Position of the boreholes for injection (BCS-D1), SIMFIP (BCS-D7), fluid monitoring (BCS-D3), and geophysical monitoring (BCS-D3-6).*

The design of the seismic instrumentation includes four geophysical monitoring boreholes. The geometry of those boreholes was designed for performing cross-hole active seismic and electrical resistivity monitoring and to place sensors for microseismicity monitoring. These geophysical boreholes are instrumented with permanently installed (electrodes and geophones) and mobile (piezo streamers and seismic sparker sources) equipment. In addition to the geophysical sensors and sources employed in the boreholes, geophones, piezo-sensors, and seismic hammer sources are installed at the surface in niche 8.
At the meeting, we will present the preliminary result of repeated short pulse tests, where CO_2 saturated water is injected at different location within the fault zone, and the associated induced seismicity.

Seismic Response to Hydraulic Fracturing in Anisotropic Rock

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The STIMTEC project is a joint project by RU Bochum, GFZ Potsdam, TUBA Freiberg, and Geomecon. The project aims at characterizing the evolution of fracture networks during hydraulic stimulation as commonly used in the production of geothermal energy. The observations from an in-situ experiment are expected to form the basis for an optimization of stimulation procedures. The mine-back experiment is located in the underground laboratory *"Himmelfahrt-Fundgrube" (Schacht "Reiche Zeche") in Freiberg*. The testing was performed at the -147 m depth level (+281 m NN, approx. 120m below surface), accessible via shaft from the surface. Small seismic events (picoseismicity) were recorded using an in-situ AE monitoring network with twelve in-situ AE sensors and three high-frequency accelerometers. All sensors were installed in eleven monitoring boreholes at distances of 5.3 m to 19.7 m from the injection borehole. The sensors are located above the 63 m long injection borehole that is dipping downwards with about 15°. Seismic waveforms were recorded both in trigger-mode recording (sampling frequency 1 MHz) and recorded continuously (sampling frequency 200 kHz) throughout the project. Monitoring periods include two 2-week long intervals before and after the stimulation, respectively, aiming to characterize potential background seismicity.

We present preliminary results from the analysis of more than 10,000 recorded seismic events. So far, seismic activity was not identified before or significantly after the pumping sequence; all seismic events correlate to ongoing fluid-injection cycles, e.g. during pressurization, or shortly after shut-in, i.e., the pressure-decay phase after termination of pumping. Most seismic events are recorded from injection intervals at 22.4 m, 24.6 m, and 28.1 m injection borehole depth, i.e., the three stimulated intervals that, out of the 10 in total, are closest to the sensor array. Few seismic events are recorded from injection borehole depth 33.9 m, and 37.6 m. No triggered events were recorded from injection intervals at a borehole depth > 40 m. This apparent difference in seismic activity likely correlates to recording limitations (e.g. due to intrinsic damping) or changes in rock properties. Seismic events outline complex structures both with vertical and horizontal orientation pointing towards (re-)activation of a fracture network.

On the variability of seismic response during multiple decameter-scale hydraulic stimulations in crystalline rock

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In early 2017, 12 hydraulic stimulation experiments were performed in a 20 x 20 x 20 m foliated, crystalline rock volume intersected by two distinct fault sets at the Grimsel Test Site, Switzerland. The goal of these experiments was to support research and development related to enhanced geothermal systems. The first series of stimulations was intended to permanently enhance hydraulic transmissivity associated with shear dislocation along existing structures (i.e. so-called hydroshearing experiments). Four of these stimulations targeted ductile shear zones (termed S1), which are characterized by a more distinct foliation compared to the host rock and brittle fractures of various orientations. Two stimulations were conducted on two brittle-ductile faults (termed S3.1 and S3.2) each consisting of a fault zone associated with biotite-rich metabasic dykes up to 1 m thick. The lateral distance between these two S3 faults was about 2.5 m and the rock mass between the faults was heavily fractured (Krietsch et al., 2018a). To gain insight on how the variable geology affects the seismo-hydro-mechanical response, the injection protocol was similar for all stimulation experiments. The far field stress state determined in a previous stress characterization campaign (along with an extensive geological characterization) suggested a higher tendency for shear dislocation for injections in the ductile shear zone S1 (Krietsch et al., 2018b).
The second series of six stimulations were performed in the same experimental volume in borehole intervals that did not contain any natural fractures using higher injection rates and injection pressures with the intention to initiate hydraulic fractures, which connect the wellbore to the existing fracture network. Multiple types of injection fluids were used to study their propensity to fracture: water and higher viscous fluids (with a dynamic viscosity about 30 times higher than water) were studied.
To measure seismicity during the various injections a comprehensive array of 26 highly sensitive acoustic emission sensors (AE, bandwidth: 1 – 100 kHz, highest sensitivity at 70 kHz) were installed. The core of this sensor network consisted of eight AEs diploid in four monitoring boreholes, which allow to reduce the distance between sensors and the injection interval in the range of 5 to 25 m.
Results of the first experiment series - the hydroshearing experiments - show higher increases in hydraulic transmissivity for injections targeting S1 shear zones compared to injections into S3 fault zones. This is expected given the higher slip tendency on S1 structures. However, the number of detected and located seismic events is lower compared to stimulations targeting S3 fault zones. The b-values (referring to the size distribution in frequency-magnitude distribution) were lower for stimulations in shear zones S1. In all the stimulations, clustering of seismic events can be observed, highlighting preexisting and new features inside the shear zones. Some of the seismic clouds also indicate new fractures that splay off from the shear zones. The high variability in seismic response from these first series of experiments is related to the different geological characteristics of the fault zones. New fractures induced in intact rock during the second series of experiments form perpendicular to the minimum principal stress and partially connect to the existing fracture network. Interpretations and conclusions of this unique induced seismicity dataset of 12 controlled injection experiments are presented in this contribution.

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Abstracts Posters, Part A

Session 9

Advances in Monitoring Induced Seismicity

Moment tensors of waste-water disposal induced seismicity in southern Kansas

Amandine Amemoutou[1], Patricia Martínez-Garzón[1], Grzegorz Kwiatek[1], Justin Rubinstein[2], Marco Bohnhoff [1, 3]

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Fluid-injection into the subsurface in the frame of reservoir-engineering activities for hydrocarbon and geothermal energy production has resulted in a dramatic increase of induced seismicity during the last 10 years. This includes four M>5 earthquakes in Oklahoma and Kansas (US) through the reactivation of previously unknown critically stressed and thus hazardous faults in the basement. We investigate seismic recordings of relocated events with local magnitudes M_L in the range [1.9, 5.2] from a regional seismic network deployed in southern Kansas since 2014 including 19 broadband stations and 5 accelerometers. Determination of seismic moment tensors and subsequent refinement was done employing the hybridMT package (Kwiatek et al., 2016). HybridMT inversion is based on the P-waves first ground displacement amplitudes from vertical components and provides unconstrained full, deviatoric, and double-couple constrained moment tensors. The results of moment tensor inversion are refined and suppresses the influence of local path, site, and sensor effects. In this study, we also implemented the use of the horizontal components, thereby increasing the input data by a factor of 3. The refined methodology was tested and tuned on synthetic datasets based on the shear-tensile source model (Vavrycuk, 2001). This model describes the source kinematics by four fault plane parameters (strike, dip, rake) and a tensile angle representing the fault opening. We find that focal mechanisms from the 3-component inversion are generally consistent with the generated synthetic fault plane parameters, signifying the correct performance of the new approach. Furthermore, moment tensor inversion of several tens of events with already reported focal mechanisms (Rubinstein et al., 2018) appear to be generally consistent between applied methods. In this contribution, first results from statistically significant full moment tensors as well as double-couple solutions from initial ~2,300 seismic events are presented and discussed in the context of their spatial and temporal changes within the investigated area.

The influence of seismic anisotropy on microseismic moment tensors and their radiation patterns

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Radiation patterns of earthquakes contain important information on tectonic strain responsible for seismic events. However, elastic anisotropy may significantly impact these patterns. Especially for microseismic events induced during hydraulic fracturing in shales this effect needs to be considered.

Therefore, we study systematically the influence of anisotropy on the radiation patterns of microseismic events. We have to account for two different effects: the anisotropy in the source and the anisotropy on the propagation path. Source anisotropy mathematically comes from the matrix multiplication of the anisotropic stiffness tensor with the source strain expressed by the potency tensor. The potency tensor is a pure kinematic description of the source process, whereas the moment tensor is already influenced by the elastic properties of the source medium. We analyze this effect using the corresponding radiation pattern and the moment tensor itself. Propagation anisotropy mathematically comes from the deviation between the polarization and the propagation direction of a quasi P-wave in an anisotropic medium. We can investigate both effects separately by either assuming the source to be anisotropic and the propagation isotropic or vice versa. We show that both effects have a significant impact on the radiation pattern of a pure-slip source.

Therefore, we propose an alternative visualization of source mechanisms by plotting beachballs proportional to their potency tensors and call this the potency isotropic equivalent (PTI). For this we multiply the potency tensor with an isotropic elasticity tensor having the equivalent shear modulus μ and $\lambda = 0$. In this way we visualize the tectonic deformation in the source, independently of the rock anisotropy, see also figure 1. There we show the radiation pattern of a pure normal faulting source, which is influenced by both effects (left side) or only the source effect (middle). We see, that both radiation patterns are not pure double couple, but contain compensated linear vector (CLVD) and volumetric components. On the right side, we show the radiation pattern of the PTI, in other words how this event would look in isotropic media. This visualization is directly proportional to the deformation in the source and is pure double couple.

Finally, we apply this theoretical findings to one of our microseismic datasets from a hydraulic fracturing treatment in a shale. We show, that the inverted moment tensors generally have very high non-double components. However, their potency tensor isotropic equivalent is nearly pure double couple. In this case, the non-double components are an artifact of the anisotropic medium. Furthermore, the source mechanisms expressed by the PTI show much more consistency compared to the moment tensors. We conclude that we should rather interpret the potency tensor, or the potency-isotropic equivalent, than the moment tensor.

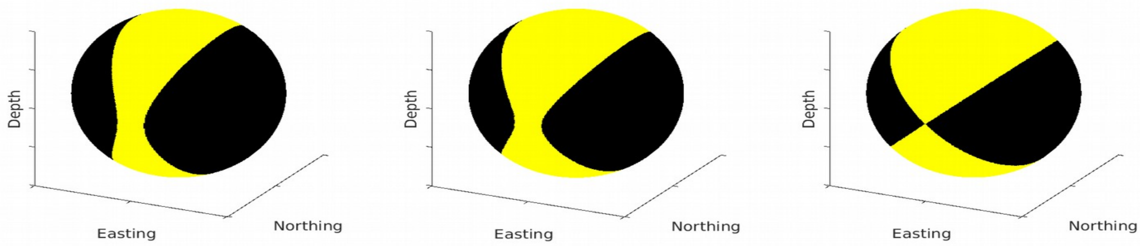

Fig. 1 Left: Radiation pattern taking into account all effects of anisotropy, middle: radiation pattern cleaned from the propagation effect, right: Radiation pattern of the PTI (potency-isotropic equivalent)

Microseismic monitoring and source discrimination at Izvorul Muntelui dam, northeast Romania

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Izvorul Muntelui is one of the largest dams in Romania, built between 1950 and 1960 and located in the Eastern Carpathians, northeast Romania. Although the water reservoirs often generate seismic events as a result of stress variation due to the weight of the water column, before 2011, Romanian earthquake catalogue (ROMPLUS) highlights only a small number of low-magnitude events associated to the dam. With the recent development of the Romanian Seismic Network, maintained by the National Institute for Earth Physics, the number of events in the catalogue show an increasing trend and a significantly lowered magnitude detection threshold. To have a better view of the seismicity patterns in the region we applied a multi-channel waveform template correlation detector to the seismic data recorded between 2012 and 2018 by a small-aperture seismic array Bucovina (BURAR), located about 100 km northwest from the dam, and a 3-component broadband seismic station Bicaz (BIZ) located in its immediate vicinity. The spatio-temporal analysis of the detected events revealed at least 3 clusters of seismic activity located in the upper part of the crust (< 15 km depth). Many of those events were generated during the day time with the locations that seem to correspond to the location of quarry explorations identified near the dam (up to 30 km). At the same time, the statistical techniques and spectral analyses allowed a partial separation between tectonic and anthropogenic events, indicating that only a low number of detected seismic events is directly associated to the water level fluctuations in the dam.

Towards Real-Time Double-Difference Hypocenter Relocation as Component for Advanced Traffic Light Systems

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In order to assess the spatio-temporal evolution of induced seismicity, high-precision (relative) micro-seismic hypocenter locations are key information in advanced traffic light systems. From such precise relative hypocenter locations, we can infer e.g. the seismogenic volume affected by stimulation procedures as well as geometries of potentially reactivated faults. The spatio-temporal evolution of seismicity (e.g. migration velocities of seismicity, r-t-diagrams), on the other hand, can be indicative for fluid-flow processes and allows first-order estimates on hydraulic properties of the reservoir as well as on the existence of possible hydraulic connections. Information on spatial extent, geometries and the spatio-temporal evolution of seismogenic structures can therefore help to improve the seismic hazard assessment of induced seismicity in real-time or near-real-time.

To make use of information provided by such high-precision hypocenter locations in advanced traffic light systems requires, however, relative relocations computed in near-real-time. This can be rather challenging, especially at the beginning of a seismic sequence, when only little or no background seismicity is available for relative relocation. In addition, an automated relative relocation process requires differential times derived from precise and reliable (absolute) automatic picks as well as from waveform cross-correlation.

In this work, we present our strategy towards a near-real-time relative relocation procedure as a component of the RT-RAMSIS framework (**R**eal-**T**ime **R**isk **A**ssessment and **M**itigation **S**ystem for **I**nduced **S**eismicity) developed by the Swiss Seismological Service. The procedure follows the strategy outlined by Waldhauser 2009 (BSSA; doi:10.1785/0120080294) and combines differential times derived from automatic as well as manual picks with waveform cross-correlations measurements. Differential times of new events are inverted for relative locations with respect to a background reference catalog using the double-difference algorithm. We present results derived by a python-based prototype applied to natural and induced earthquake sequences in Switzerland. In addition, the prototype is implemented in a new *SeisComP3* (*SC3*) module, which allows the application in a full real-time environment, using pick-based detections and locations from various existing *SC3* modules (*scautoloc*, *scanloc* and *screloc*) as input for relative relocation. In addition, detections from cross-correlation (template-matching) based methods can be later used as initial locations in the same *SC3* framework. We outline our implementation strategy, relative-relocation specific extensions to the *SC3* data model, and compare preliminary *SC3* results with results derived by our python-based prototype.

Automatic picking for induced seismicity in Iceland using an EAT (Empirically Aggregated Template) methodology

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Better understanding of how fluid injections reactivate pre-existing fractures and induce seismicity is a concern both for geothermal plants and local populations due to the seismic hazard. A combination of seismic data analysis, interpretation and modeling is required to develop a comprehensive understanding of the processes involved. The main goal of this study is to map the deep fracture network below the Reykjanes Geothermal field (Iceland) using induced microseismic events. These results will guide us in further testing and improving methods for numerical modelling of fluid flow in fractured media and the interaction of fluid flow with fracture initiation/propagation and heat transfer.

38 three-component stations comprising geophones, short period and broadband seismometers, have been deployed on the Reykjanes Peninsula (Iceland) and recorded both natural and induced seismicity from April 2014 until August 2015. In this study, we consider 4 months of data.

Using a STA/LTA triggering method on continuous data, more than 7000 seismic events were detected. Both natural and induced, and they are characterized by a low frequency content of about 2 to 20 Hz. Strongly attenuated high frequencies, a low signal to noise ratio (SNR) as well as many emergent P-phases result in difficult P- and S-onset identification. Coupled with the number of events, manual phase picking of detected events would require huge processing time and effort. Moreover, manual picking is not consistent as it strongly depends on the operator, especially with noisy data. Instead, we investigate the possibility of automatic picking based on cross-correlations, as many earthquakes present similar waveforms. The automatic picking method is divided into 2 main steps. Firstly, a pre-processing part that consists of defining a Master Event Template. Secondly, using the template to automatically pick seismic events (hereafter, called child events) through cross-correlation.

The preprocessing step is an innovative concept as we do not use simple Master Event Templates but rather, an Empirically Aggregated Template model (EAT). Earthquakes with similar waveforms and close to each other, are due to similar physical mechanisms and can be gathered in a cluster. We define representative master events (for this dataset) as seismic events characterized by a SNR greater than 2. The master events are picked and grouped into separate clusters. Each cluster is used to build a single EAT event, by selecting the best waveform (in terms of SNR) for each channel from the events within the master event cluster. Although the EAT cannot be used for location or source parameter computation, the EAT event is valid as a tool for picking the P- and S-phases of child events.

The automatic picking of P- and S- phases is also divided into two sub-steps. Firstly, for each child event, the EAT to be used for picking the P- and S-phases needs to be determined. For each EAT, a cross-correlation is performed with the child event for each trace. The EAT with the maximum average cross-correlation coefficient across the stations is selected as the best EAT. Secondly, the phases of the child event are picked. We define our search window for P- and S-onsets using the maximum P and S travel-time differences for the selected EAT. Cross-correlating these windows with the EAT P- and S-waves, the child event P- and S-phases may be picked when their cross-correlation coefficient excesses a defined threshold.

First tests on the dataset are promising but additional work is needed to define the best input parameters (e.g. filter choice, length of the P- and S-windows, threshold, etc.). The current methodology requires manual checking and some corrections. Consequently, new criteria must be found to make this method more robust, which is the focus of future work.

Practical Implementation and Evaluation of a Real-time Forecasting-based Induced Seismicity Management System

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Practical management of induced seismicity (IS) risk and effective mitigation approaches are crucial to oil and gas operations. The majority of the regulatory traffic light protocols introduced to date is reactive and based on staged magnitude thresholds. The operators are required to establish operational protocols designed to minimize the likelihood of the occurrence of large magnitude events and are in some instances mandated to implement high-resolution seismic monitoring arrays. The ultimate goal of these seismic networks and their data products, beyond simple regulatory compliance, is to provide operators with a near real-time measure of the IS risk and an indication of the implemented mitigation protocol effectiveness. One such approach includes using high-resolution seismic data products to drive maximum magnitude (M_{max}) and seismicity forecasting models in near real-time, allowing for adjustments in operational parameters to reduce the probability of a felt or damaging event.

In this study, we present the learnings from a practical implementation of a three forecasting models-based risk management system for hydraulic fracturing operations (Figure 1). The system seismicity prediction performance is validated via real-time monitoring and playback in over 30 diverse datasets. The results show that the estimated seismicity agrees well with observed seismicity in majority of cases, multiple models produce very similar results and injected volume has limited impact on seismicity forecasts. The study also highlights the limitations of this approach when a large event occurs early in the sequence. One of the most important takeaways is the impact that the quality of seismic data has on the system performance. A high-quality data recorded by a local array combined with advanced processing techniques designed to generate "research grade" seismic catalogues automatically in near real-time is a key requirement. This development also serves as an excellent example of collaboration between industry (data acquisition and array deployment), academia (model development), and service providers (data processing advancements and implementation) to understand and manage IS phenomenon.

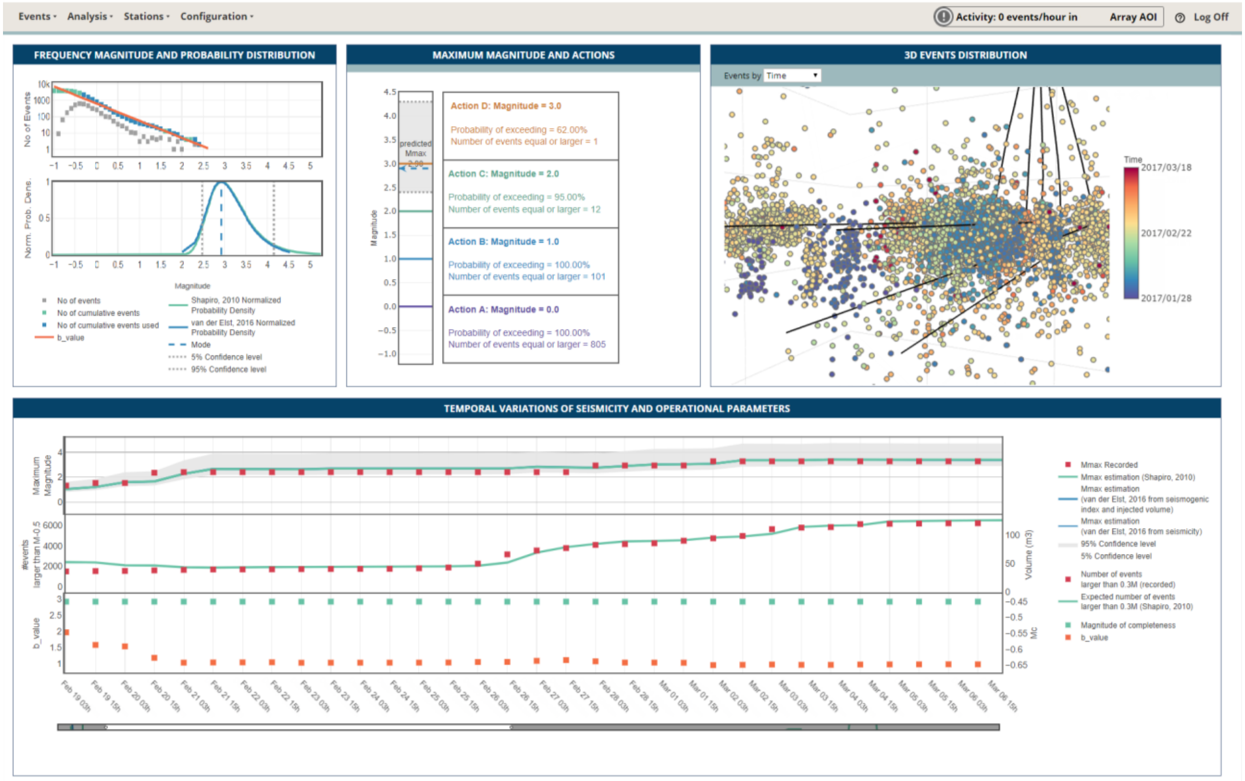

Fig. 1 Seismicity Viewer Dashboard

Automatic full wave-form based monitoring at the deep Garpenberg metal mine

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Several recent studies demonstrate the high value of array and full wave-form based automatic detection and location approaches for monitoring purposes of natural and induced seismicity. The main benefit of these approaches is generally the significant improvement in detection capacity and relative event location accuracy which improves significance of statistical analysis aiming at identifying changes of the seismic rate in space and time and nucleation phases of potential larger dynamic ruptures. In mines, the implementation of such approaches remains challenging and is today by far nonstandard but would probably significantly help to anticipate destructive rockburst events. Main challenges for usage of these methods are related to the presence of a wide range of seismic noises related to mining activities with often similar signatures as microseismic events. In addition, high sampling frequencies of seismic data (several kHz) used in these environments pose problems for real-time data transfer and processing.

Here, we propose an adapted, full-waveform based automatic processing workflow for a local Ineris seismic network located at the deepest levels (> 1 km depth) of the Lappberget district of the Garpenberg metal mine (Sweden). To deal with high frequency sampling (8 kHz) we designed a pre-processing step based on a multi-frequency detection scheme and first-order amplitude-based location. Final source location is then obtained by applying an array coherency based back-projection approach (BacktrackBB) on the preselected and reduced data set. We estimate that detection capacity compared to a usual triggered monitoring system is increased by at least a factor 100. The approach is currently implemented and tested on the local monitoring system and is continuously improved to assure reliable automatic event classification.

A second main field of current ongoing investigations focuses on the design and implementation of an automatic "wave form matching" based approach of seismic repeater families. The approach aims at measuring indirectly aseismic slip in the mining area and providing criteria for seismic hazard as asperity density and larger dynamic rupture potential. Indeed, recent results from source mechanism and parameter analysis, relocation and spatio-temporal statistics have shown that seismicity at Lappberget district seems to be dominated by seismic repeater occurrences that can be interpreted as seismic asperities that repetitively rupture (over periods of weeks to years) as a result of loading of the surrounding creeping weak rockmass (e.g. occurrences of talc) initiated from specific production blasts.

Automatic detection and location of induced and natural earthquakes using Multichannel Coherency Migration

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The occurrence and properties of (micro-) earthquakes yield a huge amount of information about physical processes. Traditionally, human analysts manually pick phase arrivals in order to locate these events, but as data volumes increase this becomes insurmountably burdensome. Instead, automatic methods are required. We propose a novel method to migrate seismic energy back to its source, based on an improved imaging condition with greater noise tolerance, and use it to detect new earthquakes beneath Uturuncu, a volcano in Bolivia, where seismicity is induced by the passage of surface waves caused by the *M* 8.8 2010 Maule earthquake.

The multichannel coherency migration (MCM) sums the absolute correlation coefficients of traces between all stations pairs, using predicted P- and S-wave windows for each imaging point in the target volume. The maximum coherency point in time and space defines the most likely event occurrence. The only adjustable parameter here is the analysis time window—though this is determined by the dominant period of the signal—which is attractive since many migration schemes typically require several parameters to be optimised for each application. Because we use the cross-correlation between stations, incoherent noise is well suppressed, and even coherent noise can be minimised provided it does not occur at a majority of stations. Event location down to signal-to-noise ratios of 0.025 (1/40) is possible in tests.

We apply the MCM to synthetic tests, which show it more reliably finds the true event than the envelope, STA-LTA and kurtosis imaging functions, even with an inaccurate velocity model. This includes the use of real noise from the Aquistore carbon capture and storage site. We finally show the MCM in action on induced earthquakes beneath Uturuncu, where we automatically detect and locate 98% of 114 hand-picked catalogue events, plus 322 verified additional events not previously detected (Fig. 1). Our locations show that seismicity is likely deeper than previously thought, down to 6 km below the surface. This improved catalogue can now be used to further investigate *b*-values, tomography and better perform any other analysis based on seismicity.

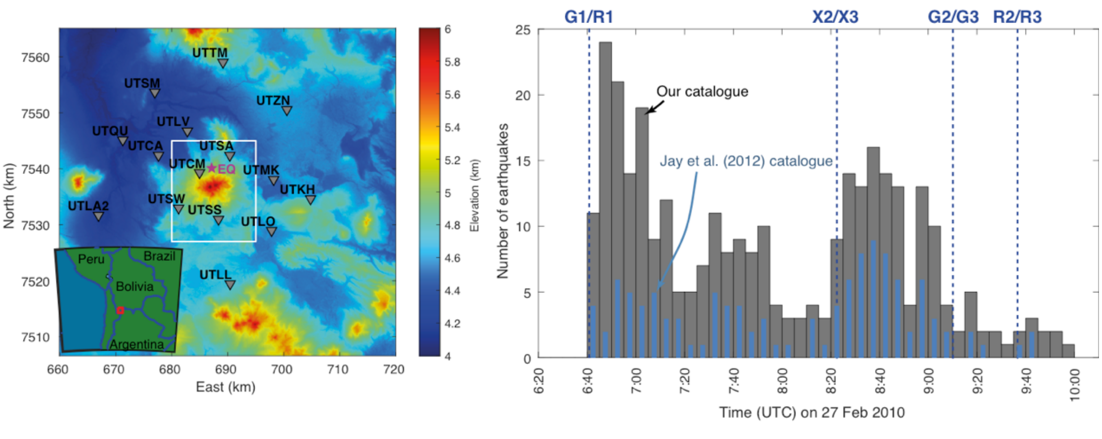

Fig. 1 Earthquakes induced by surface waves (G/R/X) of the *M* 8.8 2010 Maule earthquake. **Left**: Region surrounding Uturuncu volcano. Triangles show broadband seismometers used for event migration; white box is migration region; elevation shown by colour. **Right**: Events detected per 5-minute period. Automatic catalogue is shown in grey, versus hand-picked catalogue in blue (Jay et al., *JVGR*, 2012).

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P wave travel time changes in the Groningen reservoir

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After the M 3.6 Huizinge earthquake of 2012, the Groningen gas field in the Netherlands has become one of the most densely instrumented regions of induced seismicity in the world. In 2013 two former production wells were equipped with geophone strings at the reservoir level at 3 km depth. In a previous study Zhou & Paulssen (2017) showed that anthropogenic noise is the dominant noise source at the reservoir level, and they found that the P and S wave velocity structure along borehole SDM-1 could be accurately retrieved from noise interferometry by cross-correlation. In this study we show that signals from nearby passing trains can be used to infer time-lapse variations in the reservoir.

High-frequency (30-100 Hz) train noise is identified in the spectrograms of the 10 geophones in borehole SDM-1. Deconvolution of 20 s of train signal recorded on the vertical component of the top geophone with that of the other geophones produces a clear downgoing P wave as well as weak bottom and top reflections from the reservoir (Fig. 1). The travel times of the downgoing P wave allowed very accurate estimates of the inter-geophone velocities in the reservoir. In addition, small time-lapse variations were measured in the data of the two geophone deployments that were analyzed: Jan-Jun 2015 and Jul-Dec 2015. The travel times within the reservoir decrease by 0 – 0.1% per half year with a larger decrease in the second half of 2015. This observation correlates with bigger surface subsidence for the second half of 2015. Albeit tiny, the travel time variations cannot be explained by vertical shortening only, so an additional P wave velocity increase related to compaction is required to explain the data.

Furthermore, we found a clear travel time anomaly (up to 0.8 ms) in the time span Jul 17-Sep 2 between the bottom geophone, located just below the gas-water-contact in the reservoir, and the one above (or any of the other geophones). This anomaly is associated with the drilling of a deep borehole at 5 km distance (Jul 9-Aug 28).

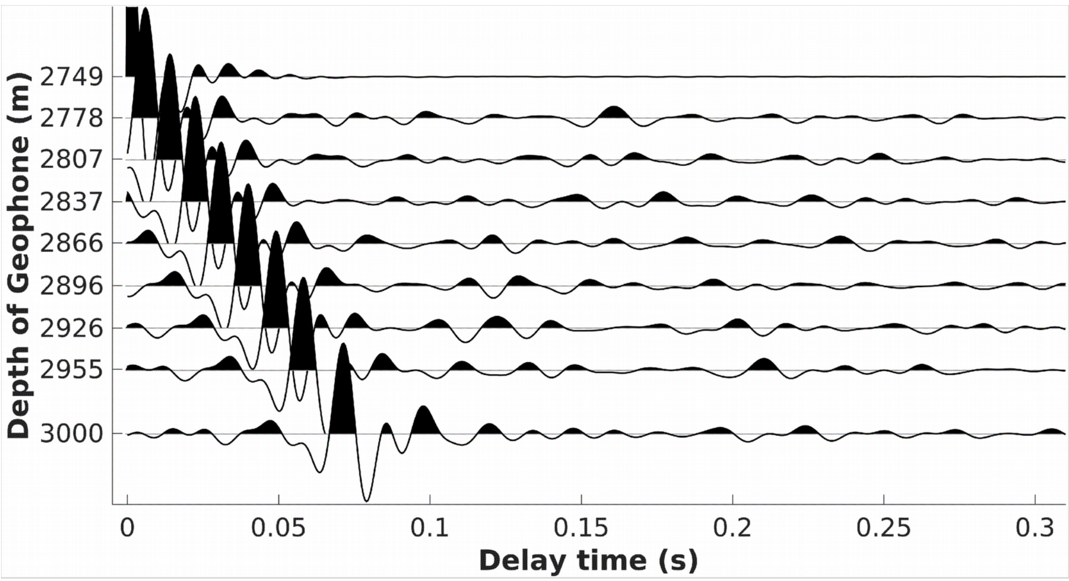

Fig. 1 Vertical component train noise deconvolutions with signal from the top geophone (Jul-Dec 2015).

The seismic monitoring system in the Velenje mine, Slovenia

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The Velenje lignite mine is located in Slovenia. The depth of mining level is around 40 m to 150 m below sea level.

Lignite deposits are characterized by a high amount of enclosed methane gas which can be released suddenly during the mining progress, which is the case in Velenje. This causes great danger for the miners through explosions; rock falls, bursting of walls or particle ejection.

The release of gas is a tension release and causes seismicity which can be detected. So a basic seismic monitoring system was installed in 1998 to get information on locations of rock falls or endangered areas. Because of the used sensors (accelerometers have been at that time the only ex-proof sensors) and the aging process of the components the sensitivity of this system was not sufficient and it was decided to update it.

Since October 2016 a reengineered, extended seismic monitoring system has been established in Velenje mine. The system consists of two seismometers (velocity-proportional sensors) at the ground surface and six seismometers (velocity-proportional sensors) in different cavern fields at a depth of approximately 100 m. The underground sensors are placed in a borehole casing for installation in horizontal boreholes. All sensor-places can be rearranged if necessary. The sensors L-10B/Ex in the mine have permission IBEXU15ATEX1131X. So the sensors are allowed to be used in a potentially explosive atmosphere.

In October 2016 the seismic monitoring system was installed and worked in a test phase and since November 2016 the monitoring system is working with its eight 1D-seismometer stations.

Only between November 2016 and October 2017 3348 seismic events were recorded and localized during the reporting time period of 12 months. Most of the seismic events occurred in the monitored area between 2 measurement points and the neighbouring areas. All other monitored areas showed also seismic events but the numbers are lower. The strongest events were recorded near one point with a magnitude of ML = 2,5 an ML = 2,0. The seismic energy release was highest in June 2017 with 828.096 kJ. In sum the amount of energy release in one year is 2.799 MJ.

Abstracts Posters, Part B

Session 4

Induced Seismicity in the Dutch Gas Fields

Elastic vs inelastic reservoir compaction: Effect on the stress path, fault reactivation, and induced seismic rupture

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Seismicity in Groningen occurs on known faults, which are reactivated as a result of poroelastic stressing and differential compaction of the reservoir. Reservoir compaction, poroelastic stressing, and fault reactivation are typically modeled assuming a linear elastic reservoir. However, recent experiments on Gronningen reservoir sandstone showed that up to 50% of the strain that develops during depletion is inelastic. Inelastic behaviour will result in different stress development on fault and different elastic strain available for seismic rupture. Here we assess the effect of inelastic behavior on the reservoir stress path and the potential for induced seismicity in the Groningen gas field.

The effect of inelastic compaction on reservoir stress and induced seismicity is modeled using the Finite Element package DIANA. Inelastic behavior is modeled using the elastoplastic Modified Cam Clay material model. Experimental research by Pijnenburg et al showed that this material model adequately fits the compaction experiments on the Slochteren sandstone of the Groningen field. We validated the model against the experimental data. The validated model is then used in a 2d fields scale model of a depleting reservoir intersected by a fault.

The results show that the stress path obtained using elastoplastic reservoir behavior for a depleting reservoir is much more stable than for elastic behavior. Fault reactivation may still occur for offset faults, but the shear stresses along the fault that develop during depletion are smaller than for the elastic case, reducing the size of the induced seismic rupture.

Clustering Characteristics of Gas-Extraction Induced Seismicity

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The Groningen gas field in the north of the Netherlands is one of the largest gas fields in the world. The field was discovered in 1964 and production from the field commenced in 1968. In 1991 the first seismic event in the field, with a local magnitude of M_l = 2.4, was recorded. Between 1991 and 2003 the seismicity rate in the field was fairly constant. Between 2003 and 2014 an increasing activity rate with time was observed. Concurrently, the largest magnitude observed increased, culminating in a M_w = 3.6 event at the town of Huizinge in 2012.

The link between the occurrence of the seismicity and the pressure depletion in the field due to the production of the gas has been firmly established. However, hazard assessment is complicated by the fact that, hampered by the general earthquake complexity, it is difficult to distinguish between induced and clustered events (events triggered by stress transfer of preceding, neighbouring events). This study focusses on the statistical features of seismic clusters. Specifically, the distributions of space-time distances between pairs of nearest-neighbour earthquakes, referred to as cluster style, is analysed.

The study documents the space-time distributions of the clustered and background parts of the seismicity induced by the gas extraction in the Groningen gas field. As the seismicity in the Groningen gas field is highly non-stationary and spatially non-uniform, both the temporal and spatial differences in cluster style are examined. The study shows that the space-time-magnitude distance between nearest neighbour events has a much broader distribution than typical for natural seismicity. In addition, the inter-event occurrence time of the clustered events is significantly longer than for natural seismicity. Only very few events occur at inter-event occurrence times typical for (fore-)aftershock activity (~5%). This is consistent with the relatively small magnitudes of the earthquakes. Analysis of clustered events occurring within one parent rupture length of the parent shows a trimodal system, distinguishing aftershocks, repeaters and semi-clustered events. The semi-clustered event mode contains the sequences of events surrounding the major events in the catalogue. This mode has not been identified before and the events are deemed background events in the nearest neighbour analysis. However, both depletion driven geomechanical and seismological models cannot explain the occurrence of these events. An ETAS aftershock model inducing 10-20% of aftershock activity (2-4 times the typical aftershock activity derived in this study) is required to match the historically observed seismicity.

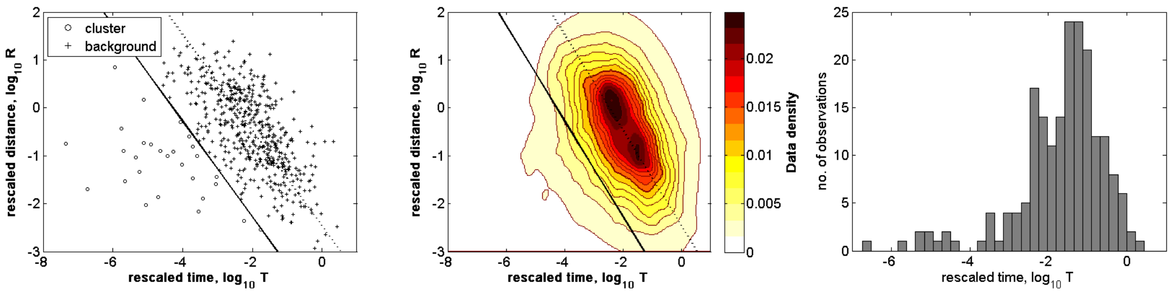

Fig. 1 (Left & Middle panel) Clustering style of seismicity in the Groningen gas field. Each panel shows the 2D distribution of the rescaled time (T) and rescaled distance (R) to the parent for the Groningen gas field in the period 1995-10/2018. (Left) shows the cluster assignment of the individual events, (Middle) shows the smoothed density of points. The solid diagonal lines denote the derived mode separation threshold, $\log_{10} \eta_0$, and the dashed diagonal lines denote the background location, $\log_{10} \eta_B$. (Right) shows the distribution of rescaled time for the offspring within one parent rupture length from the parent. Notice the trimodal distribution of aftershocks ($\log_{10}T<-4$), repeaters (peak at $\log_{10}T=-1$) and semi-clustered events (peak at $\log_{10}T=-2.5$).

Abstracts Posters, Part B

Session 5

Physics of Induced Earthquakes I

Shear induced fluid flow and permeability enhancement during fluid injection lab experiment

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It is well established that fluid injections under high pressures can reactivate pre-existing fractures or faults and induce shear slip and deformation. This phenomenon can alter the hydraulic properties of fractures, such as fluid flow and permeability. However, coupled hydro-mechanical interactions remain poorly documented.

In this study, we propose to study shear induced fluid flow and permeability enhancement during fracture shearing. We conducted tri-axial shear experiments on a saw-cut sample of andesite rock. The experimental fault formed a 30-degree angle with the vertical axis of the rock sample, and was 8 cm long. Two boreholes of 2 mm diameter were drilled reaching the fault surface, from the top and the bottom of the rock sample, respectively. Liquid water was injected through one borehole, while the second one was sealed. These two boreholes allow us to monitor the pressure during the shear experiment, and to better map the fluid diffusion in order to track the evolution of the fault's permeability due to shear slip.

We carried out experiments at different confining pressures (30, 60 and 95 MPa), as well as at four injection rates (5, 30, 60 and 350 MPa/min). Our results suggest that the fault is reactivated due to fluid injection (see Figure 1). A large instantaneous shear displacement is accumulated along the fault, while the pressure drops enormously at the injection well suggesting a strong fluid flow. Simultaneously, we observe a rapid increase in the pressure at the second well, implying a large enhancement of the fault's permeability.

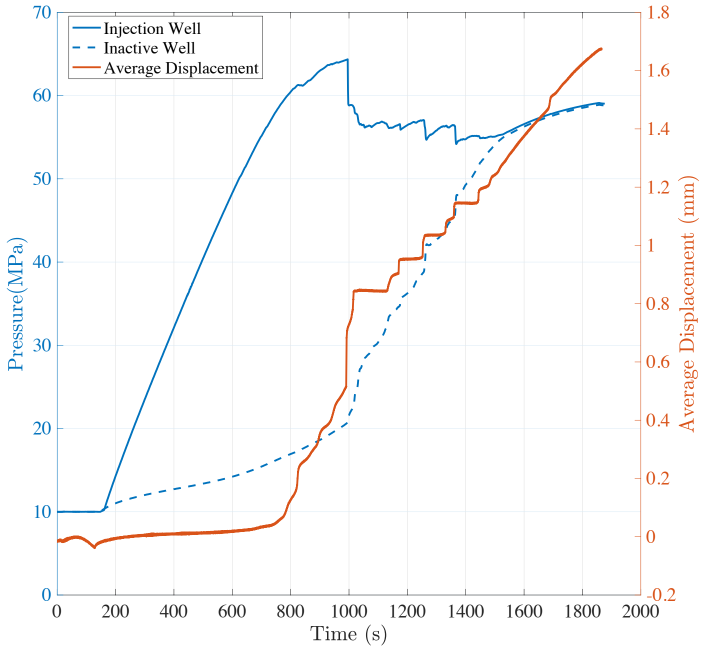

Fig. 1 Pressure at the 2 boreholes (blue curves) and average displacement along the fault (red curve) for the experiment at 60 MPa of confining pressure and 5 MPa/minute of injection rate.

Analysis of microseismicity framing M_w > 2.5 earthquakes at The Geysers geothermal field, California

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Preparatory processes accompanying or leading to nucleation of large earthquakes have been observed at both laboratory and field scale, but the precise conditions favoring them are still largely unknown. Here, we generated high resolution seismicity catalogs framing the occurrence of 20 M_w > 2.5 earthquakes at The Geysers geothermal field in California with the purpose of investigating the potential existence of emergent failure processes. The seismicity catalogs were developed using a matched-filter-algorithm. Our approach includes determination of P- and S-phase onsets and their inversion for absolute hypocenter locations with corresponding uncertainties. For each sequence a seismicity catalog of the 11 days framing the mainshock is created, containing events located within 2 km of its source region. Overall, we are able to detect and locate 3 times more events than the most detailed local catalog, decreasing the magnitude of completeness by about one order of magnitude. Our 20 selected sequences adequately sample the entire reservoir depth range, temporal periods with high/low injection rates and different tectonic settings within the field. We find a significant correlation between seismic activity displayed by the different earthquake sequences and their location within the reservoir. Sequences located in the northwestern part of The Geysers show increased seismic activity and low b-values. While the southeastern part is dominated by decreased seismic activity and higher b-values. Periods of high injection coincide with high b-values, and vice versa. These observations most likely reflect 1) changes in differential stress across the field and 2) changes in localization and distribution of damage. Furthermore, we find two distinct types of seismic response within the reservoir during times of large magnitude earthquakes. Half of the analyzed sequences exhibit no change of the seismicity rate in response to the large event. These events waveforms display clear signs of a collocated smaller earthquake right before the onset of the main rupture, suggesting that small earthquakes may grow or trigger larger events, leading to a complete release of buildup stresses. This represents the first sign of precursory processes before large magnitude earthquakes at The Geysers geothermal field.

Slip in granular fault gouges: factors influencing the slip regime.

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With recent climate changes and energetic transition's laws, research on Enhanced Geothermal Systems is increasingly relevant. If we put aside the construction's costs, one of the key obstacles of the development of the technology around the world is the induced seismicity. Using hydraulic stimulation by fluid injections into the existing fractures increases the pore pressure into the gouge and may create some slip reactivations. These slips can be seismic or aseismic and they can create different kinds of micro-seismicity.

In order to study the slip mechanism, we propose to simulate a 2D granular fault gouge under normal stress and imposed tangential displacement. The model involves two rough surfaces representing the rock walls. Between them, there is a granular gouge obtained by the wear of the previous slips. We use the DEM method with realistic non-circular grain shapes, imposing shear velocity on the upper rock wall to simulate slip triggering. The first objective of the research project is to study the influences of the different parameters of the gouge (morphology, granulometry, boundary conditions…) on the slip behaviour and on the contact between the rock walls and the granular gouge. The model is implemented with discrete simulation (multibody dynamic) for the granular part with the code MELODY. The simulation uses realistic angular grains based on grain shapes obtained from the literature. This is in contrast with most of the existing simulations which use circular/spherical grains, and angular grains could let us obtain more meaningful results. The variations of parameters and conditions give different resisting forces and friction coefficients on the upper walls. We also observe dilation-related variations on the fracture aperture, and force-chains fluctuating patterns.

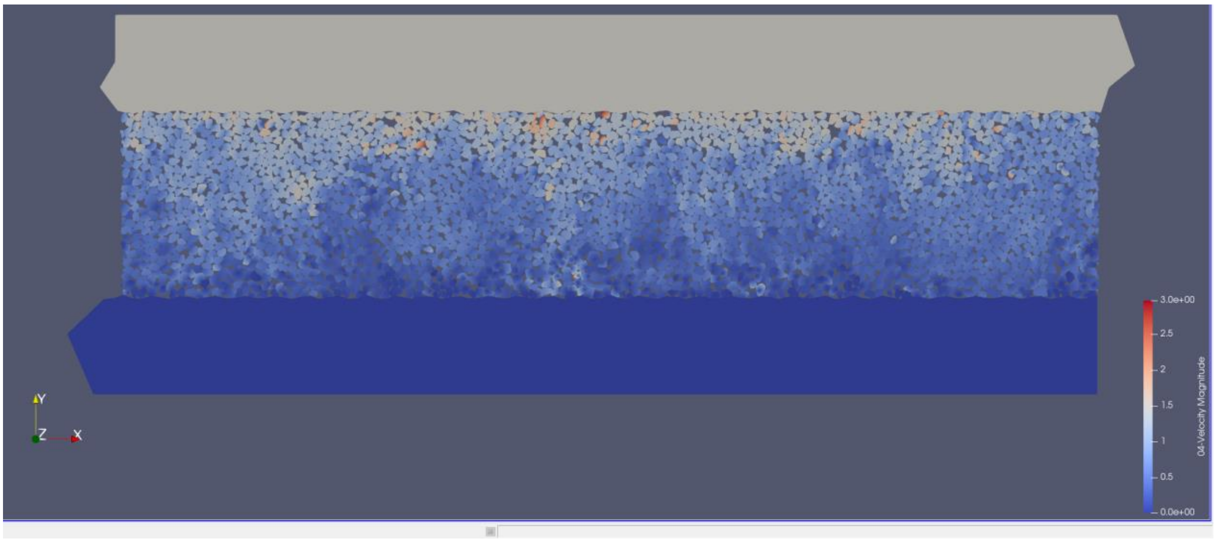

Fig. 1 Screenshot of a model with 2500 angular grains. Magnitude of the velocity of the grains with imposed shear velocity, simulated with the code MELODY.

Stress drop parameters of fracking-induced microseismicity

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Hydraulic fracturing underpins tight shale gas exploration, but also poses environmental risks, including those associated with injection-induced microseismicity, fault re-activation and earthquakes. Whilst the causes behind fracking-induced earthquakes are well understood, there is still uncertainty as to whether micro-seismicity exhibits significant differences in source-characteristics relative to tectonic earthquakes. Here, we investigate a unique dataset of fracking-induced microseismicity to shed light on the rupture mechanics and ground motions by calculating stress drops. Our dataset comprises of 90,000+ events from fracking treatment at the Horn-River basin, British Columbia with magnitudes -2.5 < Mw < 0.6. Events are recorded using 96, 3-component, bore-hole geophones with a sampling rate of 4000 Hz.

Stress drop is a uniquely favourable parameter for quantifying source characteristics because the stress drop equation is derived from assuming a relatively simple model of fault-rupture outlined by Aki (1967) and further modified by Brune (1971) and Boatright (1978). These models have now become a standard in most studies. The Fc and Mo obtained from these models are then used in the stress drop equation, defined as the average stress drop on a patch of fault after a rupture has occurred.

From qualitative analysis of processing techniques and spectra across 986 events at Horn-River, the following observations have been made:

1. Standard models for earthquake source rupture (Brune and Boatright) tend to overestimate the Fc, leading to inaccurate characterization of the source.
2. Events recorded by geophones located in shale show low SNR compared to those in limestone.

Observation 1 is not unexpected due to the events being mostly Mw < 0. Therefore a possible explanation is due to high frequency attenuation, causing misfit to standard models and overestimating Fc. This study now aims to test if introducing an extra 'Kappa' parameter into the standard model can capture the shape of the data better at high frequencies. Observation 2 is likely due to unfavourable elastic parameters in shale. This implies that borehole arrays may be better suited in geological environments with higher rock density. Once robust corner frequencies and seismic moments have been calculated, stress drop will then be calculated and compared to various parameters such as depth and time after injection.

A-seismic fracture growth driven by fluid injection and remote nucleation of dynamic rupture in a weaker part of the fault

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We investigate the propagation of a shear fracture driven by a continuous fluid injection at constant over-pressure in a pre-existing fault. We focus on the case of injection in a zone of constant friction leading to a-seismic growth and study how such a-seismic growth can trigger a dynamic rupture on a remotely located weaker (and/or frictionally weakening) part of the fault via stress transfer. In the case of constant fault permeability, such a fluid-driven a-seismic fracture propagates paced by fluid diffusion in a self-similar manner, i.e. thus proportional to square root of time. However, depending on the initial stress conditions and magnitude of over-pressure, two end-regimes can be encountered. In the limit of a critically stressed fault, the a-seismic crack propagates significantly ahead of the pore pressure perturbation front whereas on the contrary in the limit of marginally pressurized fault, the pore pressure perturbation is way ahead of the fracture tip. After benchmarking our numerical model with an analytical solution for that case (Figure 1), we investigate the case of a weaker (and/or frictionally unstable) part of the fault located away from the injection point. We determine when (and at what distance from the injection point) such a weaker part gets activated, and how a dynamic rupture nucleates from this daughter fracture. The limit of a critically stressed fault is particularly interesting as we show that a dynamic rupture can nucleate significantly away from the pore-pressure disturbance due to the stress perturbation associated with the a-seismic growth of the mother fracture surrounding the injection location. We also investigate how a-seismic growth continues after shut-in of the injection and how it modifies the observed remote nucleation of a dynamic rupture in the critically stressed case.

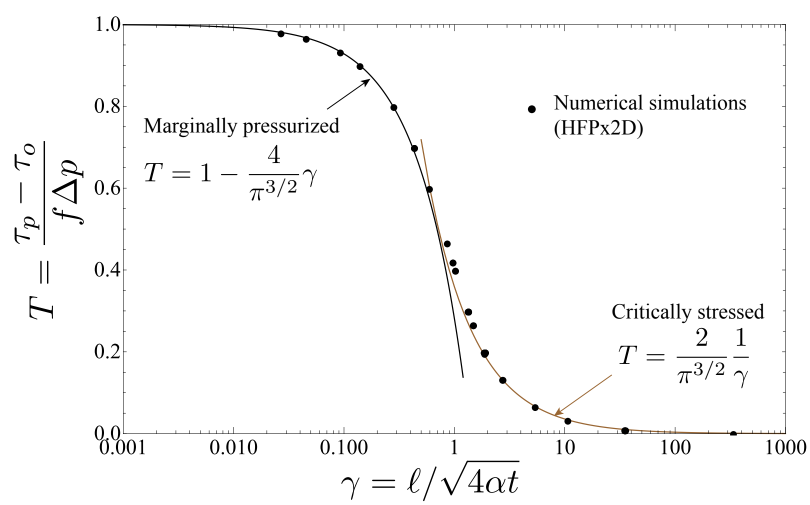

Fig. 1 Evolution of dimensionless a-seismic fracture length γ as function of stress criticality T. The aseismic fracture length scales as $L=\gamma\ (4\,\alpha\,t)^{1/2}$, with α the fault diffusivity. Numerical results displayed as dots, analytical asymptotes for the marginally pressurized and critically stressed cases as continuous lines (asymptotes obtained by R. Viesca – personal communication).

Rupture complexity of an injection induced event: the 2016 Mw 5.1 Fairview, Oklahoma earthquake

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Complex rupture processes for moderate-to-small weak earthquakes may reveal a dominant direction of the rupture propagation and the presence and geometry of one or more main slip patches. Finding and characterizing such properties is crucial to understand the nucleation and growth of induced earthquakes. We analyze one of the largest earthquakes linked to wastewater injection, the 2016 Mw 5.1 Fairview, Oklahoma earthquake is analyzed using empirical Green's function (EGF) techniques and decipher source complexity. Apparent Source Time Functions (ASTFs) are robustly obtained using 16 foreshocks and aftershocks as EGFs. Two source pulses slightly separated are easily identified at NE azimuths, while stations located toward SW record single pulses of overall shorter durations. Resulting apparent durations range from 1.05 to 2.45 s. These durations exceed empirical values and durations resolved for Mw 5.1 earthquakes, which are typically about 1 s. This fact suggests that the ASTF complexity could be due to the presence of two subevents separated in space and time. A new approach based on relative hypocenter-centroid location is developed in order to infer the relative location for the two subevents identified from the ASTF analysis. The first subevent has a magnitude of Mw 5.0 showing the main rupture propagation toward NE, in direction of the higher pore pressure perturbation due to wastewater injection (Figure 1). The second subevent appears as an early aftershock with lower magnitude Mw 4.7. It is located SW of the mainshock in a region of increased Coulomb stress, where most aftershocks were relocated. These techniques have been also successfully applied to the November 2017 Mw 5.5 Pohang, South Korea earthquake, the largest known induced earthquake at an enhanced geothermal system (EGS) site. The rupture directivity analysis and the resolved centroid-hypocenter locations suggests the failure of two subevents at close origin times and separated by small distance along the azimuth of the rupture directivity. These results have important implications to discuss the role of anthropogenic stress perturbation in controlling the direction and extent of the earthquake rupture growth.

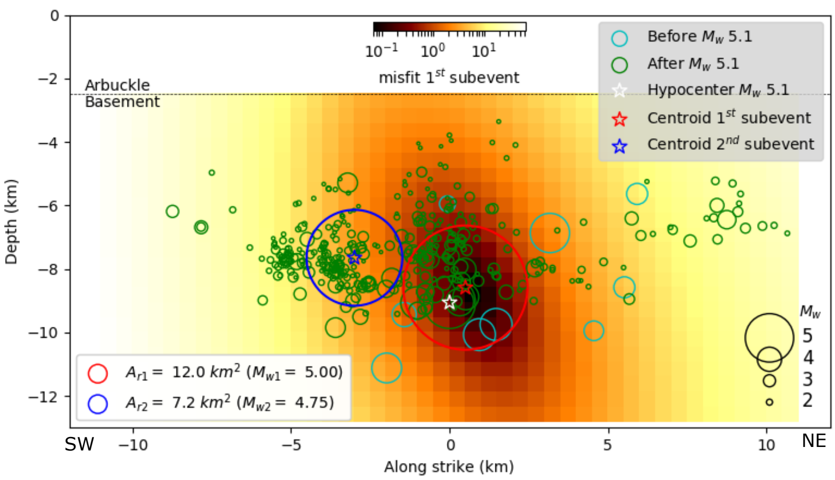

Fig. 1 Relative hypocenter-centroid location for the first and second subevent. A cross-sectional profile along the strike of the Mw 5.1 Fairview earthquake showing the misfit as a function of the centroid location for the first subevent.

Dependency of the induced seismicity b-value on the stress state of existing fractures

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The Gutenberg–Richter distribution of earthquakes is a power law relationship and it holds for laboratory scale earthquakes (acoustic emission) to subduction zone earthquakes as well as induced seismicity. The gradient of the power law is known as the b-value, which can be considered the ratio of the number of the larger earthquakes to small ones. Larger earthquakes are often observed in low b-value regions, or alternatively a b-value reduction has been observed before some main shocks. Some authors have argued that b–value is negatively correlated with differential stress level. Therefore, a b-value anomaly found in time-space analysis may be used for detection of an area of stress concentration and used for earthquake prediction or hazard risk assessment.

In the field of induced seismicity where b-value reduction has also been observed, the physical mechanism of b-value reduction has not been well understood. Since induced seismicity related with fluid injection usually occurs at depths around 1000 ~ 5000 m, a significant tectonic loading to cause a stress change during the short time period of a hydraulic stimulation might not be expected. We used borehole analysis and focal mechanism information to investigate the stress state on the existing fractures that caused induced seismicity. Then we divide the catalog into the groups with varying normalized shear stress threshold and estimated the b-value. We found that b-value for the events that occurred along higher shear stress fractures were significantly lower (figure 1a) than those from the moderate/lower shear stress fractures (figure 1b). Thus, b-value dependency on the shear stress can be observed for induced seismicity on a reservoir scale. Therefore, we propose that the reason for the observed b-value reductions in induced seismicity on a reservoir scale is the events that occur along higher shear stress fractures. Supposing that the earthquakes occur along well-orientated fractures, the b-value dependence on differential stress can be translated to dependence on shear stress. Thus, our observations about b-value are consistent with the conventional interpretations of b-value.

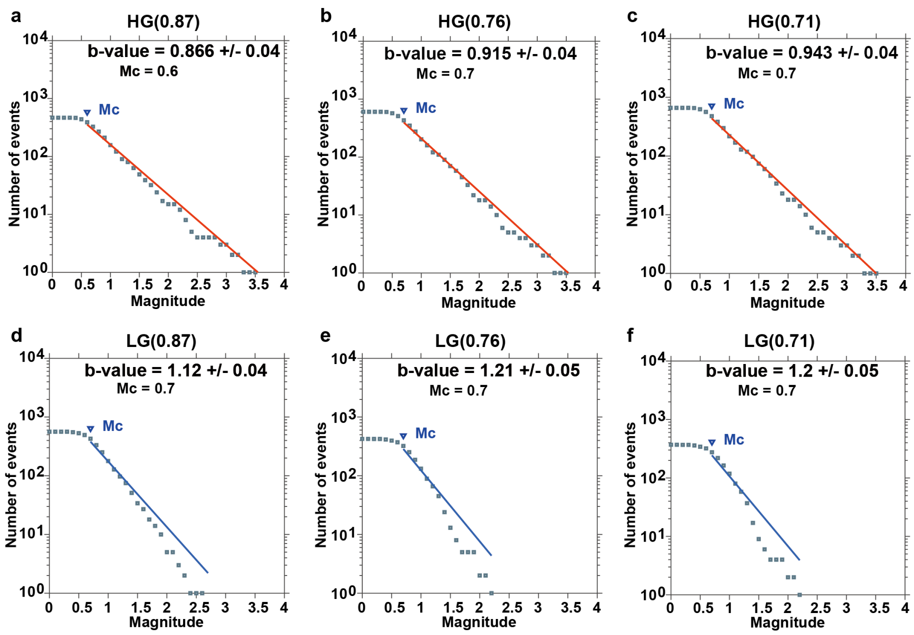

Fig. 1 Magnitude frequency distribution for events from lower shear stress and those from higher shear stress. The number in blankets means thresholds of shear stress to divide the catalog data.

High-resolution analysis of seismicity patterns in microearthquake sequences using waveform similarity methods

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One of the remaining challenges for deep geothermal projects is how to mitigate large magnitude induced earthquakes (LMIE). Our ability to forecast LMIE potential and occurrence is, however, still limited by mainly two factors. One is that geological and hydro-mechanical conditions in the subsurface cannot be mapped sufficiently well with current - and possibly also future - technology. The other is that the processes underpinning induced seismicity - and earthquake nucleation in general - are still not understood well enough.

High-resolution recordings of the seismicity during rock-fracturing experiments in the lab, or during earthquake sequences with large-magnitude mainshocks, have recently allowed resolving precursory seismicity patterns that re-initiated a discussion on the physics of earthquake nucleation. While these precursory patterns are regularly observed and well-established on the lab-scale, they remain a topic of debate on the field scale, where they are rarely observed. The latter may be - at least partly - related to an observational bias caused by the insufficient sensitivity of routine seismic catalogs.

These catalogs often do not provide the necessary completeness and precision over a sufficiently large magnitude range to resolve precursory seismicity patterns. Consequently, only a small number of these observations is documented for well-monitored earthquake sequences and mainshock magnitudes mainly larger than M5. Fortunately, induced earthquakes rarely exceed magnitudes of M5. Unfortunately, this also means that precursory seismicity patterns that could improve our understanding of LMIE occurrence, and their mitigation are documented in less than a handful of cases.

To improve this situation, we are developing and implementing waveform similarity based analysis methods for induced seismicity. In doing so, we want to improve the detection sensitivity, magnitude consistency and location precision for induced earthquake sequences for post-analysis but also for real-time applications. In a first step, we have developed a semi-automatic workflow that combines well-established seismological analysis techniques to accomplish these goals.

We take advantage of the high similarity of natural and induced seismic sequences and successfully show that we can resolve precursory seismicity patterns in microearthquake sequences with standard seismic monitoring networks. We show the first results of our analysis of natural earthquake sequences of Switzerland and their systematic classification and will discuss them in the light of geological and seismotectonic setting.

LABORATORY STUDY OF HYDROFRACTURING AND RELATED SEISMICITY

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The results of laboratory experimental study of the hydraulic fracture propagation and related acoustic emission are presented. The experimental setup differs from usual equipment designed for testing cores or cubic samples. Our setup is designed for work with samples of disk form which allows us to measure the pore pressure distribution along the sample together with acoustic emission (AE). The setup consists from two metal disks of 600 mm in diameter and 75 mm in thickness. A metal ring (height 74 mm, thickness 25 mm, the inner diameter 430 mm) is placed between the disks to form the pressure chamber with diameter 430 mm and height 66 mm. A rubber diaphragm is located between the upper disk and the pressure chamber, four thin chambers are located along the inner side of the ring (Fig.1). The stresses are applied by fluid injection into these side chambers and into the gap between the rubber diaphragm and the upper disk. The disks and the ring have holes used for mounting the pore fluid pressure sensors and acoustic emission sensors as well as for pumping fluids into or out of the model reservoir through the boreholes in the sample. Conductive strips are used to measure the fracture propagation rate.

As the sample material (chosen on the basis of the scaling criteria), the gypsum/cement mixture (proportion 9:1) with addition of 45% of water was used. The sample was saturated by gypsum water solution. The hydraulic fractures were formed by mineral oil injection into the borehole in the sample under the constant rate. The pore pressure variations and acoustic emission were measured simultaneously. In the Fig. 1, the positions of the AE sources are shown by the yellow marks; the AE positions are related with the fracture position. It is remarkable, that we did not registered any AE outside the fracture. Comparison that fact with the results of the pore pressure measurements allows to suggest, that the pressure increase due to viscous fluid injection is not enough to induce AE pulses at some distance from the borehole and the fracture. When the injection fluid has the same viscosity as the fluid saturating the sample, the pressure increase is sufficient to induce acoustic emission corresponding to the pore pressure increase.

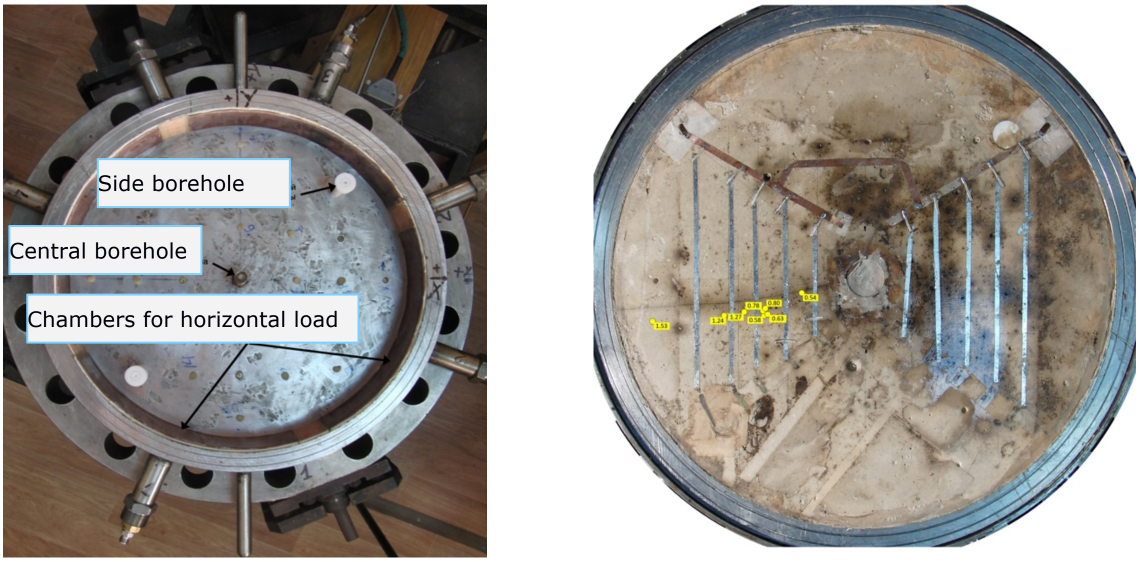

Fig. 1. Left: inside view of the laboratory setup; right: the fractured sample, yellow marks show positions of the acoustic emission sources, strips were used to measure the fracture propagation rate.

The Effect of Roughness on the Elasticity and Permeability of Fractured Media

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Departments of [1]Geosciences, [2]Engineering Sciences and Mechanics, [3]Energy and Mineral Enginering and Energy Institute, The Pennsylvania State University

We describe laboratory work to elucidate the relation between nonlinear elasticity and permeability of fractured media subjected to local stress perturbations in relation to fracture roughness and aperture distribution. This study is part of an effort to image fluid pathways and fracture properties using locally induced seismicity, associated with fluid injection.

Experiments were conducted in which intact L-shaped Westerly granite samples were fractured in-situ tri-axial condition while forcing deionized water through the subsequent fracture interfaces. After in-situ fracture, we imposed oscillations of the applied normal stress and pore pressure with amplitudes ranging from 0.2 to 1 MPa and frequencies from 0.1 to 10 Hz. During these dynamic perturbations an array of ultrasonic transducers (PZTs) continuously generate and transmitted p-wave pulses to monitor the elastic response of the granite samples. We interpret the relative change in p-wave velocities to be an analog for the elastic nonlinearity and relate it to the permeability of the fractured media. The roughness of the fractured interfaces is altered during experiments by shearing the L-shaped samples and then allowing the interface to age before applying dynamic stressing.

We characterize the effect of horizontal stress and pore pressure dynamic oscillations by calculating relative changes from before respective oscillations to after. We report that the relative change in the permeability transient recovery increases with the amplitude and frequency of pore pressure oscillations and is not affected by horizontal stressing. Though further studies are needed, we infer this is caused by pore pressure oscillations moving granular material, created from in-situ fracture and shearing, and creating more flow pathways across the interface. The ultrasonic array's velocities show spatial variation across the fractured interface and show modest evolution in the relative velocity changes as a function of horizontal stress and pore pressure oscillation amplitude. Also, we find that relative velocity changes are greater as a function of dynamic stressing frequency.

Abstracts Posters, Part B

Session 6

Physics of Induced Earthquakes II

A second-generation stress map of the intraplate USA, and its utilization for managing the hazard of injection-induced seismicity

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Over the past five years, we have added >700 new orientations of the maximum horizontal principal stress (S_{Hmax}) throughout the central and eastern USA (CEUS). Incorporation of relative stress magnitude data from earthquake focal plane mechanisms has resulted in a dramatically improved, "second-generation" stress map of this intraplate region (Fig. 1). We apply this detailed new understanding of the state of stress to areas experiencing injection-induced seismicity, in order to identify faults with a high probability of being activated by fluid injection.

Our new stress map illustrates systematic changes in S_{Hmax} orientation and relative stress magnitudes across the intraplate region of the USA. In much of the central USA, the stress field ranges from normal to strike-slip faulting. While S_{Hmax} orientations throughout the CEUS generally range between E–W and NE–SW, some areas in the central part of the country show localized but dramatic rotations. For example, in the Delaware Basin (the western part of the Permian Basin of west Texas and southeast New Mexico), the stress field is dominated by normal faulting but there is a ~150º clockwise rotation of S_{Hmax} southward across the basin. Conversely, just to the east in the Permian Basin, in the Central Basin Platform and Midland Basin, the stress field is normal faulting/strike-slip and characterized by consistent ~E–W S_{Hmax} orientation. This stress state rotates counter-clockwise across Texas until it trends NE-SW in the Fort Worth Basin of northeast Texas. In the northeastern United States, induced seismicity associated with the development of the Utica and Marcellus shales is occurring in a much more compressive stress field characterized by strike-slip/reverse faulting stress state with S_{Hmax} oriented consistently ENE–WSW to NE–SW.

We utilize the free software program FSP (scits.stanford.edu/software) to probabilistically estimate the slip potential on mapped faults in response to estimated fluid pressure increases, in a manner that accounts for parameter uncertainties. We apply this detailed dataset to induced seismicity in Oklahoma, the Fort Worth Basin of northeast Texas, and the Delaware Basin, where the faulting regime varies between strike-slip, normal/strike-slip and normal faulting, respectively. Our study illustrates the utility of mapping the stresses in detail in efforts to manage the hazard of induced seismicity, particularly when it is possible to identify potentially problematic faults before injection begins.

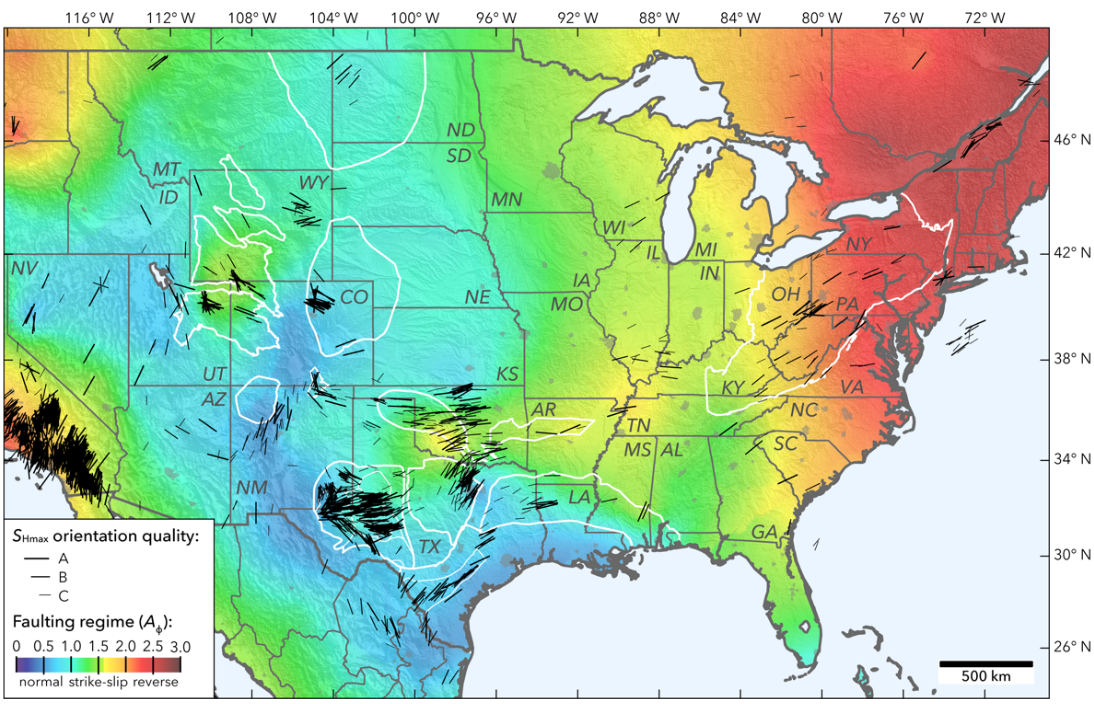

Fig. 1 State of stress in the central and eastern USA, from Lund Snee and Zoback (in prep.).

Fault reactivation during pore pressure oscillations

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An increase in pore pressure decreases the effective normal stress acting on the fault, facilitating its reactivation. In nature, pore pressure is prone to vary cyclically in space and time (e.g. oceanic tides, seasonal hydrology, cyclic fluid injections in reservoirs), which could cause hydraulic fatigue on the onset of fault reactivation. While recent studies showed that cyclic fluid perturbations seem to trigger less seismicity compared to monotonic injections, only few experimental studies aimed at understanding the influence of pore pressure oscillations on hydraulic fatigue and on the onset of fault reactivation.

To investigate these issues, we performed triaxial laboratory experiments on Fontainebleau sandstone. Samples were saw-cut at 30° from the maximal principal stress and the fault surfaces were polished with sand paper to impose a constant roughness. All experiments were conducted at 30 MPa confining pressure, with an initial pore pressure of 10 MPa. We first determined the shear stress leading to the onset of fault slip. Subsequently, the load was decreased and kept constant at a slightly lower value. The system was then solicited by sinusoidal pore pressure oscillations of varying amplitudes (from 1 to 20 MPa) and periods (from 100 to 5000 s). During deformation, both fault mechanical results and acoustic emission (AE) signals were monitored to investigate the physics underlying the role of fluid pressure oscillations, i.e. the role of hydraulic fatigue, on the onset of fault reactivation and associated micro-seismicity. Our preliminary results show that: (1) large slip events occur at the first oscillation when the pore pressure allows fault reactivation; (2) increasing the amplitude of the pore pressure oscillations leads to larger mainshocks and subsequent aftershocks activity; (3) if amplitude of pore pressure is larger than 15 MPa, this acoustic activity is influenced by oscillations. Our first investigations suggest that pore pressure oscillations do not induce mechanical fatigue on the onset of fault reactivation.

Can a deep geological repository in a clay formation maintain its integrity and still reactivate a nearby fault?

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A safe geological disposal site of radioactive waste requires identification of a rock formation that guarantees isolation to prevent unacceptable concentrations of radionuclides from migrating to the accessible environment. A common design for spent nuclear fuel disposal is the emplacement of specifically engineered canisters containing vitrified high-level radioactive waste (HLW) in a clay formation. The increase of temperature of a low permeability, fluid-saturated media may trigger significant thermal pressurization, where the expansion of pore fluid cannot be accommodated by the thermal expansion of the pore space. With the aid of a coupled thermo-hydro-mechanical numerical simulator, we investigate the possible impact of thermal pressurization during the life of a deep geological repository on the stability of a nearby plane of weakness, assuming that the clay formation maintains its sealing properties. In our model, we represent the fault as a planar structure embedded in a thermo-poro-elastic material and shear activation evaluated by a strain-softening Mohr-Coulomb failure criterion. The results show that stress changes caused by temperature and thermal pressurization of a rock mass volume around the emplacement tunnels may trigger a slip event on a fault plane in proximity of the disposal site, with rupture nucleating at depth, hundreds of meters below the repository itself (Fig. 1). We found that stress transfer plays an important role, while a direct hydraulic connection between the repository and the nucleation zone is not necessary in order to reach failure conditions. With a critical stress state (low horizontal to vertical stress ratio) the occurrence of slip may happen for a fault at a distance of up to 600m from the outermost emplacement tunnel. Intrinsic properties of the fault dictate the occurrence of seismic or aseismic slip, which may vary with depth. These results highlight the need of investigating hydromechanical properties and stress conditions not only of locally but also in nearby formations to guarantee safe operations and predictable behavior of the HLW disposal site.

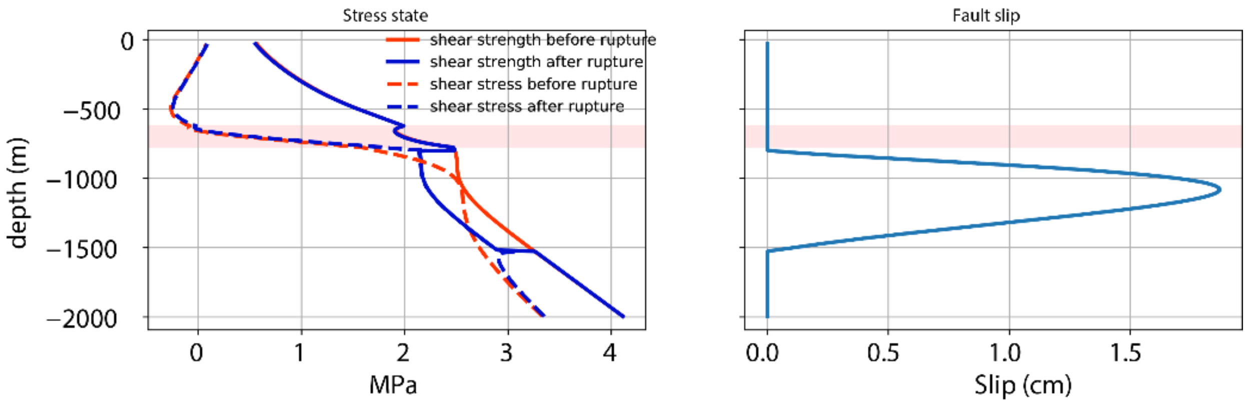

Fig. 1 Stress state before and after failure (left), and associated slip (right). Light red denotes clay formation location

Analysis of injection data for pore pressure and minimum horizontal stress magnitude estimates in the Arbuckle Formation

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A significant increase in seismicity in Oklahoma, which could be considered to be seismically relatively quiet, has been observed since 2009. This seismicity is considered to result from minor pore pressure increase due to huge waste water injection into the highly permeable Arbuckle formation. Based on detailed analysis of seismicity it has been shown previously that most earthquakes occur along faults within the less permeable basement underlying the Arbuckle formation.

Whereas the stress orientations in Oklahoma are quite well determined, there is only very few data available on stress magnitudes in Oklahoma or southern Kansas at the border to Oklahoma. Further information – at least on relative stress magnitudes - can be obtained from the style of faulting as derived from earthquake focal mechanisms. The observed seismicity mostly shows strike slip faulting in the southern part of Oklahoma and a mixture of strike slip and normal faulting in the Northern part. This leads to the conclusion that in the northern part, the maximum horizontal stress magnitude is similar to the vertical stress magnitude.

In many interpretations critically stressed faults are assumed to determine the pressure perturbation needed for fault reactivation. Under these assumption, numerical modelling showed that already small pressure perturbations would lead to the observed seismicity.

However, the assumption of critically stressed faults is somewhat contradictory to the low seismicity before the waste water injection. Furthermore, there are also regions with massive injection but without seismicity. Here we analyzed in detail injection pressures and pore pressure information in comparison to the depth of the Arbuckle formation, the hydraulic head of the partly underpressured Arbuckle in more than 150 individual waste disposal wells. The differences between the Arbuckle pressures during injection (wellhead pressure + pressure of water column between water table of aquifer and topographic surface) and the undisturbed pore pressures are partly larger than 2.5 MPa and may locally reach even more than 10 MPa, thus cannot be considered as only minor changes. Furthermore, the injection pressures with time have been considered to reduce the uncertainty for the minimum horizontal stresses at the Arbuckle formation depth and lead to minimum horizontal stress gradients of ca. 12.2 MPa/km in comparison to vertical gradients of ca. 24.6 MPa/km. The frictional coefficients of the faults (based on the injection data) have been varied between 0.6 and 1.0. Numerical models based on injection rates show that apparently only low pressures are required to induce seismicity. However, hydraulic heads have to be considered in addition to the wellhead pressures or injection rates and can lead to higher bottom hole pressures.

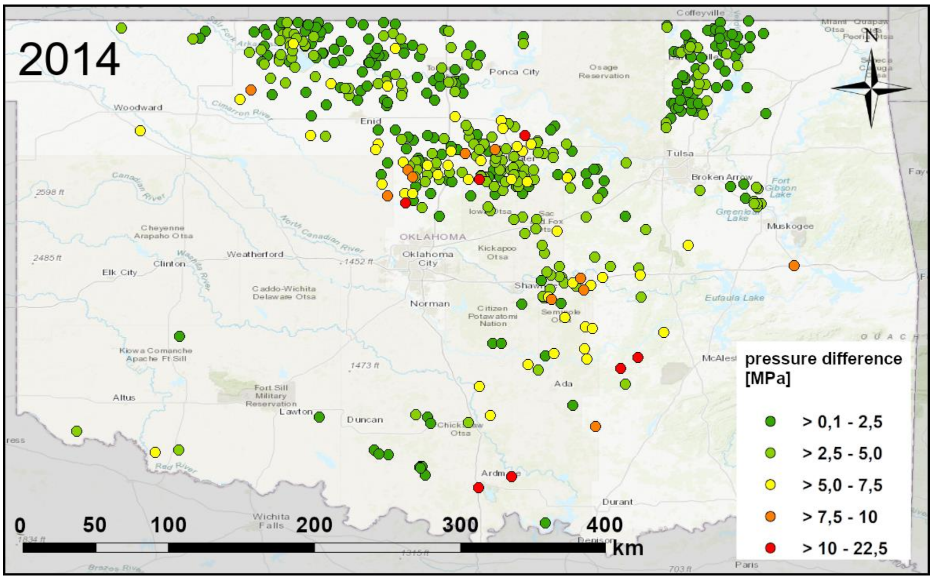

Fig. 1 Calculated differences between maximum bottomhole pressure during injection and undisturbed pore pressure for different wells in Oklahoma.
Based on brine density, wellhead pressure and the difference between ground level and undisturbed well head.

Inhomogeneous fault stability due to fluid injection

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Forecasting and mitigating induced seismicity requires understanding of the underlying physical processes. Poromechanical and thermal effects on stresses and shear slip stress transfer play a non-negligible role that has challenged the classical interpretation in which induced seismicity is caused exclusively by pressure buildup. In this contribution, we analyze how the stress changes induced as a result of fluid injection affect fault stability. We perform fully coupled hydro-mechanical simulations of fluid injection into a saline aquifer bounded above and below by low-permeable clay-rich rock. The plane strain model includes the crystalline basement, alternating soft low-permeable and stiff high-permeable sedimentary rock and a steep normal fault. The fault intersects all the layers, and is formed by a low-permeable fault core and a damage zone on each side of the core and has an offset of 25 m, corresponding to half the thickness of the injection formation. Simulation results show that maintaining a constant injection rate leads to a progressive reservoir pressurization on the side of the fault where injection takes place (Fig. 1a). Given the low-permeability of the fault core, pressure buildup is negligible on the other side of the fault. These pore pressure changes cause strong variations in the total stresses controlled by rock stiffness around the fault., Far from the fault, the horizontal total stress increases in the pressurized side of the reservoir proportionally to the pressure buildup. Pressure buildup expands the injection formation, pushing the fault away from the injection well, i.e., toward the right-hand side. At the same time, the reservoir and the caprock placed on the other side of the fault are deformed equally, while the caprock accumulates less stress than the reservoir because it is softer (Fig. 1b). Deviatoric stress changes are controlled by stress balance from the two sides of the fault: the upper part of the reservoir, juxtaposed to the stiffer reservoir on the right, has a lower increase in the deviatoric stress than the lower part, which is juxtaposed to the more compliant caprock. This implies increased fault stability in the upper part and decreased fault stability in the lower part. As highlighted by our results, fault stability is: i) non-homogeneous within the whole fault and ii) controlled by poromechanical stress changes as much as by pressure buildup.

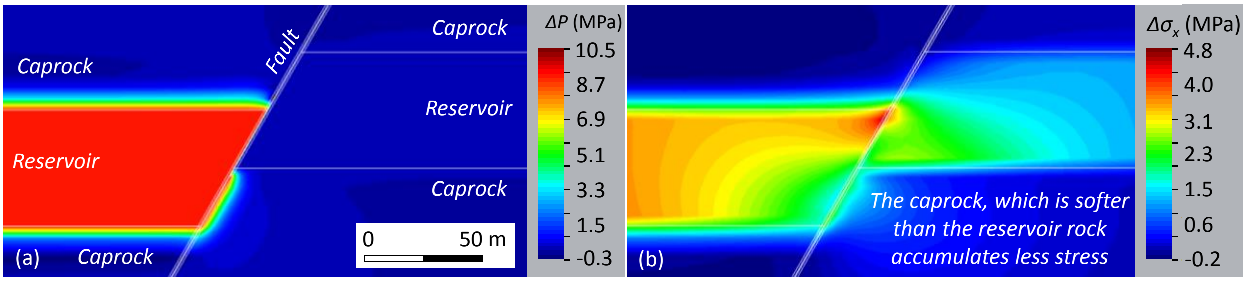

Fig. 1 Changes in (a) pore pressure and (b) horizontal stress caused by fluid injection on the hanging wall of a low-permeable fault (left-hand side of the Figures). Poromechanical stress changes are controlled by rock stiffness.

(Figure adapted from: Vilarrasa, V., Makhnenko, R., & Gheibi, S. (2016). Geomechanical analysis of the influence of CO_2 injection location on fault stability. *Journal of Rock Mechanics and Geotechnical Engineering*, 8(6), 805-818)

Modelling of long-term temperature effects on fault reactivation and induced seismicity potential in conventional geothermal doublets in The Netherlands

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The role of geothermal energy production as a source of a sustainable energy in The Netherlands is expected to grow, from 20 geothermal doublets currently in operation to around 175 doublets in 2030. Current geothermal doublets and planned doublets produce from porous sandstone aquifers of Tertiary, Cretaceous/Jurassic, Rotliegend and Triassic age and fractured carbonate rocks of Dinantian age. Production temperatures of the conventional doublets are generally between 65 – 100 °C, and fluids are re-injected at temperatures between 20 - 45°C. The long-term re-injection of cold fluids over the lifetime of a geothermal installation will lead to a gradual, but progressive and significant cooling of the reservoir rocks. Cooling of reservoir rocks and burden can lead to significant thermal stresses, which, superimposed on the pressure induced stress changes, may affect and jeopardize fault stability and lead to an increased seismicity hazard. In particular doublets drilled in competent rock types and marked by large temperature contrasts (both increasing with depth), are prone to a high likelihood for the build-up of significant thermal stresses over time (>>1MPa). For safe and effective operations, it is important to assess the long-term combined effect of pore pressure and temperature changes in geothermal operations on fault stability and associated seismicity, taking into account (1) operational parameters such as injection temperatures, pressures, flow rates volumes and (2) geological, geohydrological and geomechanical factors.

Based on semi-analytical and numerical computations, we quantified the effect of long-term cooling during geothermal operations on fault stresses, fault reactivation potential and seismic hazard, for typical conventional geothermal doublets in two common geological settings in The Netherlands, i.e. 1) a homogeneous porous sandstone reservoir (representative of the Cretaceous/Jurassic, Rotliegend and Triassic reservoirs in the southwestern and northern part of The Netherlands) and 2) a fractured carbonate reservoir (representative of the Dinantian reservoirs in the south-eastern part of the Netherlands).

Results for the homogeneous porous sandstone reservoir show that after 10 to 30 years of geothermal doublet operation, thermal stressing causes a significant increase of Coulomb stresses and can have a destabilizing effect on fault stability within the vicinity of the geothermal doublets. Increased pore pressures can cause additional positive Coulomb stressing of the faults; however, the effect of pore pressure is limited in areal extent and relatively small compared to the effect of thermal stresses, except in the first years of operation. Results for the fractured carbonate reservoir indicate that here the situations is reverse, i.e. that pressure changes in fracture and faults zones are marked by a larger areal extent and can cause significantly stronger coulomb stress changes at large distance from the injector well than the thermal effects, in particular in the initial years of production.

Acknowledments

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Coulomb Stress Changes by Fault Slip and Pore Pressure Push due to Fluid Injection

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In hydraulic stimulation, fault slip and pore pressure push are competing mechanisms for stress perturbation which contributes to induced seismicity. Since the fault slip is the irreversible mechanism distinguished from the pore pressure push, considering both mechanisms are difficult numerically and analytically. Interestingly, each mechanism was used independently and gave theoretical insights for various observation related to the seismicity (Segall and Lu, 2015; Steacy et al., 2005). To verify those approaches, the detailed comparison between fault slip and pore pressure push will give the concrete theoretical background. In addition, ignoring the minor mechanism will contribute to the high performance of the numerical simulation and the rigorous simplification for the analytic prediction.

Comsol Multiphysics was used to model the poroelasticity and the fault slip at the same time. To overcome the limitation of continuum-based modeling, the plasticity module was adopted with the Coulomb Failure Criteria as a yield function. The equivalent poisson's ratio and elastic modulus was applied to the fracture zone to model the normal opening of the fracture by the pore pressure.

In this study, fault slip and pore pressure push were compared in two generic cases of the fluid injection into impermeable and permeable matrices. All cases were assumed to contain a single fracture with the aseismic slip. The Coulomb stress changes were calculated on hypothetical fractures parallel to the defined fracture. As a result, the conditions for the dominance of one effect against the other effect were suggested.

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Abstracts Posters, Part B

Session 7

Modelling Induced Seismicity

Dynamic earthquake rupture modeling in fracture networks of geo-reservoirs accounting for the effects of thermal pressurization

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The presence of fractures in geo-reservoirs, natural or man-made, is crucial to the economics of oil & gas production and geothermal-energy harvesting. The related seismic hazard due to the (re-)activation of these fractures by external forces (fluid injection or extraction), and their ability to generate sizable (that is, strongly felt and even damaging) earthquakes, has received increasing attention within the last years. Numerical models of spontaneous earthquake rupture and wave propagation allow to investigate the conditions under which earthquakes within these fracture networks nucleate, propagate and potentially evolve into larger events, allowing to address physics-based seismic hazard assessment in geo-reservoirs.

To study earthquake dynamics in fluid-rich fracture networks, we aim to i) account for fluid effects on fault stress and strength combined with modern friction laws and ii) quantify natural fracture networks for efficient geometrical representations within a high-performance computing framework (e.g. Uphoff et al., 2017). To this end, we extend the freely available software SeisSol (www.seissol.org) based on the Arbitrary high-order accurate DERivative Discontinuous Galerkin method (ADER-DG). SeisSol employs fully adaptive, unstructured tetrahedral meshes to combine geometrically complex 3D geological structures, nonlinear rheologies and high-order accurate propagation of seismic waves.

Following Noda & Lapusta (2010) our method accounts for thermal pressurization of pore fluids mimicking the effects of rapid co-seismic slip generating heat that increases temperature and pore pressure in case of low hydraulic diffusivity of the surrounding rock. Consequently, the elevated pore pressure reduces the effective normal stress, causing dynamic weakening. Networks of fractures provide conduits for (dynamic) pressure changes, therefore, motions of these fractures may change the permeability of the system.

Besides frictional effects, variations in fault geometry have a strong influence on earthquake dynamics. Existing descriptions of fracture network characteristics are based on multi-well observations, outcrop mapping, seismic based fracture prediction and laboratory studies and reveal a vast degree of geometric complexity. Incorporating such structures with a sufficient degree of their complexity in computational models poses a major challenge for physics-based dynamic rupture simulations. We here use the statistical nature of fracture density in a novel, physics-based Markov Chain approach. 3D distributed fracture surfaces are created either uniformly distributed (Fig. 1a), according to tensile crack opening angle (Fig. 1c and e.g. Madden et al., 2017) or based on background stress orientation (Fig. 1b). The number of fractures and their length are determined by a power-law distribution (Bour et al., 2002). The generated network is subsequently mapped onto a high resolution unstructured computational mesh thus avoiding the bottleneck of explicit meshing.

The presented modeling framework will be used to run suites of 3D simulations including structural complexity of fracture networks in conjunction with realistic, laboratory based friction laws accounting for fluid effects.

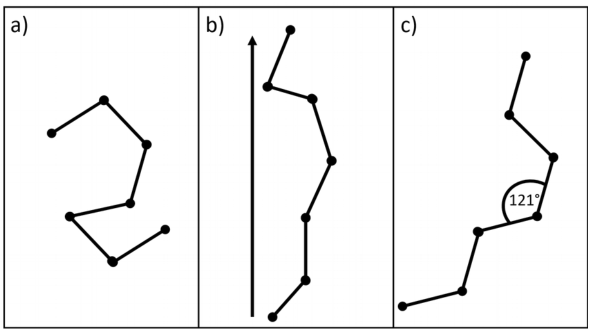

Fig. 1 Fracture network creation for physics-based dynamic earthquake and seismic wave propagation modeling with SeisSol. a) randomly, b) based on background stress orientation, or c) according to tensile crack opening angle.

Numerical Simulation of Fracture Failure and Propagation due to Fluid Injection, in the Context of Embedded Discrete Fractures

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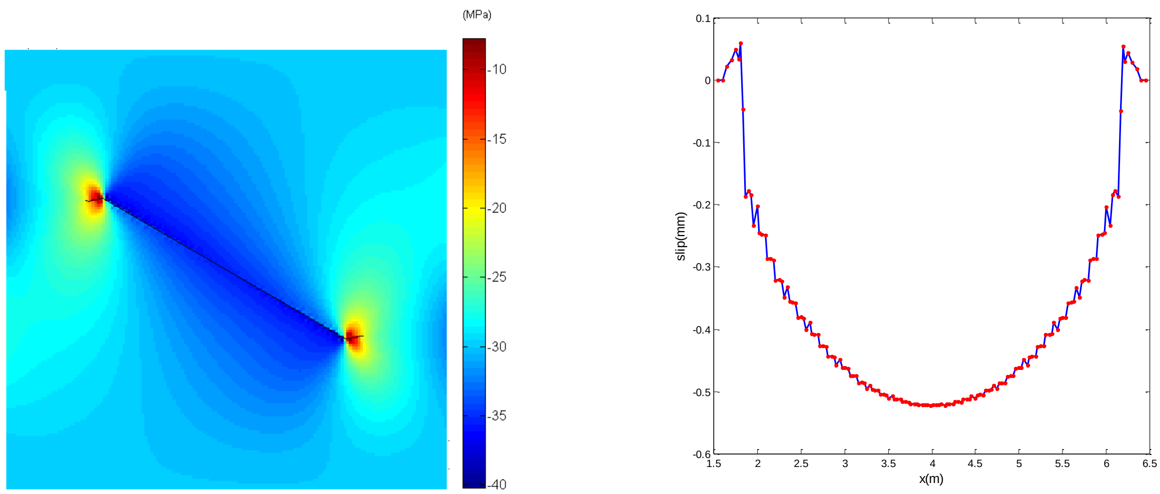
This work focuses on developing a numerical framework to study the physics of induced seismicity due to fluid injection in a fractured domain. As a consequence of shear or tensile failure due to fluid injection, new fractures are created adjacent to the tips of the preexisting ones due to tensile or mixed mode failure. Continuing the fluid injection, these new fractures then propagate and may coalesce with the other fractures or form again new fractures.

Numerical modeling of such a system requires complete modeling of the coupled solid and fluid mechanics including shear and tensile failure. We employ an embedded discrete fracture representation, where large fractures are described by discrete manifolds embedded in an elastic damaged matrix domain. To properly account for the displacement discontinuities due to irreversible failure of fractures, we employ a previously developed extended finite volume method (XFVM) [1]. Fluid flow is computed within both the damaged matrix and the fractures, while mass exchange is accounted for by modeled transfer rates.

Failure and fracture propagation is based on the local mechanical stress situation and on the fracture fluid pressure. To reduce computational cost, resolving the timescale of individual slip events is avoided by directly solving for the final slip displacement. This is achieved based on the requirement that the local shear force matches the local shear strength limit.

For initiation of new fractures or for fracture propagation, different propagation criteria such as minimum principle stress, cohesive strength and stress intensity factor at the crack tips are integrated. The accuracy of the new model will be examined for various material properties and test cases involving tensile failure and fracture propagation.

Fig. 1 shows simulation results for a case where fluid is injected through a well at the center of a natural fracture. The medium is subjected to unequal compressive forces in x and y directions. As it can be seen, wing fractures are formed at the tips of the natural fracture. These fractures then propagate in the direction of maximum principle stress.



(a) (b)

Fig. 1 (a) σ_y stress distribution, (b) tangential slip along the natural fracture and the new initiated wing fractures. High stress intensity can be seen along the formed wing fractures at the tip of the natural fracture.

Reference:

[1] Deb, Rajdeep, and Patrick Jenny. "Finite volume–based modeling of flow-induced shear failure along fracture manifolds." International Journal for Numerical and Analytical Methods in Geomechanics 41.18 (2017): 1922-1942.

Seismogenic potential of withdrawal-reinjection cycles: numerical modelling and implication on induced seismicity

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„Induced seismicity can be associated to the activity of fluid withdrawal and injection from/into the shallow crust (fracking, wastewater disposal into the deep crust, EGS technology, fluid extraction in oil fields and geothermal power plants). Long-term injection of large volumes of fluids is normally associated with induced seismicity, but the effect of withdrawal-reinjection in the same reservoir is largely unknown. However, it is common experience worldwide that small geothermal plants with withdrawal and re-injection of fluids in the same reservoir are not associated to any significant seismicity, induced or triggered. This paper aims at understanding how to discriminate the seismogenic potential of withdrawal-reinjection with respect to injection only. With this aim, we analysed the induced pressure changes, the perturbed volumes of rocks and the potential for induced seismicity due to the above activities. A set of simulations of injection or withdrawal-reinjection cycles, obtained by using the numerical code TOUGH2®, is applied to simple models of geothermal reservoirs, with varying permeability and lateral boundary constraints. For each permeability model, we then compare the time growth of perturbed volumes obtained with withdrawal-reinjection cycles to those obtained during simple injection, using the same flow rates. The size of perturbed volumes is then related to the maximum magnitude of induced/triggered seismicity, using models accredited in recent literature. Our results clearly show that, for all models, withdrawal-reinjection is by far less critical than simple injection, because the perturbed volumes are remarkably smaller and remain constant over the simulated time, so minimizing the likelihood of interference with seismogenic faults. These results have significant implications for geothermal projects, and in the assessment of the potential risk related to fluid stimulation and induced seismicity."

A Hybrid EGF Technique for Predicting Ground Motion from Induced Seismicity: Application to the Basel Enhanced Geothermal System

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An approach is presented for the prediction of site-specific surface ground motion due to induced earthquakes (Edwards et al. 2018: doi:10.3390/geosciences8050180). The method is well suited to a real-time predictive hazard or regulatory framework, where shaking estimates can be dynamically updated in light of ongoing seismicity. The approach is based on empirical Green's functions (EGFs), determined using micro-earthquakes at sites where seismicity is being induced (e.g., during shale oil and gas extraction, CO_2 sequestration, and geothermal injection). Using the EGF approach, a ground-motion field (e.g., a PGV or intensity map) can be calculated for scenario events originating within the seismic zone. Site- and path-specific effects are mapped into the predicted ground-motion field, providing a unique local ground-motion model that accounts for wave-propagation effects without the requirement of 3D velocity models, site-characterization investigations, or extensive computational resources.

As a test case, the peak ground velocity (PGV) field for the mainshock (M_L = 3.4, **M** = 3.2; Fig. 1c) resulting from the Basel Enhanced Geothermal System (EGS) was simulated using only seismicity prior to the event. The hybrid EGF method (Fig. 1d) resulted in significantly reduced uncertainty compared to predictions from a generic ground-motion prediction equation (GMPE) for induced earthquakes (Fig. 1b). The approach also resulted in improved site-specific predictions (through intrinsic inclusion of local amplification effects) compared to the generic and a locally calibrated GMPE (Fig. 1a). It was shown, however, that extrapolation beyond a couple of magnitude units leads to significant uncertainty.

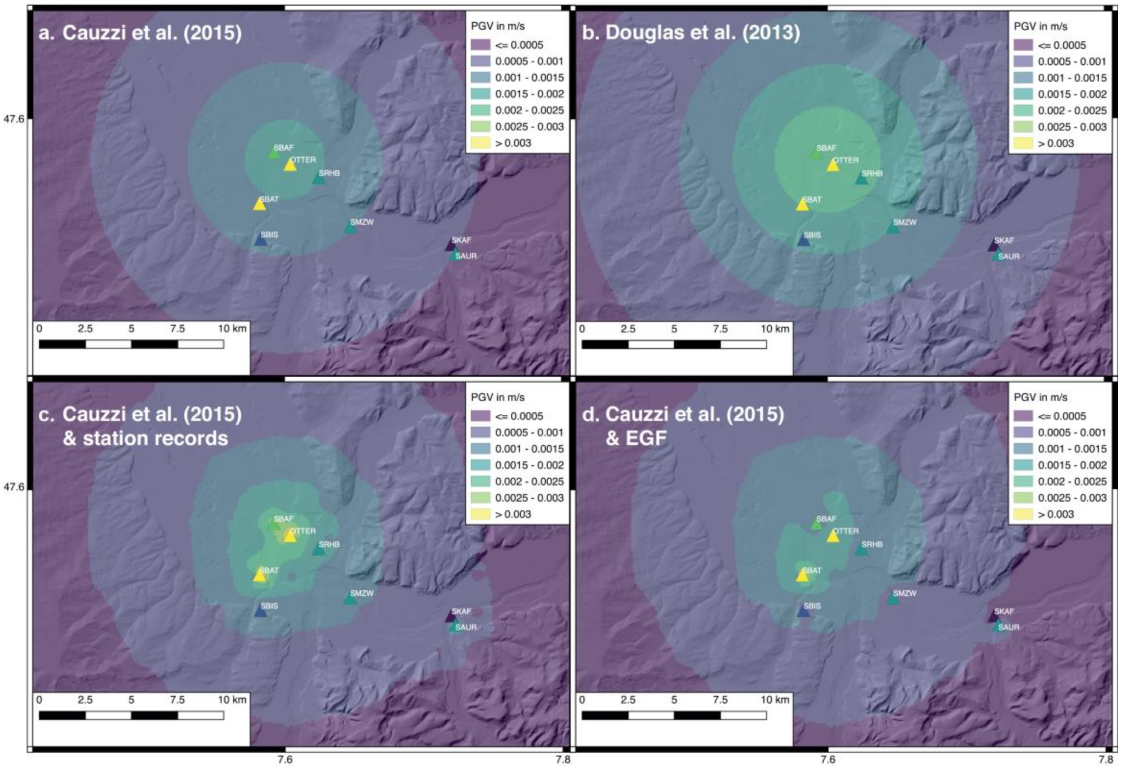

Fig. 1 Peak ground velocity (PGV) maps (background) and M = 3.2 mainshock amplitude (triangles) for the Basel event. The background PGV maps show the predictions of Cauzzi et al. (2013: 10.1093/gji/ggu404) (a), the predictions of Douglas et al. (2013: doi:10.1785/0120120197) (b), the interpolation of recorded PGV and Cauzzi et al. (2013) (c), and the interpolation of empirical Green's function (EGF) predictions and Cauzzi et al. (2013) (d). The triangles in each map are coloured according to the recorded PGV at each station.

Testing Injection Scenarios with a 3D Discrete Fracture Hybrid Model

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Moderating the risk associated with induced seismicity is a necessity, since future scenarios that are free of induced seismicity risk exist neither for reducing the greenhouse emissions nor for reducing the current amount of CO_2 in our atmosphere. Here, focus is on induced seismicity generated during the stimulation of Enhanced Geothermal Systems' (EGS) reservoirs. The development of this low emissions geothermal technology has suffered by our limited experience from successful EGS stimulations, the complexity of the problem and the high uncertainty regarding the in-situ conditions. It is no surprise that a wide range of opinions regarding the hazard of future injection scenarios exists even among experts.

Monte Carlo (MC) simulations can be a remedy to the situation. They return probabilistic forecasts that consider all possible in-situ conditions and can accurately simulate complicated scenarios for the well accepted physical processes. A three-dimensional Discrete Fracture Hybrid Model (DFHM) is employed for the MC simulation. The DFHM numerically solves pore-pressure diffusion in a fractured reservoir, where the discrete fracture network of the reservoir changes with the stochastically modeled induced seismicity. This DFHM is expected to be one of forecasting models in the Adaptive Traffic Light System developed by the Swiss Seismological Service and its coding has been optimized by the Swiss National Supercomputing Center. Its current implementation returns in real time not only forecasts of seismicity and of reservoir's performance, but it can also highlight the limitations of the modeled processes in achieving the goals of the stimulation. Last but not least, desired reservoir's features prior to stimulation can be extracted and stimulation strategies can be optimized.

Here, exemplary MC simulations with the DFHM are presented and discussed. Forecasts of the eventual reservoir's performance are presented for different stimulation strategies. Desired reservoir's features for a safe stimulation are extracted by performing sensitivity analysis and their correlations to the eventual success of the EGS project is studied.

How to model aftershocks in induced seismicity? Insight into seismicity of Kiruna Mine, Sweden

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Induced earthquakes, similar to natural ones, are often followed by aftershocks. Although the magnitudes of such aftershocks are usually not high, they may pose extra hazard to local production infrastructure, potentially weakened by the main shock, and hence the continuation of production. What is most important, though, is that they may pose hazard to people working at the production site, especially in underground mining. The existing post-earthquake mining procedures usually do not take into account any aspects of the physics of the main shocks. Numerous studies of natural earthquakes show, however, that the pre-main shock level of seismicity and the impact of the main shock rupture on the stress state in the surrounding rock – the coseismic stress changes, may be the basic input in reliable modelling of aftershock activity. In our study we try to apply that knowledge to mining-induced seismicity. We use the rate-and-state modelling to model the aftershock sequence following two strong (M ~2) events in iron ore Kiruna mine, Sweden. However, in case of any seismicity induced by the exploitation of geo-resources, the evaluation of pre-main shock level of seismicity is challenging due to constantly changing stress state in the rock caused by ongoing production. Dealing with that problem requires long-term, detailed knowledge of the mine's exploitation plans and resulting seismic activity. Our study shows that in Kiruna mine the influence of co-seismic stress changes on the distribution of aftershocks is much less than the influence of the production stress reflected in a reference seismicity rate. We show that the rate-and-state based model may work well for mining events both in terms of the number of aftershocks and their distribution. However, the model may also underestimate the number of aftershocks - we discuss the potential reasons for different model's performance, e.g. potential influence of various factors not included in the modelling on the generation of aftershocks.

Depletion-induced seismicity at the Groningen gas field: Coulomb rate-and-state models for structurally complex reservoirs

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We implement a Coulomb rate-and-state approach to explore the non-linear relation between stressing rate and seismicity rate in the Groningen gas field.

Coulomb stress rates are calculated, taking into account the 3D structural complexity of the field and including the poro-elastic effect of the differential compaction due to fault offsets. In order to achieve this we developed a novel way of calculating induced stress changes and associated seismic moment response for structurally complex reservoirs with tens to hundreds faults. Our specific target was to improve the predictive capability of stress evolution along multiple faults, and to use the calculations to enhance physics-based understanding of the reservoir seismicity. Our methodology deploys a mesh-free numerical and analytical approach for both the stress calculation and the seismic moment calculation. We introduce a high performance computational method for high-resolution induced Coulomb Stress changes along faults, based on a Green's function for the stress response to a nucleus of strain.

The spatio-temporal evolution of the Groningen seismicity must be attributed to a combination of both: (i) spatial variability in the induced stressing rate history, and (ii) spatial heterogeneities in the rate-and-state model parameters. Focusing on two subareas of the Groningen field, we show that the rate-and-state model parameters are spatially heterogeneous. The very low background seismicity rate of the Groningen gas field can explain the long delay in the seismicity response relative to the onset of reservoir depletion. The characteristic periods of stress perturbations, due to gas production fluctuations, are much shorter than the inferred intrinsic time delay of the earthquake-nucleation process. In this regime the modelled seismicity rate is in phase with the stress changes. However, since the start of production, the Groningen fault system is unsteady and it is gradually becoming more sensitive to the stressing rate.

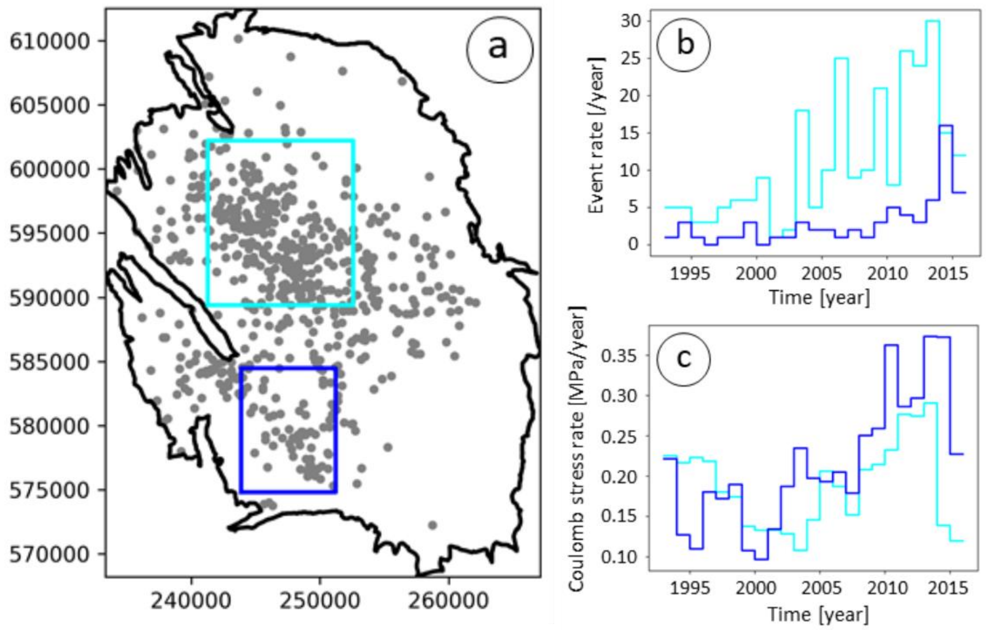

Fig. 1 Observed event rates (b) and modeled Coulomb stress rates (c) for the two sub-areas of the Groningen field (a).

Stress-based, statistical modeling of the induced seismicity at Groningen Gas Field

Gudrun Richter[1,2], Sebastian Hainzl[2], Torsten Dahm[1,2], Gert Zöller[1]

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We test whether induced seismicity related to gas exploration can be modeled by the statistical response of fault networks with rate-and-state dependent frictional behavior. The model is applied to the data set from Groningen gas field which is the largest onshore gas field under production in Europe. The depletion of the gas field started in 1963. Since 1991 an increasing number of induced earthquakes with magnitude up to M_L=3.6 have been recorded. Most of these events are of magnitude less than 2.0 and cannot be felt, but a few of them caused some damage and aroused concern in the population and government, which finally lead to the decision to reduce the production and stop it completely (https://www.government.nl/latest/news/2018/03/29/dutch-cabinet-termination-of-natural-gas-extraction-in-groningen). The long and detailed seismicity catalog (Royal Netherlands Meteorological Institute, KNMI) and the available additional information on production activities in Groningen is ideal to test induced seismicity models in regard to the operation-induced changes at reservoir level.

Because most of the earthquakes occur at the depth of the reservoir we assume that the Coulomb stress changes in the reservoir are causing the induced seismicity. We use the spatiotemporal distribution of pore pressure and compaction strain as proxi for the stress input to the seismicity models, and test the potential impact of fault density and orientation. Seismicity models with instantaneous earthquake nucleation are compared to rate-state models considering time delay and memory effects. Both models can reproduce the observed long delay of the seismicity onset. However, stress-based models with instantaneous earthquake nucleation need to assume that all faults are initially far from critical stresses to explain the delay. Our results show that the rate-state model is superior even in the later activation period. The spatiotemporal pattern of seismicity is shown to be best modeled based on the compaction data and is further improved by taking the fault density into account (see **Fig 1**). Despite its simplicity, the rate-state model can thus reproduce the statistical features of the observed activity.

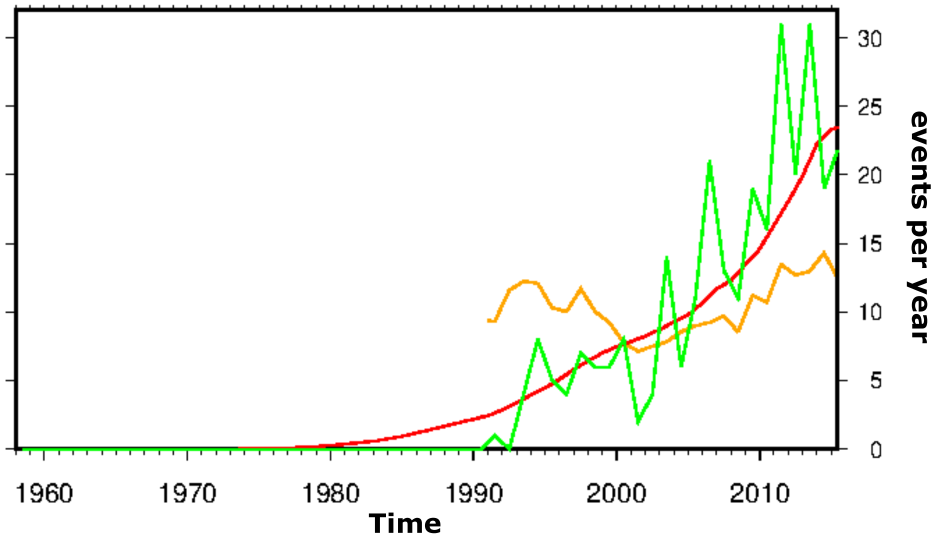

Fig. 1 Modeled seismicity rate per year based on compaction data and weighted with fault density with rate-state model (red) for the time period 1959 to 2014 and with instantaneous nucleation model (orange) for the time period 1991 to 2014. Observed seismicity for M ≥ 1.5 (green).

Numerical Analysis Of Friction Laws. Application To Induced Seismicity

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It's known that the rate-state friction law could be used to reproduce the seismic activity generated by tectonic fault sliding. The authors previously showed that the spring-block system with two-parametric friction law exhibits various types of chaotic motion. In the same time, the results of numerical experiments showed that used variant of the friction law did not allow to describe correctly some modes of the block movements. To solve this problem, several modifications of the friction law were considered, and numerical modeling of the spring-block system with modified friction law was conducted. By varying the model parameters, the various slip patterns were obtained, which were different from the patterns obtained using the "common" two-parametric friction law. The numerical results were compared with measurements of the slider-block movements in laboratory experiments; the comparisons were conducted for several variants of the friction law modifications. The modifications allowing to achieve the best matching with the experimental measurements for the different slip modes were found. But the additional term used in the modification significantly affects the possibility of obtaining chaotic motion. The periodic motion obtained in laboratory experiments can be reproduced quite accurately, but chaotic motion can be reproduced only in terms of average values (Fig. 1).

The resulting friction law was used for modeling fault slip induced by fluid injection. For this purpose 2-D model was considered. Fluid is injected near the horizontal flat fault in a homogenous medium. The remote stresses are constant. Influence of form of friction law was analyzed by comparing resulting fault slip with experimental data.

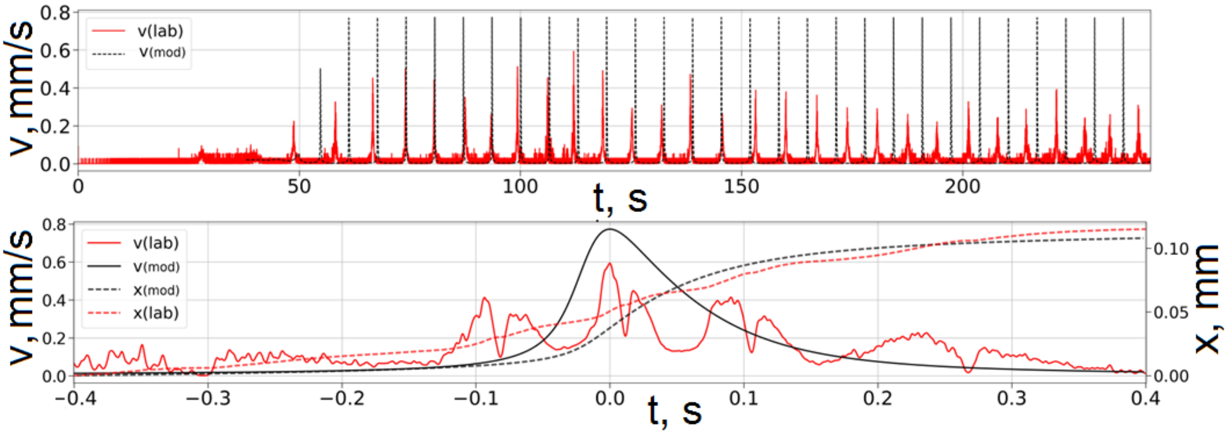

Fig. 1 Time dependence of block velocity and slip. Laboratory data and result of numerical modeling.

Injection strategies for EGS: balancing seismic risk and stimulation efficiency

Vanille A. Ritz[1], Antonio P. Rinaldi[1], Stefan Wiemer[1]

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As of today, most geothermal plants produce from hydrothermal or magmatic systems where hot native fluids from naturally permeable reservoirs are extracted. However, naturally occurring resources are scarce, and for countries like Switzerland, the development of safe Enhanced Geothermal Systems is crucial to their energetic balance in a fossil free near future. In these EGS, stimulation operations are needed to enhance the permeability of a targeted reservoir, but are susceptible to significant amounts of induced seismicity. One potential approach to limiting the induced seismic risk is directly linked to the injection method.

We propose a full 3D numerical modelling approach of hydraulic stimulation to test different injection scenarios, using TOUGH2-Seed[a]. The fully synthetical hybrid model is first checked against observed seismological results in a classical setting, then used to test the seismic response to various injection tests and features. Multiple physical processes are added to the base model to assess their influence on the modelling, as these processes (static stress transfer, seismicity dependent permeability enhancement etc.) can lead to better information for future forecasting work. The presence of a major fault zone is also investigated as it could increase the risk and affect the efficiency of the stimulation. The impact of different injection strategies is then evaluated for both efficiency of the stimulation and seismic risk, to determine more or less favourable trade-off options.

[a] Rinaldi & Nespoli, 2017

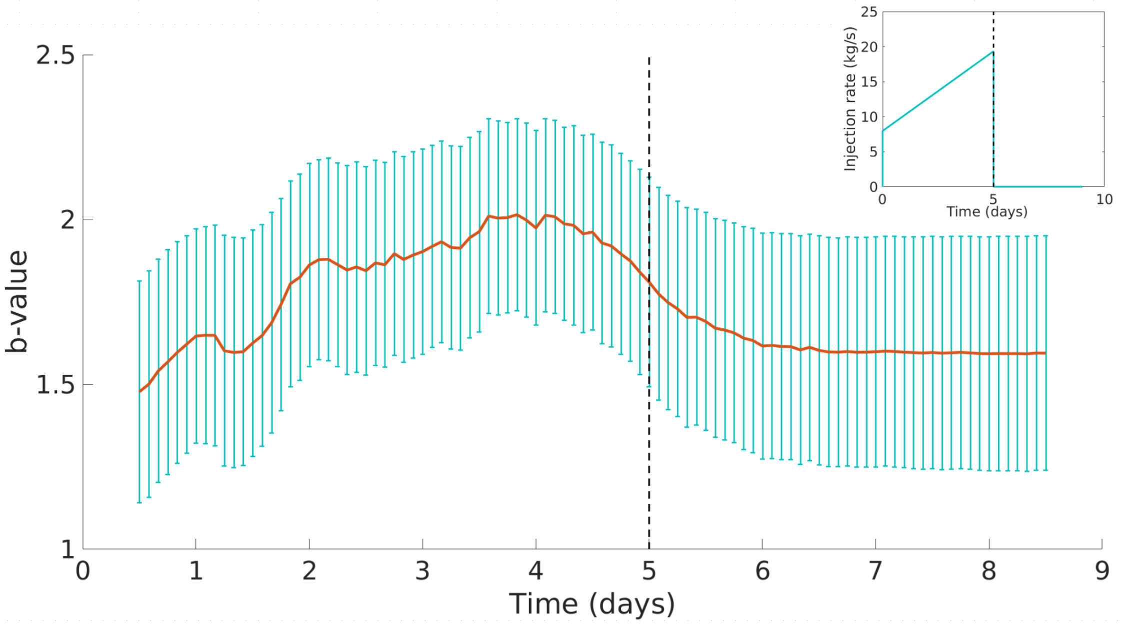

Fig 1: b-value evolution in time for a linearly increasing injection rate (bottom-hole). The dashed line represents the shut-in.

Forecasts of Induced Seismicity and its Hazard from a Hydromechanical Earthquake Nucleation Model

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We apply a seismicity model based on a rate-and-state friction framework to study the induced earthquakes in Oklahoma and Kansas. This model uses fluid pressures computed following the assumption that pressure changes are dominated by reservoir compressibility effects. Using data from all of the injection wells in the Arbuckle group, we compute the stressing conditions over the 22.5-year period of January 1995 through June 2017. Subsequently, we calculate seismicity rate forecasts over a broad range of spatial scales. The forecasts replicate many of the important characteristics of earthquake behavior including the timing of the onset and peak of seismicity, as well as the reduction in seismicity following decreased disposal rates. This forecast outperforms an observational seismicity rate forecast model for one-year forecast durations over the period 2008 - 2016. We use these rate forecasts to compute the 1-year induced earthquake hazard for 2018.

  

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