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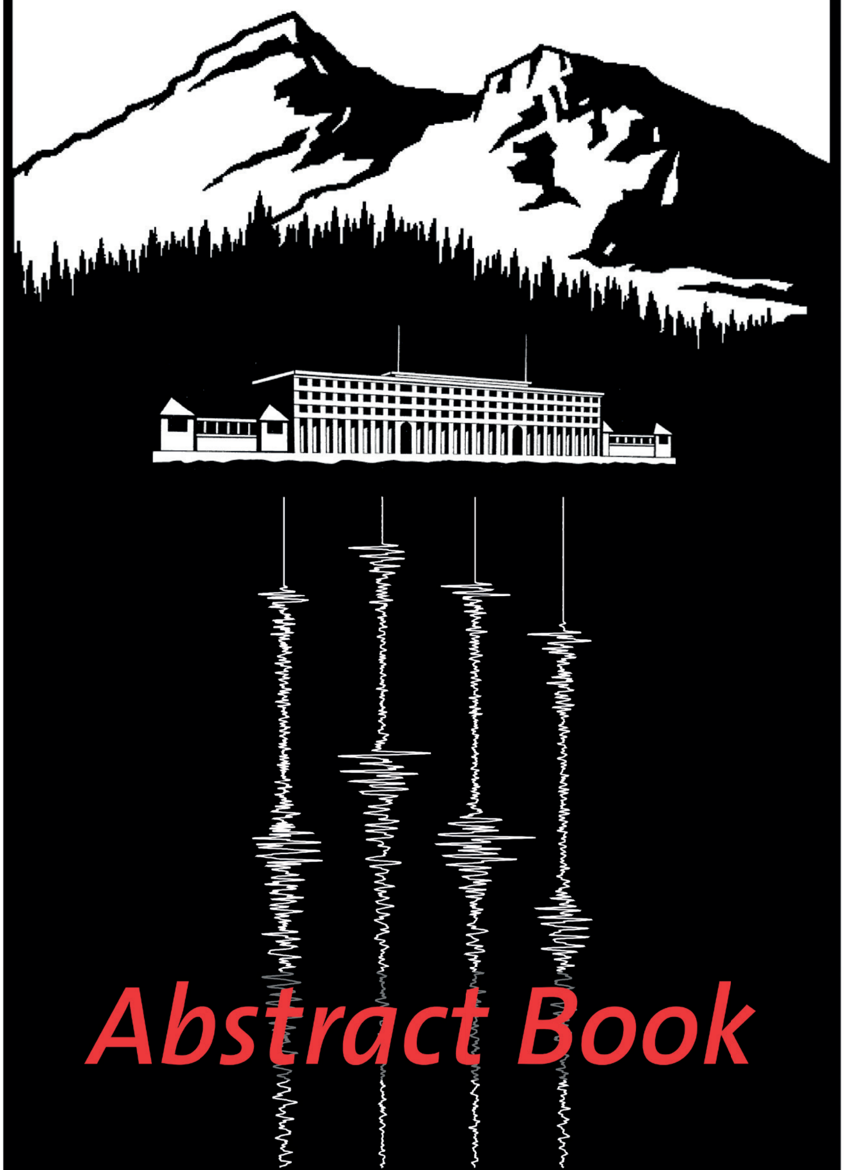

Abstract Book

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Induced Seismicity Workshop

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Session 1

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Hydrocarbon induced seismicity in Northern Netherlands

B. Dost, D. Kraaijpoel, T. van Eck† and M. Caccavale

KNMI, de Bilt, the Netherlands

The northern Netherlands has been regarded an aseismic region until the first earthquakes started in 1986, after more than 25 years of gas production from the one of the largest on-shore gas-fields in the World, the Groningen field, and accompanying smaller gas fields. Due to the shallow sources, at approximately 3 km depth, even small magnitude events cause considerable damage to buildings in the region. Since the largest recorded event in the Groningen field in 2012 with ML= 3,6, more than 30.000 damage claims were received by the mining company.

Since 1995 a seismic monitoring network is operational in the region, consisting of 8 200m deep boreholes with 4 levels of 3C 4,5 Hz geophones. The network was designed for a location threshold of ML=1,5 over a 40x 80 km region. Average station separation was 20 km. At the end of 2014, 245 events have been recorded with ML ≥ 1,5, out of a total of 1100.

Since 2003 a new mining law is in place in the Netherlands, which requires for each gas field in production a seismic risk analysis. Initially, due to the small number of events for specific fields, a general hazard (PSHA) was calculated for all gas-fields and a maximum magnitude was estimated at ML = 3,9. Since 2003 an increase in the activity rate is observed and the non-stationary character of the seismicity in the Groningen field became apparent, leading to the development of new models and a re-assessment of parameters like the maximum magnitude. More recently these models are extended to seismic risk, where also the fragility of the regional buildings is taken into account. Understanding the earthquake process is essential in taking mitigation measures. Continued research is focused on reducing the uncertainties in the hazard and risk models and is accompanied by an upgrade of the monitoring network.

In 2014 a new dense network was designed to monitor the Groningen gas field in this region (30*40 km) with an average separation of 4 km. This allows an improved location threshold (M>0,5) and accuracy (50-100m). In total 65-70 new 200m deep boreholes will be operational in 2015. At each borehole an accelerometer will be placed at the surface. In addition two deep downhole tools (3 km depth) are operational since 2013 and 4 broad-band sensors at 200m depth will be installed, covering the gas field. Results of monitoring and research will be presented.

The ICHESE report on the relationship between Hydrocarbon Exploration and the May 2012 earthquakes in the Emilia Region (Italy) and their consequences

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A sequence of significant and devastating earthquakes (4 events > 5 ML, with total collateral damage of c 12 Billion Euros and great destruction of cultural heritage) occurred in the Emilia Romagna region of Northern Italy in May-June 2012. The possibility that the sequence was influenced by activities associated with the exploitation and utilization of gas/oil/geothermal reservoirs in the neighborhood of the sequence was investigated by the Technical-Scientific Commission ICHESE (International Commission on Hydrocarbon Exploration and Seismicity in the Emilia Region). ICHESE was appointed on December 11, 2012 by the decree of Dr. Franco Gabrielli, Head of the Italian Department of Civil Protection of the Presidency of Council of Ministers, at the request of the President of Emilia-Romagna Region. The Commission was appointed with the following responsibility.

"The International Committee shall produce a report answering the following questions, on the basis of the technical-scientific knowledge available at the moment: 1) Is it possible that the seismic crisis in Emilia has been triggered by the recent researches at the Rivara site, particularly in the case of invasive research activities, such as deep drilling, fluid injections, etc.; 2) "Is it possible that the Emilia seismic crisis has been triggered by activities for the exploitation and utilization of reservoirs carried out in recent times in the close neighborhood of the seismic sequence of 2012?".

After excluding the possible influence of the production activity at four of the five active sites in the study area, (2 hydrocarbon fields, Recovato and Spilamberto, one gas storage field Minerbio, one geothermal field, Casaglia), on the basis of the state of current knowledge, the Commission declared that (ICHESE, 2014): " [..] the current state of knowledge and all the processed and interpreted information does not allow the ruling out of the possibility that the actions involved in hydrocarbon exploitation in the Mirandola field may have contributed to **'trigger'** the Emilia seismic activity".

Applying the "precautionary principle" the Emilia Romagna region halted production in the Cavone (Mirandola fields) and it became a laboratory site ("Laboratorio Cavone", http://labcavone.it/). While the ICHESE report certainly indicated the possibility of a relation between seismicity and hydrocarbon activity, it did not encourage the application of this principle in this indiscriminate manner .

ICHESE recommended the implementation of seismic monitoring systems around hydrocarbon fields located in such tectonically active areas. The Commission also suggested that the acquired data should be examined critically in as near real-time as possible to detect changes which might indicate that natural fracture systems were experiencing combined Coulomb and poro-elastic stress changes which might stimulate movement on critically oriented faults. On 27 February 2014, a working group was constituted to define guidelines for the monitoring of hydrocarbon exploitation and storage activities in Italy, in terms of seismicity, pore pressure and soil deformation according to the recommendations of the ICHESE report. The guidelines were issued on 24 November 2014 (http://unmig.sviluppoeconomico.gov.it/unmig/agenda/dettaglionotizia.asp?id=238) and will be gradually implemented to a pilot case.

Although some controversial opinions were expressed in the scientific community regarding the conclusions of the ICHESE Commission, there is a consensus that it represents a useful first step in answering the concern of communities about the risks associated to anthropogenic activities.

References

International Commission on Hydrocarbon Exploration and Seismicity in the Emilia Region (ICHESE), *Report on the hydrocarbon exploration and seismicity in Emilia Region*, (2014, http://unmig.sviluppoeconomico.gov.it/unmig/agenda/dettaglionotizia.asp?id=175).

Induced seismicity at the natural gas fields in Northern Germany

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The Northern German basin is a region of thick sedimentary cover with frequent salt dome uplifts, and exhibits relatively low seismic activity with only some rare and singular tectonic events. However, during the last decades seismicity raised in vicinity of the natural gas fields in Rotliegend situated at four to five km depth, and extending 50 km NS and 400 km EW from the border to the Netherlands in the West to Altmark region in the East The spatial correlation between epicenter locations and natural gas fields is obvious, and these events just started after beginning of gas extraction. Altogether, 46 events with M_L 0.5 to 4.5 were detected between 1977 and 2014.

The 1977 (M_L 4.0) Soltau earthquake was the first event close to gas fields, and after start of gas production. It was poorly recorded due to the sparse station distribution in an ‘aseismic’ region, and initially assessed as a tectonic event releasing stress from postglacial uplift, or by salt tectonics. The 2004 (M_L 4.5) Rotenburg event in the Söhlingen gas field then motivated the installation of additional seismic stations. Currently, an industry-operated network of borehole and surface stations monitors the eastern part of the gas fields down to M_L 1.5 while initiatives from universities and the Federal Institute for Geosciences and Natural Resources (BGR) focused on the seismically most active gas fields Völkersen with recent series of annual M_L 2 to 3 events, and Söhlingen. At Söhlingen a new monitoring concept with dense and tri-partite small aperture arrays is investigated by University of Stuttgart. Despite these initiatives there is still no systematic monitoring of the western area of natural gas production in Northern Germany.

Due to the poor noise conditions in thick sedimentary cover of densely populated and industrialized Northern Germany, earthquake recording is not complete below M_L 1.5, although well-instrumented spots like Söhlingen are now monitored down to M_L 0.5. The epicenter determination suffers from large azimuthal gaps, and the precision of depth determination is still insufficient to identify rupture sources below, within, or above reservoir level reliably. Up to now, it is not clear whether the relative lack of fore- and aftershocks, and smaller earthquakes in general is inherently characteristic for induced events versus tectonic earthquakes, or if this observation just reflects the inappropriate seismic surveillance during the last decades.

The process of earthquake generation is still not well understood. Various options are discussed, like heterogeneous compaction within a reservoir, variation of local stress field from reservoir compaction, hydraulic stimulation measures for tight gas, or injection of disposal fluids. Subsidence mapping, production data from industry, and stress field modeling are rarely available leaving investigation of possible trigger mechanisms in its infancy state. More information about production parameters, week seismic events, precise hypocenters, and moment tensor solutions are required to proceed with a more detailed analysis. Known so far is a delay of seismic activity more than ten years after start of extraction, and a clustering of seismicity to just some gas fields leaving out even close neighbors.

When comparing seismicity at the natural gas fields in Northern Germany with those in nearby Netherlands, some remarkable differences appear despite their common geology in Rotliegend. Gas fields in Netherlands are more shallow (2 km depth), much larger with accumulated surface subsidence up to half meter, and generate more frequent but smaller earthquakes with $M_L$max 3.6 compared to 4.5 in Rotenburg. In Northern Germany, the induced events are mostly located at the rims of the gas fields, whereas in the Netherlands they are typically situated inside.

For most of the larger events, like the recent 2005 (M_L 3.8) Syke, the 2012 (M_L 2.9) Völkersen, and the 2014 (M_L 3.2) Syke macroseismic evaluations were performed which gave maximum intensity IV to V, maximum PGV of a few mm/s, and radii of felt recognition from 5 km to 24 km indicated shallow sources with comparatively high local hazard potential.

From hazard assessment to hazard management.
The case of mining induced seismicity.

Stanislaw Lasocki

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Mining induced seismicity (MIS) is the oldest known undesired dynamic rockmass response to technological processes. Stronger MIS earthquakes, which reach even more than M5.0, can both endanger mining staff, damage mining installations and interrupt production and, due to their shallowness, pose significant hazard to ground structures. Assessment of the hazard due to MIS is a problem of paramount importance. Development and common use of in-mine seismic systems have resulted in gathering streams of high quality seismic data, and modern data processing methods convert recorded signals in sets of accurate source parameters. This, in turn, builds an exceptional observational base for studying the phenomenon and for improving hazard evaluation methods.

A substantial local change in stress from its ambient state, caused by mining activities, is a main factor controlling mining seismicity. Most of the MIS events are induced. These induced events are linked directly to mining operations, and they cluster around mining stopes and follow mining works. The second kind of mining seismic activity, called triggered by mining, consists of generally higher-energy events that occur in geologically disturbed areas. It results from stress redistribution caused by a summarized impact of the whole mining activity in the region and tectonic stresses in combination with locations of local discontinuities and reduced strength zones. The triggered events often occur farther from mining works without much impact on production but they are major sources of damage to surface structures. These two components of MIS process are reflected in complex, often bimodal magnitude distribution of MIS populations. In this connection a model-free approach based on kernel non-parametric estimators is recommended to estimate source size distribution functions for seismic hazard analysis purposes.

The fact that most of MIS takes place close to active mining openings, mined out volumes and goafs results is a variety of the possibilities of source mechanics. MIS events have often extended sources with significant non-DC components.

Mining activities change in time, which implies more or less irregular time variability of the local stress field inducing the seismicity and hence in the variability of the seismicity itself. Unlike the tectonic earthquake process, the mining-induced process is inherently non-stationary. This time-variability of MIS is accepted in principle in most of the techniques aiming at determining the local time-dependent seismic hazard. They deduce the present and future hazard from past-to-present time variations of a parameter or parameters obtained from seismic series. Every value of such indicative parameters is related to a particular moment of time and is usually estimated from respective values of appropriate parameterization of a number of consecutive events that occurred just before this time-moment.

Furthermore, rigorous statistical testing has evidenced that MIS processes are internally correlated. Some of the associated parameter processes have both long and short memory. It also turs out that in spite of the fact that mining originated stress field variations dominate in the overall stress field changes in a mining seismogeneic zone, the stress alterations due to coseismic displacements play an important role in generation subsequent seismic events in mines.

The complex, multicomponental link between mining works, the cause, and MIS, the result, on the one hand requires complex, interdisciplinary investigation of the phenomenon but on the other hand implies a possibility for managing hazard due to MIS through modifications of operational practices.

Abstracts Talks

Session 2

Injection Plays
Deep Geothermal, Wastewater Disposal, Fracking, CO_2 Storage

Earthquake Hazard When the Rate is Non-Stationary: The Challenge of the U. S. Midcontinent

William L. Ellsworth, US Geological Survey

In July 2014, the U. S. Geological Survey released an update of the 2008 National Seismic Hazard Map for the coterminous U. S. The Map provides guidance for the seismic provisions of the building codes and portrays ground motions with a 2% chance of being exceeded in an exposure time of 50 years. Over most of the midcontinent the hazard model is derived by projecting the long-term historic, declustered earthquake rate forward in time. However, parts of the midcontinent have experienced increased seismicity levels since 2009 – locally by 2 orders of magnitude – which is incompatible with the underlying assumption of a constant-rate Poisson process. Both the developers of the Map and its critics acknowledge that the remarkable rise of seismicity in Oklahoma and nearby states must be addressed if we are to assess the hazard in both space and time. The key issues were addressed in a November 2014 workshop held in Midwest City, Okla., cohosted by USGS and the Oklahoma Geological Survey. The 150+ participants from regulatory agencies, petroleum industry, academic researchers and users of hazard models provided clear advice that short-term (~1 year) and frequently updated (<< 1 year) hazard models are needed. Here I discuss the development of a logic tree approach that addresses short-term changes in seismicity rates. A key challenge is to develop an operational earthquake forecasting capability that anticipates where activity may either initiate or shut-off in response to changing forcing functions. Forecasting more than "last year's earthquakes" will require a deeper understanding of the physical processes and conditions that link human perturbations to the Earth system to its response in seismic events.

Wastewater Disposal, Hydraulic Fracturing, and Seismicity in Southern Kansas

Justin L. Rubinstein, William L. Ellsworth, Steven Walter, Harley Benz, Andrea Llenos
US Geological Survey

The earthquake rate in southern Kansas has dramatically risen in the same area where oil and gas activities have greatly expanded at the same time. The spatial and temporal coincidence of the seismicity and expanded energy activities suggests that fluid injection is responsible for some or all of the increase in the earthquake rate.

Earthquakes were nearly unheard of in southern Kansas until September 2013, when two M2 earthquakes occurred. Since then, the earthquake rate has risen dramatically. In the eleven months from December 2013 to November 2014, 40 M≥3 earthquakes occurred in Harper and Sumner counties. Two M≥4 earthquakes occurred in the same time period, the largest a M4.8 earthquake in November 2014. Residents of the area have reported feeling far more earthquakes.

In response to the surge in earthquakes, the USGS deployed a 14-station seismic network to monitor earthquakes in southeastern Harper and southwestern Sumner counties. Supplemented by stations in deployed by the Oklahoma Geological Survey, we have identified and located hundreds of earthquakes that have occurred since the network was first deployed in May 2014. We are currently detecting and locating earthquakes as small as M0.5. While the network is identifying many earthquakes south of our network in Oklahoma, we focus on the seismicity in Kansas. In southern Kansas we identify numerous lineations and clusters of seismicity, with some lineations extending up to 10 km in length. The duration of these features is highly variable; some features are persistent throughout the entire study period, while others only have seismicity for brief periods of a few days. Focal mechanisms indicate normal faulting, consistent with the local tectonic stress field.

These earthquakes are occurring within the Mississippian Lime Play, an area of rapidly expanding oil and gas development stretching from central Oklahoma to northwestern Kansas. In Kansas, new development of the play is largely in the adjoining areas of Harper and Sumner counties, increasing dramatically beginning in 2012. In 2013, Harper County experienced its highest yearly production volumes to date, which were approximately five times larger than those in 2010. Projections of production volumes show that production will have again increased in 2014. Wastewater injection volumes have also dramatically increased, with total yearly volumes increasing by over a factor of five from 2010 to 2013. Much of the increased injection is being accommodated by new, high injection-rate wells.

The spatial and temporal correlation of the increased oil and gas activity and seismicity in southern Kansas suggests a potential relationship between the two. It is possible that both wastewater injection and hydraulic fracturing are inducing seismicity in the area. Some of the earthquake clusters and lineations lay within 1-2 kilometers of recently established, high-rate wastewater injection wells (some as large as 600,000 barrels/month), suggestions a causal relationship. Other, short-lived clusters of seismicity are found to be adjacent to production wells shortly before they were completed, the time at which a production well would be fracked. Not all of the clusters of seismicity can easily be connected to wastewater injection wells or frack jobs. Similarly, not all injection wells or frack jobs can be easily tied to earthquakes.

The deployment of these 14 stations provides a unique opportunity to study potentially induced seismicity. Some stations are very close to much of the seismicity, allowing for precise locations, low detection thresholds, and ground motion studies. Of particular note, one seismometer was within 4km hypocentral distance from the M4.3 earthquake on October 2, 2014. Accelerations of 70% of the strength of gravity were recorded at this station.

Developing Decision Support Tools and Quantifying Changes in Site Hazard for Induced Seismicity through Bayesian Inference

Jack W. Baker and Abhineet Gupta, Stanford University, USA

This paper employs Bayesian inference to detect changes in seismic hazard from induced seismicity, to support hazard and risk calculations and decisions on operations linked to induced seismicity. There has been a significant increase in seismicity in Central and Eastern Unites States (CEUS) in recent years. Since the increase in seismicity is observed in real time, it is not possible to incorporate this information into probabilistic seismic hazard analysis using conventional tools involving historical seismic rates. The authors describe a methodology to address the problem of utilizing real-time data to detect a change in seismicity. Change Point detection using Bayesian analysis can detect changes in seismicity rates in real-time and can also provide information about occurrence rates of events before and after the change point. This model is validated using a simulated data set with a known change point, and then applied so seismicity data in Oklahoma to detect that date and amount of seismicity change for locations throughout the state. Seismic hazard and seismic risk calculations are presented to demonstrate how Change Point calculations can be utilized in seismic hazard and risk assessment calculations.

Additionally, there is a desire to utilize real-time data from seismic monitoring to assist in decision making on whether to continue, monitor or pause operations linked to induced seismicity. The Change Point model can be used as a decision support tool to assess hazard and risk from operations in a given region to inform these decisions. It can also be used to develop guidelines for monitoring seismicity prior to and after setting up a project to quantify any statistically significant change in seismicity associated with the project.

A detailed analysis of initial seismicity induced by wastewater injection in the Val d'agri oil field (Italy)

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Mauro Buttinelli, INGV, Rome

The Val d’Agri is an extensional basin in the southern Apennines seismic belt (Italy) that hosts the largest European inland oil field. In this study, we analyze high-quality recordings from a dense temporary network of 23 stations of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) to investigate a swarm of 109 micro-earthquakes (M_L<1.8), which occurred in June 2006 during the first stage of wastewater injection in a deep well. 3-D hypocentral locations are at minimum distance of 1 km from the well bottom. Events are confined inside a high-Vp, high Vp/Vs zone, that corresponds to fractured and water saturated carbonates of the reservoir into which fluids are injected. High-precision Double-Differences relative locations illuminate a NW-SE trending, NE-dipping fault-zone with a down-dip length of 1.4 km. The fault-zone is located just underneath the well. Extensional focal mechanisms are coherent with the fault geometry and the local stress field inferred by borehole breakouts from two close oil wells. Seismicity begins the same day of injection start-up. The rate and magnitude of the events correlate to the injection rate and well-head pressure showing a quasi-instantaneous response of the system to the increase/decrease of the injection activity. Also, seismicity rate correlates to temporal variations of the Vp/Vs ratio and of the anisotropic parameters (estimated by S-wave splitting analysis) of the crustal block surrounding the disposal well. These results support the interpretation that seismicity is induced by a rapid increase in pore pressure within the carbonate reservoir and by diffusion along a pre-existing fault-zone that is favorably oriented with respect to the extensional field. After June 2006, induced seismicity continued to be recorded by permanent stations of the local operator ENI and of INGV installed in the Val d'Agri area. After 7 years of injection, a total number of 210 events occurred within 5 km of the well with a maximum magnitude M_L 2.3. Accurate 3-D locations define a continuous fault-zone in the reservoir with a down-dip length of 5.5 km. The lower tip of the fault is located just below the disposal well at 2 km distance from the well bottom. The fault illuminated by earthquakes appears as a blind structure topped by flysch deposits that cover the carbonate reservoir. During the long-term evolution of the system, the pattern of seismicity occurred close to the disposal well is not uniform. Long periods (multi-month) of very low activity are separated by swarms that lasted from a few days to several weeks. Two main swarms were in June-October 2006, following the beginning of injection, and from September 2010 to February 2011. Both these swarms follow prolonged phases of injection activity and build-up of well-head pressure up to the largest values in the whole period (13-14 MPa in 2006 and 12-13 MPa in 2010-2011). The two largest events (M_L=2.3) occurred during the 2010-2011 swarm. The spatiotemporal distribution of earthquakes indicates that the seismogenic volume grew rapidly throughout the first stage of injection (June-October 2006) and continued through 2007-2008, but has stabilized since 2009. During 2006-2008, seismicity migrated from the initial cluster of June 2006 mostly upward in the SW direction and downward in the NE direction, illuminating the 5.5-km-long fault zone. Afterward, seismicity has been characterized by sparse events surrounding the fault-zone and by the occurrence of deep events to the NE and SW of the well.

Our results indicate that the continuous monitoring of seismicity with high standard networks and procedures is effective to recognize the seismicity diffusion on active and preexisting faults that might be re-mobilized by pore pressure changes caused by disposing wells. The Val d'Agri basin was struck by a destructive M7 earthquake in 1857. Since only a few moderate (M < 4.5) earthquakes have occurred after the 1857 event, an appreciable deficit of slip is plausibly ready. Seismic hazard in the region is therefore one important issue and a careful monitoring of events correlated with the exploitation of the oil field is demanding.

Natural Resources Canada's Induced Seismicity Research

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Geological Survey of Canada, Natural Resources Canada

The majority of observed seismicity in Canada is related to tectonic processes along the western and northern margins of the North American continent. Intraplate earthquakes are also common in eastern Canada, whereas the continental interior is relatively quiet. As the high-pressure fluid injection technique was introduced in the 1970's and 80's to enhance the recovery of oil and gas in British Columbia (BC) and Alberta (AB), there have been reports of felt earthquakes, with magnitude as large as 4.3, in the vicinity of oil and gas drill sites. Since late 2006 when the extraction of shale gas started in northeast BC, Natural Resources Canada (NRCan) began to observe a clear change of pattern in background seismicity that appeared to be associated with the practice of hydraulic fracturing (HF). To determine the possible effect of shale gas development on the regional earthquake pattern and to understand the significance of seismic risk associated with induced seismicity, NRCan initiated the Induced Seismicity Research (ISR) in 2012. By providing observation-based science, the primary goal of NRCan's ISR is to enhance the regulatory performance of provincial authorities to reach a balance between public safety and economic benefit. With contributions from provincial partners, academia and industry, the first task of ISR focused on improving earthquake monitoring capability for major shale gas basins across Canada where the development has started or was imminent. New state-of-the-art seismic arrays were set up to compliment the routine operations of the Canadian National Seismograph Network (CNSN) in the Horn River and Montney basins (BC and AB), the Moncton sub-basin near Elgin (New Brunswick), the St. Lawrence Lowlands (southern Quebec), and the Norman Wells region (Northwest Territories). In BC and AB, historical seismograms from existing CNSN stations were re-examined to better calibrate the patterns of regional background seismicity for both pre- and post-HF eras. A detailed database of operation parameters, including both HF and wastewater reinjection, was compiled from reports collected by the BC Oil and Gas Commission. Our results confirm that the increased level of background seismicity in the Horn River Basin was related to the expansion of local HF operation. Induced seismicity in the Montney Basin could be associated with either HF or wastewater reinjection. Preliminary analysis of the Norman Wells dense array data indicates that the new array has improved the detection of local earthquakes by a factor of 10 within a radius of 400 km. In east Canada, HF was performed for exploration purposes at a very low scale. No clear cases of induced seismicity were found. For NB and NT, research is being done to better define the base level of seismicity prior to an eventual production of shale gas. Collectively, these new observations provide more insight to the understanding of seismogenic processes associated with induced seismicity in a variety of different tectonic and geological settings.

Saltwater Disposal and Triggered Earthquakes in Oklahoma: Implications for Large Scale CO2 Sequestration in Saline Aquifers

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Over the past five years, several areas in Oklahoma have experienced marked increases in the number of small-to-moderate sized earthquakes. In seven study areas that encompass 90% of the recent seismicity, we show that the increases in seismicity follow five- to ten-fold increases in rates of wastewater injection. The cause of this seismicity appears to be large increases in the volume of produced water - saltwater co-produced from oil reservoirs – that is being injected into sedimentary formations in hydraulic contact with crystalline basement. The increase in pore pressure resulting from injection appears to be spreading out with time, triggering slip on critically-stressed faults in crystalline basement rocks. Although the recent small-to-moderate earthquakes occurring in Oklahoma has posed little threat to the public, it is not possible to discount the possibility of triggering potentially damaging earthquakes on large basement faults. There are direct parallels between the volumes of saltwater being injected into saline aquifers in Oklahoma (and the associated seismicity) with plans to inject large volumes of CO_2 in saline aquifers in relatively stable intraplate areas in many parts of the world. Should the CO_2 injection trigger the widespread occurrence of small-to-moderate earthquakes, it could compromise the seal integrity of the CO_2 repository.

Abstracts Talks

Session 3

Modeling of Induced Seismicity

Numerical Modeling, Geomechanical Aspects, and Physical Constrains

Lessons from Natural Vein Swarms on the Factors Affecting Hydrothermal Flow in Fault-Fracture Systems

Richard H. Sibson, Department of Geology, University of Otago, NZ

Mineralized fault-fracture meshes (vein swarms) occupy substantial rock volumes and have clearly served as conduits for large volume hydrothermal flow, providing analogs for the fracture networks developed by fluid injection in HDR projects. They form a continuum ranging from sheeted veins occupying subparallel extension fractures, through Hill (1977: *J. Geophys. Res.* 82, 347-352) fault-fracture meshes where dilatant extension fractures are interlinked by faults, to sets of mutually cross-cutting conjugate faults (Fig. 1). Factors affecting the type of mesh that develops include: (1) the prevailing stress and fluid-pressure states; (2) the orientation of existing planar discontinuities; (3) variations in rock competence (cf. tensile strength); and, (4) orientation of the stress field w.r.t. competence layering. Sustained high-flux flow through a dilatant mesh is likely to be maintained only when the tensile overpressure condition ($\sigma_3' < 0$ or $P_f > \sigma_3$) is met, at least locally, either through stress heterogeneity or fluid overpressuring. This requires an absence of through-going low-cohesion faults that are favourably oriented for reactivation.

Failure mode plots define the stress/fluid-pressure conditions under which mesh conduits are likely to form. Gaping hydraulic extension fractures may form under hydrostatic pore-fluid pressures in the near-surface (< 1-2 km) of actively extending crust and also, but to a lesser extent, in strike-slip regimes. The depth extent of such gaping fractures depends on the bulk tensile strength of the crust which may be increased by pervasive silicification or other forms of 'ground preparation'. Fluid overpressuring above hydrostatic is needed to dilate extension fractures at greater depths. However, in the absence of marked stress heterogeneity, opening of flat-lying extension fractures in compressional/ transpressional regimes requires near-lithostatic levels of pore-fluid pressure at all depths.

Naturally occurring examples of 3D mesh conduits at various stages of development are considered from different tectonic environments. Important messages are: (1) in may cases, high dilation meshes appear to predate the formation of through-going faults; (2) the presence of a through-going planar low-cohesion fault prevents attainment of the hydrofracture condition and the formation of a distributed fault-fracture mesh; (3) competence layering contributes to the development of Hill-type meshes; and (4) σ_2 directional permeability parallel to fault-fracture intersections may combine with inherent anisotropic permeability to strongly deflect flow. Dilatant overpressured fault-fracture meshes are likely to be highly unstable with propagation influenced by the stress field, the hydraulic gradient, and directional permeability. Distributed fault-fracture meshes with dilatant extension fractures are only likely to develop in intact rock, or in a rock mass where cohesive strength of existing faults has been restored by hydrothermal cementation, etc., or where existing faults are severely misoriented for reactivation.

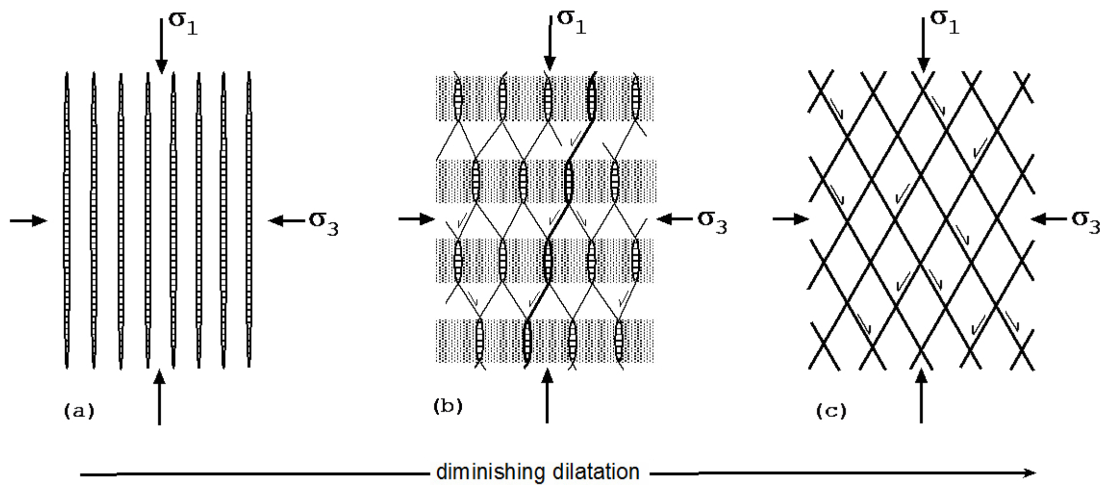

Figure 1 – (a) sheeted extension veins; (b) Hill-type mesh; (c) intersecting conjugate fault sets.

Predictive Modeling of Induced Seismicity: Numerical Approaches, Applications, and Challenges

Marc McClure, University of Texas at Austin

Computational modeling of induced seismicity is an emerging field that offers considerable opportunity for assessment and mitigation of hazard and risk from induced seismicity. In this talk, I will review different approaches to induced seismicity modeling, provide examples from the literature, and discuss key challenges and opportunities. For induced seismicity modeling, perhaps the most challenging aspect is the simulation of the earthquake rupture process, and I will review a variety of approaches. A large number of input parameters are required, involving details like fault geometry, frictional behavior, and stress state. It is a major challenge to populate these parameters and account for the resulting uncertainty. I will describe some of my work using a model that couples fluid flow with rate and state earthquake simulation. I will describe the governing and constitutive equations and numerical details of how the problem is solved. The modeling results help explain post-injection seismicity and suggest strategies that could be used to reduce overall induced seismic hazard. I will also compare and contrast rate and state friction modeling to other approaches, considering factors like convergence to mesh refinement, ability to reproduce Gutenberg-Richter magnitude frequency relations, prediction of seismic and aseismic slip, and computational efficiency.

Simulation of seismic events induced by CO_2 injection at In Salah, Algeria

James Verdon, Anna Stork, Michael Kendall, Max Werner, University of Bristol; Clare Bond, University of Aberdeen; Rob Bissell, Carbon Fluids Ltd.

Concerns have been raised that the injection of large volumes of CO_2 into sedimentary reservoirs for CO_2 sequestration (CCS) will trigger seismic activity. To mitigate this risk, operators should construct geomechanical models of the target reservoir, and they should monitor seismicity before, during and after the project is operational. To ensure confidence in geomechanical simulations, and to aid the interpretation of field observations, methods are needed to link geomechanical models with observations of induced seismicity.

It is generally assumed that where injection pressures do not exceed the minimum horizontal stress, seismicity occurs where shear stresses exceed the Mohr-Coulomb failure criteria on pre-existing faults and fractures. On this understanding, if the location, size and orientation of faults and fractures in a reservoir are known (or can be approximated), and the changes in effective stress caused by injection can be modelled, then it should be possible to simulate when and where fractures exceed a failure threshold, triggering a seismic event. This understanding forms the basis of the work presented here, as we model seismicity induced by CO_2 injection at In Salah, comparing our simulation results with microseismicity observations made at the field.

We use a geomechanical reconstruction tool to model the locations, sizes and orientations of fractures at In Salah. The reservoir geometry is restored from an initial condition, providing a map of strain intensity across the field, which is converted into a fracture model. We model over 300,000 fractures in total. To simulate the stress changes during injection, we use a coupled fluid-flow/geomechanical model provided by the field operators (BP).

The effective stress changes from the geomechanical model are mapped into shear and normal stress changes on each modelled fracture. Where shear and normal stresses exceed the Mohr Coulomb failure envelope, an event is declared. The event magnitude, focal mechanism and stress drop are subsequently computed from the fracture size and the magnitude and orientation of the shear stress vector at the time of failure. The result is a population of events that can be compared to field observations.

We find a good agreement between modelled and observed event rates. Upon the restart of injection in 2010, a few events are recorded. When injection rates increase in mid-2010, the rates of observed and modelled seismicity increase, falling again once injection rates fall later in 2010. Our modelled event locations and event magnitudes also provide a reasonable match with field observations. Recording geometry at In Salah precludes the observation of event source mechanisms or stress drops, so we are unable to compare these modelled parameters with observation. Overall, the matches between observed and modelled event rates, locations and magnitudes are encouraging. Our work highlights the importance of both modelling and monitoring geomechanical effects at CCS projects, and the importance of linking models with field observations.

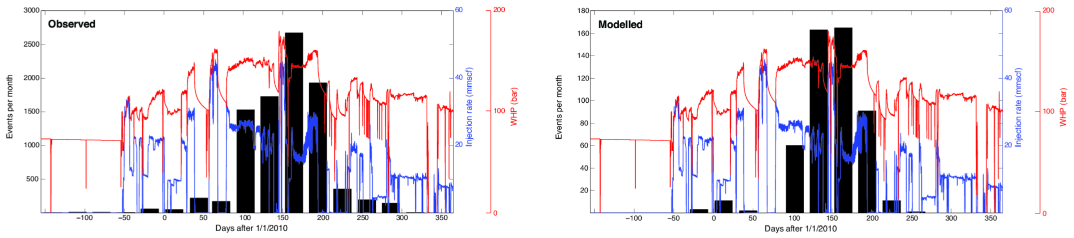

Figure 1: Observed (left) and modelled (right) monthly seismicity rates at In Salah. The injection rates (blue) and pressures (red) are also marked.

Constraints on maximum magnitude of induced seismicity derived from rupture dynamics models

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Understanding what controls the maximum magnitude of induced seismicity is of crucial importance for the quantitative assessment of the earthquake hazard resulting from fluid injection and withdrawal. Empirical relations have been previously proposed between net injected volume and maximum induced earthquake magnitude, which have been then rationalized based on simplified mechanical or geometrical models. One aspect missing in those models is a mechanical relation between earthquake size and the characteristics of the triggering stress perturbation consistent with current physics-based models of the earthquake rupture process. The main purpose of this work is to fill that gap by exploiting and extending recent results on the nucleation and arrest of dynamic rupture derived from numerical simulations and fracture mechanics theory.

In previous work, we derived theoretical relations between the properties of overstressed nucleation regions (their size, shape and overstress level) and the ability of dynamic ruptures to either stop spontaneously (sub-critical ruptures) or runaway (super-critical ruptures). The main basis for these relations is fracture mechanics theory, and their pertinence was verified by comparison to 3D dynamic rupture simulations on faults governed by slip-weakening friction. We also found that similar arguments successfully predict the relation between rupture arrest distance and external loading in laboratory experiments in which frictional sliding is nucleated by localized stresses. Here, we apply and extend these results to situations that are representative of the induced seismicity environment.

We assume that the stress and fluid pressure change generated by fluid injection on a candidate fault can be estimated by hydromechanical and poroelastic modeling. We address the following question: given the amplitude and spatial extent of a fluid pressure perturbation on a fault and given the background state of stress and fracture energy of the fault, does a nucleated rupture stop spontaneously at some distance from the pressure perturbation region or does it grow away until it reaches the limits of the fault? We will present fracture mechanics predictions of the rupture arrest length in this context, and we will compare them to the results of 3D dynamic rupture simulations. The implications for the maximum magnitude of seismicity induced by fluid injection will be discussed, as well as for the dependence of stress drop of induced events as a function of distance to the injection well.

This work is a first step towards a more complete integration of earthquake physics and rupture dynamics into a theoretical and computational framework for modeling induced and triggered seismicity.

Monte Carlo Simulations of EGS Stimulation Phase with a 3-D Hybrid Model

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Electrical power plants that use Enhanced Geothermal Systems (EGS) technology are expected to cover a significant portion of Switzerland's future energy needs. Before operating such a power plant, the EGS wells need to be stimulated in a safely manner, where the resulting impedance between the wells allows the circulation of fluids at commercially interesting flow rates. The induced seismicity during stimulation should be kept under control. Since induced seismicity cannot be deterministically forecasted, the induced seismicity hazard and the EGS thermal revenues need to be probabilistically forecasted for each stimulation scenario.

Monte Carlo (MC) methods are frequently employed for performing probabilistic forecasting in similar problems. The values of the uncertain properties are stochastically sampled, each realization is accurately simulated and then, the probability of certain events to occur can be approximated. Here, a hybrid model that performs three-dimensional Hydro-Thermal-Seismic (HTS) simulations of EGS reservoirs and is used for performing MC simulations, is presented. This hybrid model couples HFR-Sim with the so-called 'seed model'. HFR-Sim is the in-house EGS simulator of ETH Zurich and it models flow and heat transport in dynamically changing Discrete Fracture Networks (DFN). DFN realizations are generated by the seed model, which simulates stochastically induced seismicity and is used by the Swiss Seismological Service (SED) for forecasting induced seismicity hazard. The presented hybrid model can simulate both induced seismicity and expected thermal revenues from each DFN. Moreover, it can simulate each realization within few hours even in one processor, so MC simulations are feasible with it. This hybrid model will be used for real time Probabilistic Induced Seismicity Hazard Assessment (PISHA) by SED.

The main elements of this hybrid model are presented. Well treatment, upscaling of low-magnitude earthquakes, and discrete fracture modeling for large-magnitude earthquakes are explained. Single realizations and MC simulations are demonstrated and their implications are discussed.

On the role of processes interaction in the triggering of post-injection seismicity in Enhanced Geothermal Systems

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Deep fluid injection is a necessary operation in several engineering sectors, like geothermal energy production, natural gas storage, CO_2 storage, etc. The seismicity associated to these activities has, in some occasions, reached unexpected magnitude, raising public concern. Moreover, the occurrence of such seismicity after the injection shut-in pointed out the incompleteness of the knowledge and the inability of fully managing these processes. On the other hand, the growing attention toward clean energy makes it clear that we cannot abandon these procedures, which have a huge potential. Therefore, deeply understanding the mechanisms that induce seismicity is crucial.

Here we consider hydraulic stimulation of deep geothermal systems and analyze the mechanisms that may induce or trigger seismicity. Given that the basic mechanism is fluid pressure increase, secondary triggering processes have been studied. In detail, we attempt to identify the potential mechanisms that may trigger seismicity in the post-injection phase, when the overpressure decreases. These mechanisms have been investigated with a coupled and uncoupled approach, in order to understand the individual effects of each one and the effects of the interactions between them on the reservoir stability.

Besides fluid overpressure, another relevant process is the temperature variation. Indeed, in the case of enhanced geothermal systems, the temperature contrast between the injected cold fluid and the deep hot reservoir is great and induces thermal stress, which sensibly affects the *in-situ* stress field. Therefore, we have studied overpressure and temperature effects by means of analytic solutions and by means of hydro-mechanical and thermo-hydro-mechanical numerical simulations. Results show that in fractured rocks the spatial variability of hydraulic and mechanic parameters provokes no isotropic variation of the tensional field, in response to pressure and temperature perturbations.

Another potential mechanism is due to the slip stress transfer. Once failure conditions are reached along a fault or fracture, shear slip is activated and seismic waves propagate. It is well-known that this slip movement affects the stress field in the neighborhood of the slipped fault or fracture. We analyzed the rotation of the stress tensor due to the slip stress transfer and applied it to the thermo-hydro-mechanic simulation results. Results show that the interaction of these different processes may explain post-injection seismicity on not favorably oriented faults.

Abstracts Talks

Session 4

Scaled Experiments
Underground Labs, Petrophysical Labs

What Can we Learn about Induced Fracturing from Acoustic Emission Monitoring in the Laboratory?

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Microseismic monitoring is of fundamental importance for understanding of temporal changes in induced fracture geometry and for identifying its final extent and orientation during stimulation in hydrocarbon or geothermal reservoirs and during CO_2 sequestration. We performed series of laboratory tests of stressed rock fracturing by fluid injection with monitoring of Acoustic Emission, which is high-frequency analogue of microseismicity recorded in the field. Two kinds of injection tests were performed. During the first series of tests, fracturing of 50 mm diameter sandstone samples induced by water injection at the pressures significantly lower than applied stresses was studied in GFZ- German Research Centre for Geosciences. It was found that injection of water into critically stressed dry sandstone induced appearance and diffusion of AE cloud, and later the increase of pore pressure led to shear fracture of the rock. Ultrasonic velocity measurements and direct measurements of injected volume confirmed close connection of the water front position with the tip of induced AE cloud. Propagation of induced AE parallel to bedding plane is faster than perpendicular to bedding and related to anisotropy of permeability. Initial increase of pore pressure shows significant increase of tensile type of AE events, while approaching the failure, both shear and pore collapse types of AE events became dominant. At a critical pressure of injected fluid, a brittle fault nucleated from a cloud of induced AE events in all samples.

During the second series of tests, fracturing of 279 x 279 x 381 mm sandstone samples, induced by injection of different viscosity fluids was studied in poly-axial loading frames made by TerraTek, A Schlumberger Company. In this case, hydraulic fracturing was studied with fluid pressures rising above minimum principal stress. It was found that the viscosity of the injected fluid has a strong influence on the initiation of hydraulic fracturing, fracture propagation and fracture geometry. Injection of high viscosity fluid results in slower fracture propagation and wider fractures that initiated before wellbore pressure reached maximum value, or before breakdown. Low viscosity fluid injection results in significantly faster fracture propagation and narrow fractures that initiated simultaneously with wellbore pressure breakdown. The rock microstructure investigated by analysis of SEM images after the test, demonstrates the development of a leak-off zone near the wellbore and a dry fracture at a farther distance from the wellbore. We also investigated the effect of preexisting interfaces on hydraulic fracture propagation and found that acoustic emission indicates the intersection of hydraulic fractures with interfaces; in the case of a low viscosity fluid, we monitored the process of the fluid spreading along the interface, and in the case of the high viscosity fluids -- the intersection of interfaces. In all our tests, performed in GFZ and in TerraTek, microstructural analysis of fractured samples shows excellent agreement between location of AE hypocenters and macroscopic fractures. AE is very powerful tool for monitoring the dynamic of fracturing induced by fluid injection. Results of our research give us a reference for interpretation of microseismic monitoring data recorded in the field.

Laboratory simulations of fluid-induced seismicity in shallow volcanic settings

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Seismicity and ground deformation are the short-term precursory phenomena most frequently detected before a volcanic eruption. The final approach to eruption is commonly preceded by accelerating occurrence rates of both high-frequency volcano-tectonic (VT) earthquakes and low-frequency (LF) events. These characteristic seismic signals are unique to volcanoes and associated with fluid movement. Whilst great progress has been made in understanding short term VT signals, the precise details of the mechanisms involved in generating LF earthquakes, as well as any associated VT-LF transitions between them, remain poorly understood.

This research presents new rock deformation experiments designed to simulate shallow volcano-tectonic pressure/temperature conditions, and new data linking pore fluid flow and fluid-driven seismic swarms. To achieve this, a triaxial apparatus is used to impose pressures equivalent up to 2km depth on a sample of rock (4cm diameter and 10cm length), whilst monitoring the development of a fracture/damage zone during an imposed axial stress via an array of acoustic emission (AE) sensors of different dominant frequency. This is generally accepted as the laboratory analogue to seismic activity. A particular emphasis is placed on the conditions of pressure and temperature required to stimulate LF activity and to better understand the role of pore fluid in terms of rock-fluid coupling. To stimulate rapid pore fluid movement through the newly generated shear fracture, we impose a rapid pore pressure release or “venting” via a small pre-drilled axial conduit (3mm diameter). For this, an electrically operated valve is used, coupled with a high speed rate data logger to record the pore pressure during its release, and time matched to the AE datastream. Experiments were carried out at a range of different pressure – temperature conditions centered around the boiling point of the pore fluid used (under those P/T conditions).

Experiments are initially conducted to generate a through-going shear fracture, with pore fluid connectivity to this fracture achieved via the pre-drilled axial conduit. The shear failure is imaged via AE location with ~mm scale accuracy. After the failure, the sample was brought to hydrostatic condition to prevent further movement along the shear zone during the withdrawal of the fluid. The second stage of the experiments, venting pore fluid pressure in order to stimulate rapid fluid movements, is accompanied by a swarm of LF activity akin to Long Period (LP) activity on active volcanoes. We find that a pronounced step change in the dominant frequency of LF events is recorded as pore fluid pressure decrease though, and beyond, the water boiling point and the transition between LF and VLF occurred at the pressure at which the superheated water turn to vapour. In addition, we observe a significant dependence of the recorded LF upon the fluid flow rate. Finally, we present new data using low frequency (200 kHz) AE sensors, in conjunction with our standard 1 MHz-central-frequency sensors, which permit us to better record LF and VLF events with lower attenuation, and hence a derived an improved characterization of these LF seismic signals. Data are used to forecast the final time of failure via the fracture forecast methods of Kilburn (2004), showing a good correlation between measured sample failure time and the forecast time based on AE event rate. Our data showed little change in forecast accuracy when using LF data compared to regular HF data, illustrating the importance of newly fracturing surfaces in the application of such models.

In addition to the primary research focus on active volcanic areas (which exhibit a complex interplay between heat flux, active pore fluids, over-pressurised fluids/gasses, and under complex stress regimes), this research has applications to other areas of applied geoscience such as geothermal reservoirs and hydraulic fracturing, both systems featuring the movement and extraction of fluids, and their implication in seismic wave generation. Future research will apply the above methods to such systems by simulating tensile fracture via over-pressurised conduits, monitoring the seismic locations in 3D as a function of stress, time, and fluid pressure/phase.

Modeling slip precursors at frictional interfaces

J.F. Molinari, D. Kammer, M. Radiguet, EPFL

Local slip instabilities, which involve rupture initiation and propagation along interfaces, are of fundamental importance to engineering and geosciences. The mechanics behind these local slip events is however highly complex and not well understood. Recent experimental observations [1] reveal that the propagation speed of the slip front varies along its path and is coupled to the static local shear to normal stress ratio. In order to reproduce these laboratory-earthquakes experiments, we simulate with the finite-element method the propagation of slip fronts at frictional interfaces between viscoelastic solids. The adopted friction law is based on the experimental Prakash-Clifton law [2] to smoothen the variation of the interface shear strength due to an instantaneous variation in the normal stress, and to avoid the ill-posedness of Coulomb friction law [3,4].
Numerical results reveal that the slip front speed varies with a changing static stress state along the interface, which is coherent with experimental observation [1]. However, a static stress criterion does not seem to be sufficient to fully characterize the propagation speed of the interface rupture. Instead, we show that a dynamic energetic criterion, which relates the slip front speed with the relative rise of the energy density at the slip tip, captures all acquired data [5]. We also discuss the transition from sticking to sliding at the frictional interface, which is marked by the occurrence of local slip events, called slip precursors. These initiate at shear levels much below the global static friction coefficient threshold. These precursors stop before propagating over the entire interface, and their length increases with increasing shear force, which can be fully predicted by linear elastic fracture mechanics. We also show that the propagation of a given slip event is significantly influenced by the slip history on the interface [6]. Interestingly, the heterogeneous state of stress at the interface created by each precursor event cumulate, leading to highly non-uniform interface stresses by the time the rupture propagates through the complete interface (macroscopic sliding).

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Monitoring of Microseismicity in Deep Gold Mines in South Africa

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Active, deep mines provide an excellent opportunity for observing earthquake sources, because the spatial and temporal scales involved are intermediate between those of natural earthquakes and typical laboratory experiments, the earthquakes occur close to observation sites, and they occur on geological structures rather than on the artificial faults used in the laboratory. In deep gold mines in the Republic of South Africa (RSA), relatively large events (up to ~M3) occur near the advancing mining front, where stress changes for a few years may exceed tens of MPa. Therefore, based on geological information and the mining plan, we developed very sensitive seismic networks at a depth of ~3.3 km in Mponeng gold mine and of ~1 km in Cooke4 gold mine in RSA to precisely investigate spatial and temporal variations in microseismicity associated with stress perturbation due to mining.

In case of Mponeng mine, we deployed eight high-frequency AE sensors, one triaxial accelerometer, and two strainmeters along an access tunnel traversing a 30-m-thick gabbroic dike in quartzite host rock in June 2007. The smallest magnitude of micro-earthquake (AE events) determined by this network was Mw −4.4. The tabular reef in the mine was in the host rock. The dike was left as a pillar supporting a substantial load. Our observation site was 90 m below the reef. An earthquake of Mw2.2 (mainshock) occurred ~30 m above our observation site on 27 December 2007. For 150 hours following the mainshock, more than 20,000 AE events were located by manually picking P- and S-wave arrivals. More than 10,000 events (aftershocks) among them showed a tight concentration on a plane (aftershock plane) mostly confined in the dike with a strike sub-parallel to the dike and 68° in dip. Strain monitoring revealed that nearby mining increased the subvertical compression more in the dike than in the host rock. The hypocenter location and the CMT solution of the mainshock indicated that it was the normal faulting on the aftershock plane. Therefore, the aftershock plane is the rupture plane of the mainshock. Detailed investigation of the aftershock distribution clearly depicted structural complexity such as branching and bending of the rupture plane of the mainshock. Rock samples in the mainshock source region were recovered by drilling. Evidence of ancient hydrothermal alteration on the rupture plane of the mainshock suggests that the mainshock occurred on a preexisting weakness. Foreshock activity was also significant. The foreshocks distributed over a half extent of the aftershock plane, but most of them concentrated in three clusters (F1-F3), which we interpret as representing nucleation at multiple sites. Activity averaged over the entire foreshock area was constant. However, the clusters F1 and F3 faded out with stop of mining in holidays from 6 days before the mainshock, while F2 activity was kept accelerated. The foreshock sources during the final 41 hours migrated from F2 to F1, with F1 being in the neighborhood of the mainshock hypocenter, suggesting the coalescence of the two nuclei. The mainshock occurred 0.4–2.3 days earlier than expected based on an extrapolation of accelerated foreshock activity at F2. Nucleation of the mainshock may have been advanced to the criticality for dynamic instability in a stepwise manner by the coalescence of nuclei.

The observation network in Cooke4 mine consists of six triaxial accelerometers and 24 AE sensors in a volume of ~95 m (NS)×50 m (EW)×30 m (depth). Advanced mapping techniques were applied to 291,230 AE events down to M<–4 occurred over a course of 50 days (July-September 2011) close to the active front of tabular mining. We first applied joint hypocenter determination (JHD) to improve absolute locations, and then the double-difference relative location algorithm to the JHD output. Conventional seismic monitoring has suggested that seismicity ahead of stope front occurs in the seemingly continuous cloud of ~ 20 m width along the stope front. However, our observation revealed that they occur selectively in several discrete, tabular clusters a few meters thick and 10–30 m in dip extent. The tabular clusters are separated by quiet zones a few meters in width. The clusters have a strike parallel to the face and a steep dip of ~65°, resembling commonly observed large shear fractures along the plane of maximum shear. In general, the activity of different clusters changed with different timings that were consistent with the face advancement, but each cluster stayed in the same position and the gaps between them remained impressively quiet. These demonstrate the formation of large structures of localized damage in the highly stressed rock mass ahead of the stope front.

Physics-based models of stress shadows for rates of induced seismicity

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Micro-seismicity is recognized as a valuable tool for completion, optimization, characterization and modelling of reservoirs or storage facilities. However, although the probabilistic description of seismicity is established in seismology since decades, a probabilistic approach is still not common practice for induced seismicity and reservoir studies in industry. A possible reason may be that seismicity models in seismology are often based on steady state or quasi static loading rate conditions, a situation rarely valid for engineering activities. Therefore, seismicity models considering the stress and pressure loading conditions of engineering activities need to be further developed and validated.

The presentation combines rate and state seismicity models with physics-based models of hydrofracs and pore pressure diffusion. The rate and state seismicity model is able to consider different types of stress and pressure loadings. It can be adapted to different cases of induced and natural seismicity (e.g. Passarelli et al., 2012), or to the study of aftershocks (e.g. Cesca et al., 2013). We discuss specific examples from mining induced microcracks (Fig. 1), hydro-fracturing and pumping related seismicity.

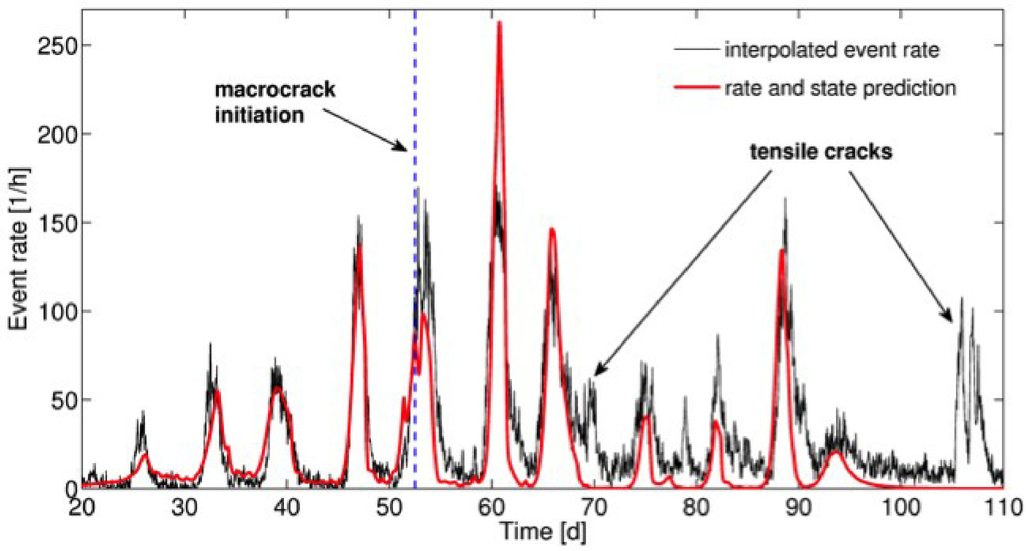

Fig. 1: Example of observed (black line) and predicted micro-crack rate from the rate and state model (red line) for a sub-volume on a salt mine, which was loaded in cycles by thermal induced stresses. The formation of a macro crack and the occurrence of tensile cracks (not considered in the model) is indicated. See Becker at al. (2014) for explanations.

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Partitioning of seismic and aseismic strain

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Fluid injection into, or withdrawal from, the subsurface perturbs the local natural stress field, and can increase seismicity significantly above background tectonic levels. In seeking to quantify, forecast and manage the risk of induced earthquakes, it is necessary to develop predictive models for its evolution. Here we consider the evolution of the scaling of the partition factor φ – the relative proportion of seismic to total strain, or equivalently the ratio of seismic moment ($\sum M$) to total moment. This factor is needed to incorporate surface measurements of strain or volumes of injected fluid into estimates of seismic potential.

We develop insight into the processes governing strain partition from laboratory experiments and the results of a discrete element model for deformation of porous reservoir rock, and derive mean-field equations to describe its evolution in the approach to system-sized failure. We then test these hypotheses on published field-scale data for seismicity associated with fluid injection of known volume (ΔV), using a Bayesian Information Criterion as a model discriminant that takes account of the different number of model parameters as well as the full uncertainty structure of the data.

We show that a power-law relation $\varphi \sim \Delta V^n$ is positively preferred to φ being constant, or increasing exponentially with injected volume, which both score roughly equally. Nevertheless the exponent n is around 1/3 or so and the best-fit confidence limits cover some 5 orders of magnitude, indicating respectively a relatively weak control on φ by injected volume, and a large spatial variability in the response of the Earth to the same stress perturbation. Subject to these caveats, the results can be used as a constraint in estimating the future rate of seismicity and/or the maximum magnitude from planned injection scenarios.

Abstracts Talks

Session 5

Risk Governance, Societal Acceptance, and License to Operate

Risk governance for induced seismicity: a view from the social sciences

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Risk governance became a term en vogue in the last years and has partly replaced in many documents terms like "risk management". This makes one wonder if "risk governance" is not just old wine new bottles. Taking a social scientific perspective, I will first visit some of the core characteristics that the term of "governance" carries with it (cf. Rhodes, 1997: e.g. multiple actors, networks and partnerships; new forms of authority and control; multi-level and issues of scale). Secondly, I will take a look at some of the most prominent social scientific contributions to "risk governance", more specifically the contributions by Ortwin Renn for the International Risk Governance Council (Renn 2005, 2008) and of Gordon Walker and colleagues within the 7th framework program project CapHaz-Net (Walker et al. 2010, 2014). Based on this review I will then thirdly consider the eminent works by Ernie Maier and colleagues (2012) on the Induced Seismicity Protocol in the US and propose some amendments and refinements at least for a Swiss or Central European context. Concluding, I will argue for an integrative approach involving natural, engineering and social scientists in developing a risk governance framework for induced seismicity.

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Latest Thoughts on the Elements of Induced Seismicity Protocols due to Fluid Injection

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As more attention from both the public and private sector is being focused on induced seismicity there has been an evolution of what are the critical elements of a protocol and how it should be applied. It is often the case that the agency(ies) in charge of regulation does not have detailed expertise or experience to properly or easily regulate injection practices. This often leads to uncertainty and/or delays in many energy projects on both the regulatory as well as the industry side. It is clear that there is no universally accepted set of best practices that satisfies the public, the private sector, regulators or policy makers. Presented will be suggested fundamental elements of best practices based upon existing and developing best practices, and experiences to date in the energy industry. Examples of best practices, pros and cons to various approaches and examples from field application will be given.

Seismogenic Index, Bounds of Magnitude Probability and Triggered versus Induced Earthquakes

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Induced seismic hazard is a topic of significance in the shale-oil and gas industry. Its understanding is of a considerable importance for mining of deep geothermic energy. It is of significance for CO2 underground storage and possibly also for other types of geo-technological activities. Identifying parameters that control magnitudes and their statistics is a key point for evaluating the seismic hazard of fluid injections.

Similarly to the tectonic seismicity, statistics of the induced seismicity can be rather well described by the Gutenberg-Richter frequency-magnitude distribution. We start with a model of point-like independent seismic events. This model describes well the statistics of numerous small-magnitude earthquakes. The model allows to formulate a simple description of the seismicity rate and to introduce parameters quantifying the seismo-tectonic state of a fluid-injection site in the frame of the Gutenberg-Richter distribution. One of such useful parameters is the seismogenic index. It helps to predict the probability of given-magnitude events.

However, the model of point-like events tends to overestimate the probability of significant magnitudes. Fluid-induced seismicity results from an activation of finite rock volumes. The finiteness of perturbed volumes influences frequency-magnitude statistics. We observe that induced large-magnitude events at geothermal and hydrocarbon reservoirs are frequently underrepresented in comparison with the Gutenberg-Richter law. This is an indication that the events are more probable on rupture surfaces contained within the stimulated volume.

We theoretically and numerically analyze this effect. We consider different possible scenarios of event triggering: rupture surfaces located completely within or intersecting only the stimulated volume, and derive lower and upper bounds of the probability to induce a given-magnitude event. The bounds depend strongly on the minimum principal size of the stimulated volume. We compare the bounds with data on seismicity induced by fluid injections in boreholes. Fitting the bounds to the frequency-magnitude distribution provides estimates of a largest expected induced magnitude and a characteristic stress drop, in addition to improved estimates of the Gutenberg-Richter a and b parameters.

The observed frequency-magnitude curves seem to follow mainly the lower bound. However, in some case studies there are individual large-magnitude events clearly deviating from this statistics. We propose that such events can be interpreted as triggered ones, in contrast to the absolute majority of the induced events following the lower bound.As more attention from both the public and private sector is being focused on induced seismicity there has been an evolution of what are the critical elements of a protocol and how it should be applied. It is often the case that the agency(ies) in charge of regulation does not have detailed expertise or experience to properly or easily regulate injection practices. This often leads to uncertainty and/or delays in many energy projects on both the regulatory as well as the industry side. It is clear that there is no universally accepted set of best practices that satisfies the public, the private sector, regulators or policy makers. Presented will be suggested fundamental elements of best practices based upon existing and developing best practices, and experiences to date in the energy industry. Examples of best practices, pros and cons to various approaches and examples from field application will be given.

Hybrid Modeling of Induced Seismicity: Towards Adaptive Traffic Lights

Stefan Wiemer, Dimitrios Karvounis, Jeremy Zechar, Eszter Király,
Toni Kraft, Antonio Pio Rinaldi, Lukas Heiniger and Arnaud Mignan

Swiss Seismological Service, ETH, Zurich

The majority of observed seismicity in Canada is related to tectonic processes along the western and northern margins of the North American continent. Intraplate earthquakes are also common in eastern Canada, whereas the continental interior is relatively quiet. As the high-pressure fluid injection technique was introduced in the 1970's and 80's to enhance the recovery of oil and gas in British Columbia (BC) and Alberta (AB), there have been reports of felt earthquakes, with magnitude as large as 4.3, in the vicinity of oil and gas drill sites. Since late 2006 when the extraction of shale gas started in northeast BC, Natural Resources Canada (NRCan) began to observe a clear change of pattern in background seismicity that appeared to be associated with the practice of hydraulic fracturing (HF). To determine the possible effect of shale gas development on the regional earthquake pattern and to understand the significance of seismic risk associated with induced seismicity, NRCan initiated the Induced Seismicity Research (ISR) in 2012. By providing observation-based science, the primary goal of NRCan's ISR is to enhance the regulatory performance of provincial authorities to reach a balance between public safety and economic benefit. With contributions from provincial partners, academia and industry, the first task of ISR focused on improving earthquake monitoring capability for major shale gas basins across Canada where the development has started or was imminent. New state-of-the-art seismic arrays were set up to compliment the routine operations of the Canadian National Seismograph Network (CNSN) in the Horn River and Montney basins (BC and AB), the Moncton sub-basin near Elgin (New Brunswick), the St. Lawrence Lowlands (southern Quebec), and the Norman Wells region (Northwest Territories). In BC and AB, historical seismograms from existing CNSN stations were re-examined to better calibrate the patterns of regional background seismicity for both pre- and post-HF eras. A detailed database of operation parameters, including both HF and wastewater reinjection, was compiled from reports collected by the BC Oil and Gas Commission. Our results confirm that the increased level of background seismicity in the Horn River Basin was related to the expansion of local HF operation. Induced seismicity in the Montney Basin could be associated with either HF or wastewater reinjection. Preliminary analysis of the Norman Wells dense array data indicates that the new array has improved the detection of local earthquakes by a factor of 10 within a radius of 400 km. In east Canada, HF was performed for exploration purposes at a very low scale. No clear cases of induced seismicity were found. For NB and NT, research is being done to better define the base level of seismicity prior to an eventual production of shale gas. Collectively, these new observations provide more insight to the understanding of seismogenic processes associated with induced seismicity in a variety of different tectonic and geological settings.

Using hazard information for establishing a rationale decision-making

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Effective strategies for reducing the potential losses for society (the risk) must encompass different kinds of expertise. There is a scientific domain in which the occurrence of the threatening event and its effects on the environment are rigorously explored and assessed. There is a decision-making domain in which each interested stakeholder translates the scientific information into rationale (and defensible) mitigation actions. Finally, there is a communication domain in which all partners involved into the risk reduction process establish an effective and comprehensive messaging among them and eventually towards the society and any interested stakeholder. Notwithstanding the involvement of different expertise is key to successful risk mitigation process, very often the specific role and responsibilities of each partner are unclear.

In my experience, which is primarily related to earthquake and volcanic hazards, scientists are often asked not only to render scientific assessments, but also to advise how to reduce the risk. The popular term 'scientific advise' often mingles scientific and decision making domains, blurring any distinction of competences. In some circumstances, scientists are called to act as decision-makers in more subtle ways; for instance, some governmental scientific institutions have the duty to select the specific hazard scenario to be used in risk-mitigation planning, and/or to declare warnings of impending natural events. However, the selection of the scenario for reducing the risk and the decision of when issuing (or not) a warning require competences far beyond the scientific expertise, since they are intimately related to the definition of acceptable risk.

In this talk, I discuss a possible conceptual framework rooted on few basic principles that makes clear the roles of each partner and facilitates the integration of different expertise for establishing a rationale decision making. Such a framework may i) allow each partner to protect the integrity of their specific assessment; ii) clarify the competences required at each step of the risk reduction process; iii) facilitate the establishment of transparent and clear decision making protocols. This framework is applied to the specific case of operational earthquake forecast in Italy that has several similarities to the threat posed by induced seismicity, because it is focused on tracking how the seismic hazard (and risk) evolves with time even in short- time intervals. In particular, it is explored how in this context scientific information affected by large uncertainties can be integrated in a rationale strategy to reduce the seismic risk.

Abstracts Talks

Session 6

Monitoring and Analysis of Induced Seismicity

The Uses of Dynamic Triggering and Dynamic Permeability Enhancement For The Study of Induced Seismicity

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(1) UC Santa Cruz; (2) Lamont-Doherty Earth Observatory

Dynamic triggering of earthquakes by seismic waves is a robustly observed phenomenon with well-documented examples from over 30 major earthquakes. We now may be in a position to use dynamic triggering to probe the reaction of faults to the known stresses from seismic waves. For instance, dynamically triggered earthquake rates shows that in some regions faults are uniformly distributed over their loading cycles with equal numbers at all possible stresses from failure. Regions under tectonic extension, at the interface between locked and creeping faults, or subject to anthropogenic forcing are most prone to triggered failure. There is potential to utilize dynamic triggering as an indicator of the seismic consequences of human activity.

Dynamic permeability enhancement is a closely related phenomenon that also has implications for induced seismicity. Continuous measurement of permeability via tidal reponses has shown that seismic waves from earthquakes can increase permeability by factors of 3-4 and the permeability increases can last for up to a year. Laboratory experiments suggest that a viable mechanism is fracture unclogging by the seismically forced fluid flow. In the laboratory experiments, flow rate during the forced oscillations is the best predictor of permeability enhancement. The feedback of the seismic wavefield of induced earthquakes on reservoir permeability has not yet been incorporated in reservoir models.

Interpretation of moment tensors of induced earthquakes: a review

Václav Vavryčuk, Institute of Geophysics, Prague

The moment tensors describe equivalent body forces acting at a seismic point source and are the basic quantity evaluated for natural as well as induced earthquakes on all scales. The most common type of the moment tensor is the double-couple (DC) source which represents the force equivalent of shear faulting on a planar fault. However, accurately determined moment tensors of induced earthquakes reveal that they frequently deviate from shear faulting and contain significant non-double-couple (non-DC) components. The non-DC components are reported, in particular, for cavity collapses in mines, in hydraulic fracturing and fluid injection experiments and in geothermal fields. The DC as well as non-DC components of the moment tensors provide essential information about details of source processes and tectonic stress conditions of the rock mass.

In this paper, I review the recent methods for interpreting the DC and non-DC components of the moment tensors and discuss their applications to induced seismicity. I show that the DC components of moment tensors evaluated for a set of earthquakes can be inverted for tectonic stress, fracture orientations and fracture instability (Vavryčuk, 2014). Analysing the DC components of induced earthquakes, it is possible to monitor spatial and temporal changes of stress and pore pressure, and to map systems of cracks or fractures in oil/gas reservoirs or geothermal fields. The non-DC components can be exploited for characterizing the mode of fracturing and for determining rock properties in the focal zone. Using the model of shear-tensile earthquakes (Vavryčuk, 2011), the non-DC components can be used for distinguishing whether the crack systems are opening or closing and the opening/closing angle between the slip and the fracture plane can be evaluated. Furthermore, the v_P/v_S ratio of rocks in an isotropic focal zone or the tensor of elastic parameters in an anisotropic focal zone can be determined (Vavryčuk et al., 2008).

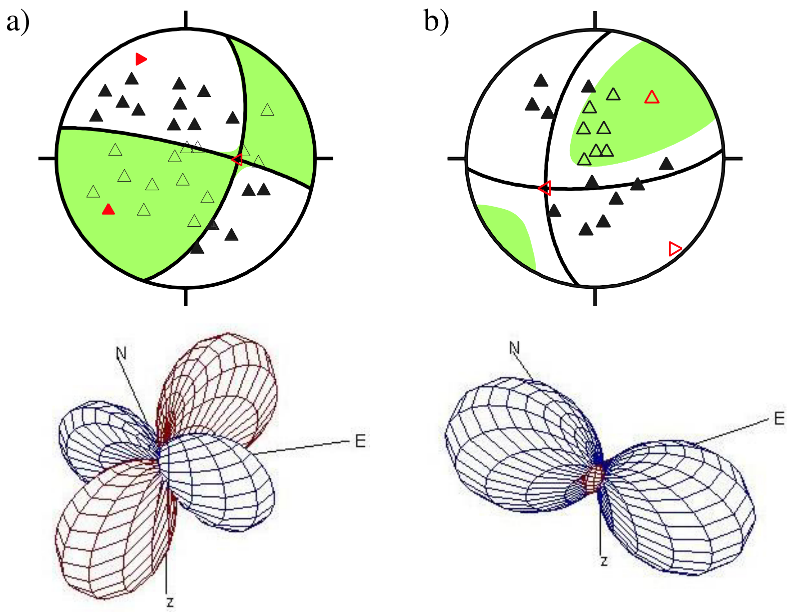

Figure 1. Examples of the DC (a) and non-DC (b) induced events that occurred during the 2000 injection experiment in the KTB, Germany (Vavryčuk et al., 2008). Upper row – beach balls with positions of stations, lower row – P-wave radiation patterns.

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Migration based detection and location of the microseismicity induced at Rittershoffen geothermal field (Alsace, France)

Emmanuel Gaucher, KIT, Alessia Maggi, EOST, Nicolas Cuenot, EEIG, Vincent Maurer, ES-G

Seismic monitoring of Enhanced Geothermal Systems (EGS) is now required since fluid circulation generally induces microseismicity, especially during reservoir stimulation where felt seismic events may occur and become a concern. Moreover, real-time processing of the seismic data becomes mandatory for setting up robust alarm systems. Hence, the development and application of reliable and automatic techniques for processing the data acquired by these local seismic networks are crucial.

In Rittershoffen, Alsace, France, an EGS plant is being developed by the ECOGI Company. Once operational, the power plant should deliver 25 MWth to a bio-refinery plant located 15 km away. To reach this objective, a geothermal doublet is being developed at 2.5 - 3 km depth, into the Triassic sandstone and the Paleozoic granitic formations. After drilling the first well, hydraulic stimulation was carried out in June 2013 to enhance the connectivity between the well and the geothermal reservoir. This operation induced seismicity which was continuously recorded by a surface network composed of 17 seismic stations.

In the framework of this study, we replay the seismic record dataset through an automatic kurtosis-based migration detection and location technique, called Waveloc. The software, developed by EOST (University of Strasbourg) and applied successfully on volcano seismicity, first transforms the raw data into kurtosis-based waveforms which enhances the first arrivals of seismic events observed over the network. By considering only P-waves, the migration step consists in applying source-scanning, move-out and stack of the kurtosis waveforms over the target volume and over time. The resulting movie highlights the location and occurrence time of the seismic events associated to the maximum of the stacks in space and time. Such a procedure, which intrinsically integrates the detection, picking and location of the seismicity, automatically generates a catalogue of seismicity. However, calibration of the parameters is necessary to adapt the automatic processing to the site. In our context, we used a restricted dataset of manually processed data for this calibration.

The results of this processing approach will be analyzed and compared to existing catalogues of the seismicity induced during the stimulation. The aim will be to measure the detection and location capabilities of the Waveloc method using the existing seismological network; especially the trade-off between increased detection capability and decrease of location certainty. This can partly be done through forward modelling of the resolution of the technique within our context (network lay-out, velocity model). Additionally, we should be able to quantify discrepancies in the locations between Waveloc automatic results and other results, and to verify the consistency of the automatic method.

If we succeed in qualifying the Waveloc method for use at Rittershoffen, it will be possible to replay the whole dataset acquired on this site, which covers about 1.5 years, with the aim of enlarging the seismic catalogue by applying consistent processing over the period. Furthermore, we will envisage the possibility of applying this technique, in real-time, to continuous seismic records acquired on existing or future sites.

Rupture Characteristics of Hydraulic Fracture Induced Seismicity with M>0

Ted Urbancic, Gisela Viegas, and Adam Baig, ESG, Kingston, Canada

It is becoming widely evident that hydraulic fracture stimulations in shale reservoirs can result in the generation of events with magnitudes M>0. Whether these events are of concern to the public as potential geo-hazards possibly affecting groundwater conditions and surface infrastructure, or to engineers for optimizing productivity and engineering design, they are of continuing debate. Typically, in hydraulic fracture stimulations, recording bandwidth limitations has resulted in a bias towards the consideration of events with M<0. This in turn has limited the observable fracture sizes to those typically smaller than lithologic unit thicknesses. By extending the recording bandwidth to lower frequencies, the dimensions of the observable fractures are also extended to include larger fractures/faults activated during the stimulation.

In this paper, we discuss the results of extending the recording frequency band, from 0.1Hz to 4kHz through a combination of near-surface Force Balance Accelerometers (FBA), 1Hz, 2Hz, and 4.5Hz triaxial geophones, and FBA's, 4.5Hz and 15Hz geophones at varying depth approaching the reservoir. This allowed for a unique opportunity to characterize the rupture processes and source scaling behavior of the M>0 events. It is our intent to utilize these data to address fundamental questions associated with these stimulations such as the role of fluids and proppants versus stress in initiation of failure, fracture/fault growth, and the modes of failure associated with M>0 events occurring during the injection process.

Here, we examined the interrelationships between static and dynamic source parameters, such as dynamic and static stress drop, radiated energy, seismic efficiency, and the failure components as derived from moment tensor inversion, fault plane orientation and rupture velocity. Specifically, we have been able to examine the role resisting frictional stress and the influence of stress perturbations under the local stress field, the partition of energy into the different physical processes during failure and characteristic rupture behaviors.

Initial analysis of the results of this study revealed interesting correlations between rupture behavior and other source parameters. On average, the seismic events have low radiated energy, low dynamic stress and low seismic efficiency, consistent with obtained slow rupture velocities. Events fail in overshoot mode (slip weakening failure model), with fluids lubricating faults and decreasing frictional resistance. Events occurring in deeper formations tended to have faster rupture velocities and were more efficient in radiating energy. Variations in rupture velocity tended to correlate with variation in depth, fault azimuth and elapsed time, reflecting a dominance of the local stress field over other factors. These observations suggest that these processes may be further be used to classify dynamic rupture processes in fracture models and improve fracture treatment designs. Further investigations of the rupture characteristics over different scales of observation are currently being carried out.

Lessons learned from the 2013 ML3.5 induced earthquake sequence at the St. Gallen geothermal site

Toni Kraft, Stefan Wiemer, Tobias Diehl, Benjamin Edwards, Anne Obermann,
Eszter Kiraly, Thessa Torman, Eduard Kissling, Nicholas Deichmann

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The goal of the Sankt Gallen geothermal project was to exploit postulated hydrothermal aquifers in Mesozoic sediments of the Swiss Molasse Basin at about 4.5 kilometers depth. In a large-scale 3D seismic survey, the project operators identified a nearly 30 kilometer long NNE-SSW striking segmented fault zone (SGFZ) cutting the Mesozoic sediments, identified as a zone of potentially higher permeability and hence a target for the water extraction Based on the lack of recent seismic activity, they concluded that the fault zone was not likely to be seismically active. In July 2013, a testing and stimulation program began in the Malm sediments and a low-level of microseismicity, strongly correlated with this activity, was observed on a dedicated seismic network operated by the Swiss Seismological Service. The seismicity in this period did not exceed magnitude ML0.4 and was judged to be well within the expected range. Around noon on July 19 ,a gas-kick occurred, releasing methane from an unknown source into the borehole, and operators decided to start well control measures by pumping a mix of water and drilling mud down the well. Even though well head pressure decreased steadily, seismicity started to suddenly increase at 7 pm on July 19. The operator designed traffic light system was triggered in the early phase of this seismicity increase by an ML1.1 earthquake. Yet, operators decided to continue the well control operation instead of stopping the pumps, in order to ensure drill site safety. During this period the seismicity intensified and culminated in a ML3.5 event in the early morning of July 20 that was widely felt in the area.

In the following days, the operators were able to stabilize the well and filled-in the open hole section. Seismicity rapidly decreased to a low rate but never reached the background level in the following 30 days. The largest event in the filled-in period had a magnitude of ML1.2. After an intensive evaluation phase the operator decided to perform a production test to assess the achieved permeability increase in the reservoir. The open hole section was cleaned-out and as soon as small mud losses started to occur in mid September seismicity rates increased significantly again. The largest event in the clean-out phase reached a magnitude of ML1.7. With the start of the production test on October 14, seismicity was essentially turned off. Only eight further microearthquakes with magnitudes ML<=0.7 were detected on the activated fault segment until December 18. Even though the detection sensitivity of the seismic monitoring system has not decreased since this date (M_{min}~-1.7ML; M_c~-0.4ML) not a single earthquake has been detected since than. Unfortunately, the production test indicated productivities much below economic needs. In combination with the observed intense seismic response of the underground to injection the city of St. Gallen decided to terminate their geothermal project in October 2014. If the tapped methane resource is large enough to allow a continuation of the project in natural gas in the future has to be investigated.

The results of the analysis of the induced seismic sequence at St Gallen obtained by the Swiss Seismological Service indicate that:

- Seismicity high-lighted a 2km-long fault segment, partly identified by 3D seismic. Already the small-scale injection tests microseismically illuminated the fault patch the later ruptured in the ML3.5 earthquake.
- St. Gallen sequence shows the highest seismic productivity per injected cubic meter when compared to past injection induced sequences, and challenges the McGarr relation between injected volume and maximum observed magnitude.
- A microseismic response of the underground to the gas kick was not detected. Yet, ambient seismic noise analysis indicates an aseismic response occurred at the same time.
- Peak ground motions observed for the ML3.5 event in St. Gallen are very similar to the ones observed ML3.4 at Basel in 2006. Yet, macroseismic intensities in St. Gallen only reach IV(EMS) versus V(EMS) in Basel.
- The seismic traffic light system was overruled by standard drilling safety procedures to fight the gas kick. In future projects seismologists and drilling engineers have to closely cooperate to identify discrepancies in seismic or drilling safety procedures.

Seismic Monitoring and Analysis of a Deep Geothermal Project in St. Gallen, Switzerland

Benjamin Edwards, Toni Kraft, Carlo Cauzzi, Philipp Kästli and Stefan Wiemer, Swiss Seismological Service, ETH Zürich.

Monitoring and understanding induced seismicity is critical in order to estimate and mitigate seismic risk related to numerous existing and emerging techniques for natural resource exploitation in the shallow-crust. State of the art approaches for guiding decision making, such as traffic light systems, heavily rely on the data, such as earthquake location and magnitude, which are provided to them. In this context we document the monitoring of a deep geothermal energy project in St. Gallen, Switzerland. We focus on the issues of earthquake magnitude, ground motion and macroseismic intensity which are important components of the seismic hazard associated to the project. We highlight the problems with attenuation corrections for magnitude estimation and site amplification that were observed when trying to apply practices used for regional seismicity monitoring to a small scale monitoring network. We developed a simple procedure, calibrated using larger events, which allowed the calculation of M_L on only stations of the local monitoring network, without bias. A simple relation between the amplitude at the central borehole station of the monitoring network and M_L was then found to provide robust estimates (±0.17 units) for events down to M_L -1. This relation could then be used to estimate the magnitude of even smaller events (M_L < -1) only recorded on the central borehole station. We analysed ground-motion and detailed macroseismic reports resulting from the St. Gallen M_L3.5 (M_w3.3-3.5) mainshock and compared it to a similar M_L3.4 event (M_w 3.2) that occurred in 2006 at another deep geothermal project in Basel, Switzerland. An empirical green's function approach was used to isolate the source spectra of the largest events in both cases (Figure 1). The ground motion and, to an extent, the associated macroseismic observations could be explained in terms of the different moment magnitudes at long periods and the different stress-drops (Basel: 3.5MPa vs St. Gallen: 2.1MPa) and corresponding M_L at short periods, respectively.

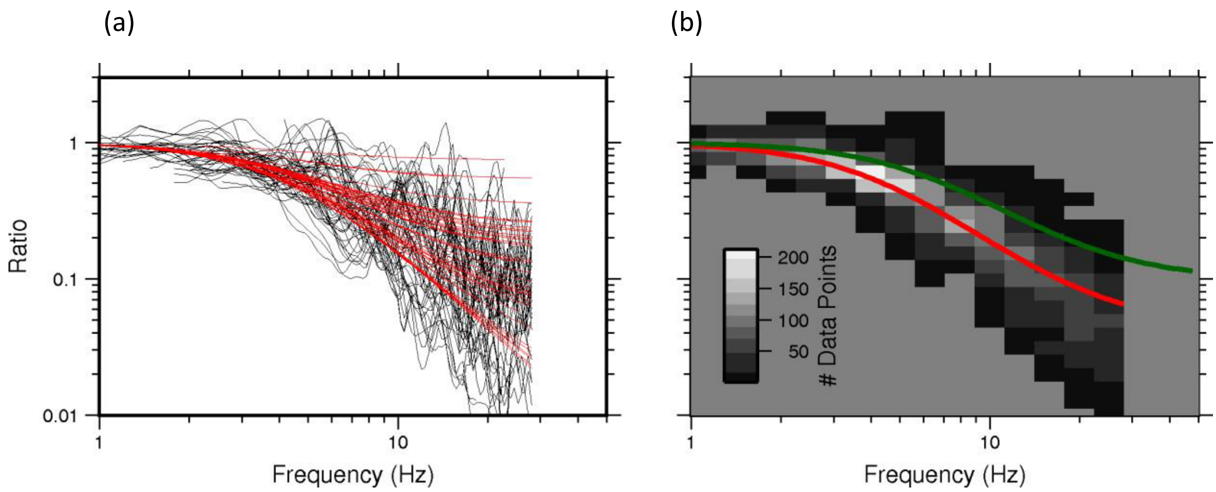

Figure 1: (a) EGF spectral ratios between the St Gallen mainshock and the small co-located events (black: observed; red: modelled). (b) All spectral ratios normalized to a common co-located event with $f_{c,2} = 20\ Hz$ (red: normalized model; Green: normalized Basel model).

Ground Motion Prediction for Induced Seismicity Using the Ambient Seismic Field

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(1) Stanford University; (2) Scripps Institution of Oceanography

Prediction of strong ground motion in earthquakes is an essential element of seismic hazard analysis. Engineering seismologists typically approach this through Ground Motion Prediction Equations (GMPEs) that are developed by fitting intensity observations from earthquakes to simple, parameterized equations. In the absence of data from earthquakes, such as might occur in areas of potential induced seismicity, the data-driven approach of developing ground motion prediction equations may be difficult. Ground motion prediction through simulation is gaining traction as an alternative approach; however, one must characterize the source as well as the linear and possibly nonlinear response of the Earth in order to do that. While such a model-driven approach is powerful, it requires a tremendous amount of knowledge of source behavior and of Earth structure, and requires high-performance computing. We have developed an alternative, hybrid, approach that uses the ambient seismic field to characterize the effect of three-dimensional Earth structure on seismic wave propagation. In this talk we demonstrate that once ambient-field Green's functions are corrected for depth and mechanism, the "virtual earthquakes" that result closely match the recorded waveforms of earthquakes. We show for cases in Japan and California, that we can resolve basin effects, and that we can parameterize basin response in a manner that is suitable for use in GMPEs. Although this is a promising approach, there is still work to do in understanding the source of the ambient-field excitation, and in understanding and modeling nonlinearity. Moreover, there are technical challenges related to the ambient-field Green's functions in: developing the 9-component Green's tensor with unbiased amplitudes, pushing the technique to higher frequencies, and discerning body waves in the data. Despite these caveats, we believe that the virtual earthquake approach is an important development because it is active, rather than passive, in that we can sample source and site locations of interest simply by deploying seismic instrumentation. For areas of low seismicity, in which induced earthquakes are a concern, the virtual earthquake approach has the potential to provide essential constraints on ground motion prediction for seismic hazard analysis.

Abstracts Talks

Session 7

Industry Projects and Future Initiatives

Future Multi-stage EGS projects in Switzerland

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In Switzerland the large geothermal potential for electrical power production can only be used if Enhanced Geothermal Systems (EGS) will be technically feasible because 90% of the deep underground consist of low permeable crystalline rocks. Based on the data of the Deep Heat Mining Project Basel a new multi-stage stimulation concept has been developed which reduces the risks of induced seismicity and promises a better return of energy. The mitigation plan for induced seismicity includes three major points. First, induced seismicity will be reduced by limiting the areas of the hydraulically stimulated fracture planes. This can only be achieved with a borehole completion allowing the hydraulic isolation of up to 30 individual borehole sections within the reservoir. Secondly, the site selection criteria lead to avoid densely populated areas, areas with high natural seismic activity and placing the geothermal reservoir at a safety distance of at least one kilometer from regional or major fault zones. Third, in addition to deterministic risk studies we have applied a probabilistic approach recently developed by the Swiss Seismological Service to show that the multistage stimulation of smaller fracture zones has a better risk profile than the massive stimulation concept of the Basel project.

Monitoring and Mitigating Induced Seismicity: Some Practical Considerations

Shawn C. Maxwell

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Over the past few years, reports of injection induced seismicity have increased and at the same time environmental concerns around safe industrial activities has also grown. Injection induced seismicity can occur from various activities including waste disposal and geothermal stimulations, but here there is also growing evidence of isolated cases of induced seismicity resulting from hydraulic fracture stimulation of oil and gas wells. Unconventional reservoir development has made hydraulic fracturing operations more wide spread and occasionally industrial activities have occurred in regions of natural seismicity, leading to questions of injections inducing seismicity and in some cases challenges establishing cause and effect with the operations. In some locations, unconventional reservoir production has also resulted in extraction of water leading to injection for waste water disposal and associated questions around induced seismicity.

Typical of industrial instances of induced seismicity, various versions of oil and gas operational protocols have been developed for managing seismic hazard. These protocols can be broken down to three basic steps: assessment, monitoring and mitigation. Monitoring system are typically centered on “traffic light systems” where operations are modified if magnitudes reach a warning threshold and ultimately stopped if a red light threshold is exceeded. If increased magnitudes are encountered, protocols dictate somehow modifying the operation to mitigate the seismic hazard. But how? Shut-in the well and wait for some period of time? Lower the injection rate or volume? Flow the well back? Skip hydraulic fracture stages to potentially move further from a fault? Lower the injection rate or volume? Mitigation based on the traffic light system also raise questions of how to reverse the traffic lights if problems are encountered.

The presentation will discuss some of the practical aspects of implementing operational protocols, including both monitoring considerations and engineering decisions. Case studies will be utilized in order to illustrate some of the specific challenges.

Seismicity induced by Shale Gas Hydraulic Stimulation:
Preese Hall, Blackpool, United Kingdom

Peter Styles, (University of Keele, UK),
Huw Clarke, Peter Turner (Cuadrilla Resources UK),
Leo Eisner, (Seismik s.r.o, Czech Republic)

On the 1st of April 2011 at 02:34 am UTC, the British Geological Survey (BGS) reported a 2.3 Ml earthquake, which was widely felt in the Blackpool area of the UK while Cuadrilla Resources were conducting the first vertical, multiple stage hydraulic fracture operation for shale gas exploration in the Carboniferous gas-bearing Bowland Shales at Preese Hall-1 in Lancashire, UK, This was the first of 2 felt seismic events which were later shown to be associated with the hydraulic fracturing operations (Eisner et al 2014)

This felt seismicity induced by hydraulic fracturing attracted significant public concern in the UK and worldwide interest and resulted in a government enquiry and 2 years + suspension of operations. First observed at Rocky Mountain Arsenal, long term, high volume (>10000m^3), low pressure (<1000psi), injections for waste-water disposal have induced. or more likely triggered. natural seismicity (Healy et al. 1968). The use of hydraulic fracturing to create enhanced permeability uses much more modest volumes of fluid and was considered unlikely to generate felt seismicity. However, since 2011 three further cases have been reported where felt seismicity was most likely induced by relatively modest hydraulic fracturing operations: Oklahoma, USA (Holland, 2013), British Colombia, Canada (BC Oil and Gas Commission, 2011) and Ohio, USA (Frieberg et al, 2014).

The preliminary event location was 1.8 km from the Preese Hall-1 well at a depth of 3.6 km. While the first frac stage caused no activity the second stage of hydraulic fracturing with injection of 2245 m^3 of fluid and 117 tons of proppant which terminated at 16.00 hrs UTC on March 31st 2011, is believed to be the cause of this event. The event, while it was detected on seismometers as far away as Keele had a poorly constrained location and initially raised only slight concerns about the contemporaneous nature of the earthquake and the hydraulic fracturing operations.

A number of surface seismic stations were installed by Keele and BGS enabling better monitoring of possible aftershocks. As no significant seismicity was observed over the following weeks, hydraulic fracturing resumed on May 26th but on May 27th 2011, at 00:48 am UTC the BGS reported a 1.5 ML event approximately 1 km away from the Preese Hall well and at this point the operator, after discussion the Department of Energy and Climate Change (DECC) and Keele University, suspended operations and organized an international geomechanical study (de Pater et al 2012, Green et al 2012).

This study describes the relationship between the seismic events of April 1st and May 27th and the hydraulic fracturing operations showing that the first felt seismic event was preceded by a screen-out (proppant backing up into the wellbore) during fracturing, possibly caused by fluid loss into a permeable fault or induced fracture. Waveform cross-correlation detected a sequence of c 55 events some of which preceded the 2.3 ML event. The hypocenters lie some 300-400m east, and 330-360m below the injection point. No obvious evidence of any fault intersecting the wellbore trajectory was seen despite extensive logging with imaging tools. However, a strike-slip focal mechanism calculated using the best recorded seismic event, a later November 2011aftershock, gives a hypocentral depth of about 2930m which agrees with a reverse transpressional fault formed during Late Carboniferous (Variscan) basin inversion seen on subsequent 3D seismic imaging. These observations provide important information for modification of operational parameters to mitigate seismic hazard associated with shale gas development and a traffic light-based operational system will be used to monitor and control subsequent hydraulic fracturing operations for shale gas in the UK.

Probabilistic Seismic Hazard Assessment for Seismicity Induced by Gas Extraction in the North of the Netherlands

Dirk Kraaijpoel, Mauro Caccavale, Torild van Eck, Bernard Dost, KNMI, De Bilt, The Netherlands

Natural gas production in the North of the Netherlands induces earthquakes of moderate magnitudes (largest M=3.6, up to dec 5, 2014). The stronger events cause considerable nuisance and substantial damage, due to the shallow origin (~3 km) and soft soil conditions. The annual number of felt events has been rising steadily over the last decade or so, especially in the Groningen field, the largest (~900 sq. km) natural gas field in Europe. Figure 1 displays the annual number of events in the Groningen field above the magnitude of completeness (M>=1.5) of the regional network in place since 1995.

Due to the non-stationary situation classical probabilistic seismic hazard analysis (PSHA) has some extra challenges: (1) Estimation of the annual number of events. This can be based on empirical data and trends from the past assuming some statistical model (see Figure 1). (2) Estimation of the spatial distribution of events and possible variations in time. We use smooth kernel (Woo, 1996, BSSA) and zonated models, see Figure 2. (3) Estimation of the magnitude-frequency relation. The Groningen dataset has a nice Gutenberg-Richter distribution, but how do we assess M_{max}? Or can we use a stochastic distribution for M_{max}? (4) We need a ground motion prediction equation specific for the area. We adapt (Bommer, 2014, pers. comm.) a recent pan-European dataset (Akkar et al., 2014, BSSA) to a regional dataset.

Ideally, challenges (1)-(3) should be related directly to production parameters. However, these relations are complex and introduce a lot of extra uncertainties. Our approach here is largely based on empirics and estimation of sensitivities (including disaggregations). We investigate and compare a number of modeling choices. Figure 3 displays a hazard map for a single set of choices.

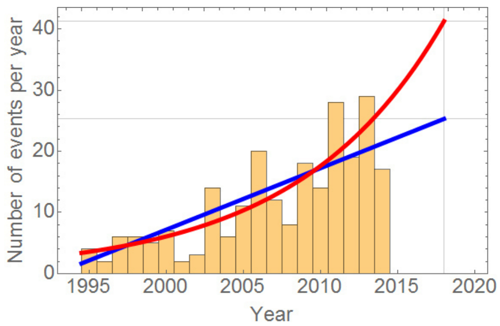
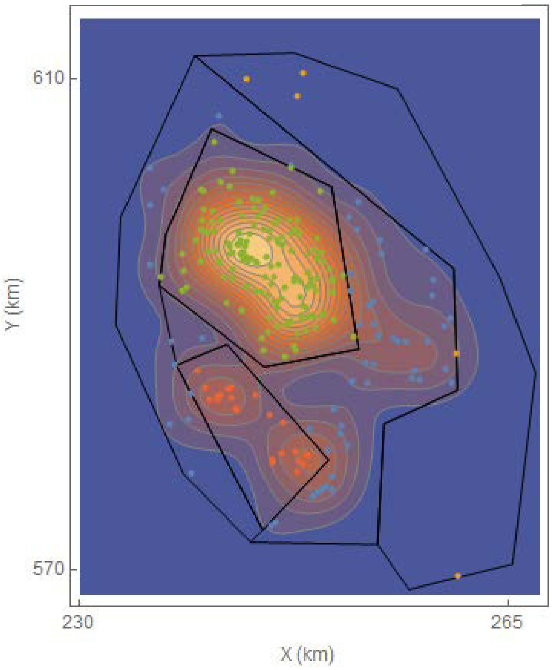
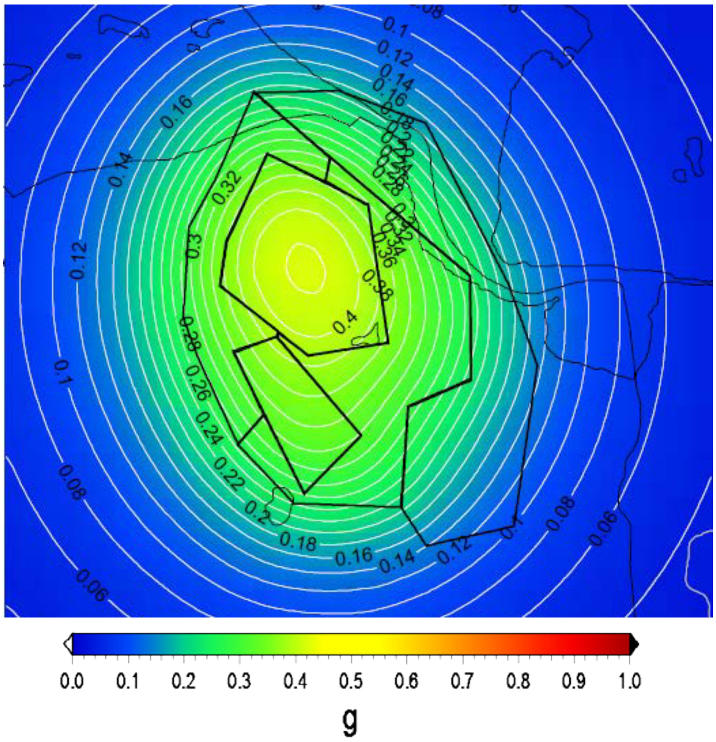


Figure 1 (left): Annual number of events (M>1.5) in the Groningen field, complete up to December 1, 2014. Includes sketch of extrapolation towards 2018 following linear (blue) and exponential (red) scenarios.
Figure 2 (bottom left): All historic events (M>=1.5) with source zone model and smooth empirical distribution (smoothing kernel 2km). Event colors depict zone.
Figure 3 (below): Hazard map for PGA for a 0.2% annual chance of exceedance. This example assumes 40 events per annum, distribution in zones of constant event density proportional to the historic catalogue, and uniform M_{max}=5, b-value=1.





Implementing data provision and services for solid Earth sciences: the EPOS integrated approach

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The European Plate Observing System (EPOS) aims at creating a pan-European infrastructure for solid Earth science to support a safe and sustainable society. In accordance with this scientific vision, the mission of EPOS is to integrate the diverse and advanced European Research Infrastructures for solid Earth Science relying on new e-science opportunities to monitor and unravel the dynamic and complex Earth System. To this goal, a long-term plan to facilitate integrated use of data and products as well as access to facilities from mainly distributed existing and new research infrastructures has been designed. EPOS will enable innovative multidisciplinary research for a better understanding of the Earth's physical processes that control earthquakes, volcanic eruptions, ground instability and tsunami as well as the processes driving tectonics and Earth surface dynamics. Through integration of data, models and facilities EPOS will allow the Earth Science community to make a step change in developing new concepts and tools for key answers to scientific and socio-economic questions concerning geo-hazards and geo-resources as well as Earth sciences applications to the environment and to human welfare.

The big challenge to be addressed by EPOS is enabling the use of research infrastructures and services across traditional disciplines and fostering the development of new ideas for these uses, leading to new insights regarding user requirements. A data-management process will promote the use of data in novel ways, not only providing access to a wealth of observational data, but also to the data products to offer intelligible integrated knowledge and solutions. Once the EPOS integrated services will be operational, this new infrastructure will further facilitate sharing the outcomes of research, not solely by linking data to publications by guaranteeing data traceability and re-use, but also in convincing scientists to share the products of their investigations (that is, generating new data products). Geoscientists are generating products through their research activities (such as maps, Earth models, earthquake source models, lava flow simulations…) and most of these new data products can be further integrated and made accessible through the new platform.

The EPOS integration plan will make significant contribution to geo-hazards yielding new data for hazard assessment, new data products for engaging different stakeholders, new services for training, education and communication to society. Numerous of the national research infrastructures engaged in EPOS have been deployed for the monitoring of areas prone to geo-hazards and the surveillance of the national territory including areas used for exploiting geo-resources. Technical developments responding to increasing needs for energy and minerals will be then associated with parallel developments of new methods for the assessment of environmental and societal impacts, and for the evaluation and mitigation of anthropogenic hazards resulting from technological activities. One of the EPOS aims is to integrate distributed research infrastructures to facilitate and stimulate research on anthropogenic hazards especially those associated with the exploration and exploitation of geo-resources. The innovative element is the uniqueness of the integrated research infrastructure which comprises two main deliverables: (1) Exceptional datasets, called "episodes", which comprehensively describe a geophysical process induced or triggered by human technological activity, posing hazards for infrastructure, people and the environment; (2) Problem-oriented, bespoke services uniquely designed for analysing correlations between technological activities, geophysical response and associated hazards. These objectives will be achieved through the science - industry synergy, ensuring bi-directional information exchange, including unique and previously unavailable data furnished by industrial partners and innovative solutions coming back to industry. The episodes and services to be integrated have been selected using strict criteria. The data and services are related to a wide spectrum of inducing technologies, with seismic/aseismic deformation and production history as a minimum dataset requirement. Impact of these research infrastructures for geo-resources will be also reflected in a more inter- and multidisciplinary approach to education, and an opportunity for students to obtain skills, competences and knowledge in the anthropogenic hazards field. Open access to various resources will provide students with learning tools; the cooperation and data/know-how exchange between industrial partners and research institutions will enable them with up-to-date information on the state-of-the art in the field.

The EPOS community is therefore already trained to guarantee all services to public (civil defence agencies, local and national authorities) and private (petroleum industry, mining industry, geothermal companies, aviation security) stakeholders. The integrated access to multidisciplinary data and services together with the dedicated access to tutorials, dissemination and training tools will enhance the capacity to provide novel services to users and will facilitate research innovation to support European society now and in the future.

A new Deep-UnderGround Laboratory infrastructure in Switzerland to validate the safe extraction of Deep Geothermal Energy

Domenico Giardini, Florian Amann and the DUG-Lab team

Swiss Competence Center for Energy Research - Supply of Electricity (SCCER-SoE), ETH Zurich

The Swiss Energy Strategy 2050 (ES2050) sets a future target of 7% national electricity supply from Deep Geothermal Energy (DGE), corresponding to over 500 MWel installed capacity.

In Switzerland, we find temperatures of 170-190°C at 4-6 km depths, and hydrothermal water is scarse and difficult to locate; to exploit DGE we need to create deep reservoirs in hot crystalline basement rock (EGS). To reach the ES2050 target, we will need to install on average one 20 MWel petrothermal plant per year between 2025 and 2050; to reach this capacity and demonstrate the DGE feasibility, we work to successfully complete three EGS reservoirs over the next 10 years.

The Swiss Competence Center for Energy Research - Supply of Electricity has been established to coordinate the R&D required to reach the ES2050 targets. The SCCER-SoE DGE 10-yr innovation roadmap includes a national experimental and modeling infrastructure comprising rock deformation laboratories and a Deep UnderGround Laboratory infrastructure (DUGLab).

The specific objectives of the DUG-Lab are to:

- perform controlled stimulation experiments in deep underground laboratories, at depth of few hundreds to over 2km and on scale of 10 to 100 m, with accurate multi-parameter monitoring of rock deformation, stimulation and fluid migration;
- establish a coordinated swiss R&D agenda to target the key technology barriers identified to limit the present development of EGS technology, covering resource and reservoir exploration, assessment and characterization, fractures and reservoir creation, reservoir modeling and validation, induced seismicity;
- integrate multi-disciplinary expertise and modeling techniques, including rock deformation laboratories, earthquake physics underground facilities, numerical modeling, geophysical imaging, reservoir engineering and risk management;
- validate protocols and technologies to support the industry in the creation of deep geothermal reservoirs in hot crystalline rock at 4-6 km depth, including new pumps for geothermal applications, innovative drilling technologies, sensors for harsh environment, diverter and zonal isolation technologies for well completion, stress-field diagnostics, smart tracers, advanced seismic and imaging techniques for seismic and aseismic deformation and fluid flow, injection protocols to minimize size of induced events and data-driven, risk-based probabilistic traffic-light systems.
- design and validate risk-mitigation protocols for the stimulation of deep reservoirs and the injection and production sequences while maintaining the induced seismicity within prescribed thresholds;
- build a strong international network of experimental test and monitoring facilities and infrastructures (GeoEnergy Test Beds), aimed at understanding the subsurface processes that affect georesources (including hydrothermal heat, mining, oil&gas, shale gas, CO2 and gas storage) and enhancing subsurface environmental sustainability in densely populated regions.
- team up with other relevant EU projects and national programs (including the NER 300 pilot sites), with programs of similar scope in the US (DOE FORGE) and Australia (Newcrest), and with international programs (EERA-JPGE, IPGT).

The DUG-Lab activities and underground tests start in spring 2015, with support and participation of all the relevant academic partners, industry and federal agencies.

Abstracts Posters

Session 1

Extraction Plays
Oil and Gas, Coal Mining, Ground Water, etc.

Reservoir induced/Triggered seismicity: a Review

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It is well known that the filling of impoundment basins may generate earthquakes. As for the field of hydrocarbon exploitation, the anthropogenic seismicity connected to dams can be also divided in "induced" and "triggered".

Reservoir-Induced-Seismicity (RIS) is constituted of earthquakes of non-tectonic origin and was first observed in 1932 for the Quedd Fodd Dam in Algeria. Probably the first correlation between water level variations and seismicity was reported in 1949 for the Hoover Dam. Since then, more than 70 cases of RIS have been reported; the most prominent example is the M6.7 earthquake on Dec 11, 1967 at Koynanagar (W-India) that killed more than 200 people.

Reservoir-Triggered-Seismicity (RTS) is composed of earthquakes of tectonic nature caused by seismo-tectonically active faults situated close to large reservoirs and may thus be more significant in terms of seismic hazard. The initial stress rate is already close to failure, such that a minor stress change or a reservoir-related small variation of the fault strength may trigger seismic events. The M7.9 Sichuan earthquake of May 12, 2008 that killed more than 60 000 people is suspected to be related to the construction of the Zipingpu Dam. Since in tectonically active areas already small mechanical disturbances may be sufficient to lead to failure and to trigger seismic events, it is a great challenge to discriminate the anthropogenic contribution of such seismic events.

RIS and RTS at dams both correlate with stress changes in the underlying crust, likely caused by (i) the static or cyclic load of the water column in the reservoir and (ii) the changes in pore pressure in pre-existing faults beneath the reservoir (fault lubrication). Although magnitude, distance range and timing of both factors differ, it is often not trivial to distinguish between them. Even if some observations indicate a connection between earthquake magnitude and dam height or water volume, respectively, this relation may probably not be generalized. A further question concerns the distance/depth range that may be influenced by pressure variations induced by the reservoir depending directly on the diffusivity and permeability of the crustal volume. What is the maximum hypocentral distance that can be ascribed to the influence of an impoundment basin – or better – how can the trigger potential be quantified? What are the elastic short-term and long-term responses of the affected crustal volume? Is it possible to establish general rules or does the behaviour of RIS vary for every reservoir?

We review cases of dam related seismicity (RIS/RTS) and discuss a scheme how to combine a probabilistic discrimination with physical modelling of Coulomb stress for RIS and RTS.

Recent seismicity within the oil and gas fields' area in the northeastern offshore zone of Sakhalin Island (Russia)

Alexey Konovalov, Andrey Stepnov, Andrey Sychov

Institute of Marine Geology & Geophysics, Far Eastern Branch of Russian Academy of Sciences

An earthquake with a moment magnitude of Mw=5.6 occurred on June 12, 2005 at 4 h 17 min UTC in the northeastern part of the Sakhalin Island (Russia) in the vicinity of the offshore oil and gas field being developed since 1999.

We collected and analyzed all the available instrumental recordings to develop a reliable source model. The recent seismicity within the oil and gas fields' area was analyzed according to the induced/natural seismicity monitoring data. The obtained results were compared with the new data on geological and tectonic settings in the examined area. The seismogenic zone within the oil and gas fields' area was identified as a thrust fault.

We analyzed the seismic regime of foreshock-aftershock sequences of significant earthquakes related to the fault zones without any human made activity as well as hydrocarbon production areas in the context of characteristic Omori times. The results tend to be dependent on rheology and stress state of geological medium.

The present study provides a basis for developing the objective criteria for natural and triggered seismicity discrimination in tectonically active regions including the oil and gas fields' area in the northeastern offshore zone of Sakhalin Island (Russia).

The study was supported by the Federal Special-Purpose Program "Research and development in priority areas of scientific and technological complex of Russia for 2014-2020" on 2014-2016 years on the theme "Development of new technologies for monitoring and control of natural and human made seismic risks related to the offshore oil and gas fields production" (Government Agreement No. 14.607.21.0105).

Flooding of seismically active mine regions

Simon Kremers and Ralf Fritschen

DMT GmbH & Co. KG Essen

On 2008 February 23 a 4.0 magnitude seismic event occurred in close proximity to a deep underground longwall coal mine in the German Saar mining district. Preceding this event was a series of smaller seismic events, which can be traced back to geological structures. A seismic network was installed to observe and analyse the seismic events. Seismic events are of similar fault plane strike and are organized in several clusters, associated with local and regional tectonic elements. It was found from backcalculation that fault planes with friction angles as low as 8° must have been present. The role of pore pressure on the fault stability is discussed and found to play no role in generating the seismic events.

As a response to the Ml = 4 event mining activities in the Saar district were stopped, however, the seismic monitoring in the region continued until today. Recently, parts of the old workings were flooded in a controlled process. On September 15h 2014 a 2.7 magnitude seismic event occurred close to the hypocenter of the 2008 event. Furthermore, the estimated event depth shows a good correlation with the controlled water level of the mine flooding process. It is assumed that the increasing pore pressure induced slip on the previously active fault zone. Understanding and quantifying this process is important to assess seismic hazard in regions that were heavily mined in the past.

Stress and strength at seismic event hypocenters in deep South African gold mines and the M5.5 Orkney Earthquake

Hiroshi Ogasawara (Ritsumeikan Univ., SATREPS), Gerhard Hofmann, Lourens Scheepers (Anglogold Ashanti), Harumi Kato (3D Geoscience), Yasuo Yabe (Tohoku Univ.), Masao Nakatani (Univ. Tokyo), Makoto Naoi (Kyoto Univ.), Artur Cichowicz (Council for Geoscience), Ray Durrheim (CSIR/ Witwatersrand Univ.), Hirokazu Moriya (Tohoku Univ.) and SATREPS* research group

Yabe et al. (this workshop keynote lecture) report on acoustic emission researches, one of the greatest outcomes from Japanese German Underground Acoustic emission Research in South Africa (JAGUARS; Nakatani et al. 2008), JST-JICA** SATREPS* project "Observational studies in South African mines to mitigate seismic risks (2010-2015; Ogasawara et al. 2009, 2014; Durrheim et al. 2012), JSPS***, and other associated Japanese projects in South African gold mines. This report is on other outcomes from these projects which have been going on at five of the top ten deepest mines in the world and a 1.0km-depth shaft-pillar with stress as high as at the deepest mines.

* Science and Technology Research Partnership for Sustainable Development, ** Japan Science and Technology Agency – Japan International Cooperation Agency, *** Japan Science Promotion Society

We report on two topics, stress and strength at hypocenters and a M5.5 earthquake.

In the previous published reports on 3D stress tensor measurements in South Africa, the ranges of depth and maximum principal stress (σ_1) were limited to depths less than 2.7 km and stresses less than 90 MPa, respectively (e.g. Stacey and Wesseloo 1998; Handley 2013). That has been because no cost-effective methods for routine measurements of local 3-dimensional stress at sites where borehole breakout or core discing prevails and only small pneumatic machines for AX or BX drilling are available. Ogasawara et al. (2012, 2014) overcame these limitations by introducing a downsized Compact Conical-ended Borehole Overcoring technique (CCBO; Sugawara and Obara 1999; ISRM suggested). The largest depth and maximum principal stress that they successfully measured were 3.4 km and 146 MPa, respectively. The assumption of far-field stress vertical-gradient (Lucier et al. 2009) was then well calibrated by the increased number of in-situ measurements. Hofmann et al. (2012, 2013) constrained the range of σ_1 to about 100 to 180 MPa for seven mining-induced events (M_L = 2.1 to 4.0) located by the in-mine seismic network, based on inferences from geological observations. JAGUARS (e.g. Yabe et al. 2009; Naoi et al. 2011) and the subsequent drilling into the M_w2.2 hypocenter (Yabe et al. 2013) offered us a rare opportunity to investigate stress and strength further. Hofmann et al. (2012) found that Excess Shear Stress (or Coulomb Failure Stress) was largest on the aftershock plane and successfully constrained the strength reproducing the fault ride equivalent to the seismic moment observed by the in-mine seismic system, just after the completion of mining in the month of the M_w2.2 event. The stress Yabe et al. (2013) constrained was qualitatively in good agreement with the stress Hofmann et al. (2012) calculated. These efforts allow better simulation of mining induced seismicity by numerical modelling.

A M5.5 earthquake took place on 5 August 2014 near Orkney, South Africa, with located hypocenter below the gold mines. This earthquake, being the largest recorded to date around the mining regions of South Africa, is mysterious for several reasons. The mechanism was a left-lateral strike-slip on a NNW-SSE striking and nearly vertically dipping plane (mystery 1), significantly different from typical mining induced earthquakes with dip-slip on NE-SW striking normal faults intersecting mining horizon. The geological structures mapped on the mining horizon in the Orkney district are characterized by a horst and graben structure trending NE-SW, intruded by multiple dykes trending NNW-SSE. So, the strike-slip might be on a dyke (mystery 2). However, the hypocenter was significantly (at least 1 - 2 km) deeper than the mining horizon (mystery 3), and no dyke intersection or seismic fault rupture was reported on the mining horizon at all. The maximum principal stress that was measured in situ at 3.0 km depth and several km from the hypocenter was almost vertical. The intermediate principal stress was horizontal, trending NNW-SSE almost parallel to the M5.5 fault plane (mystery 4). In order to assess seismic hazard by such earthquakes as this, it is very important to understand stress field and loading mechanism (or tectonics) to address the above mysteries, because such dykes may prevail elsewhere. At the workshop, with updated information, we introduce what we can do.

Abstracts Posters

Session 2

Injection Plays
Deep Geothermal, Wastewater Disposal, Fracking, CO_2 Storage

Rupture events inferred from the injection induced seismicity at Castor UGS, offshore Castellón, Spain

Mikel Díez, Rodrigo del Potro and Pablo Palacios, School of Earth Sciences, University of Bristol

Cases of induced seismicity where the external forcing is controlled can contribute significantly to our understanding of the response of the crust to stress perturbations caused by fluid movement and the associated rupture events. In this work we analyze the 2013 September-October seismic sequence associated to the injection of natural gas into the Castor UGS, offshore Castellon, Spain, which has forced the stop of storage operations to date. The third period of gas injection was accompanied by small ($M<3$) and widely distributed seismic events. After injection was stopped seismic activity became more localized, eventually developing into mainshock ($M\sim4$)-aftershock sequences in early October, returning after to near-background levels. We use tools of statistical seismology to analyze the seismic sequence. Of particular interest is the application of the weighted average magnitude method, which shows escalations in average magnitude of the seismic events (or energy release of the system), which we interpret as rupture events, and which correlate with changes in injection rate. Furthermore, it shows that the system became unstable at some point during the injection, amplifying small fluctuations of the stress field, that possibly lead to the events of $M\sim4$ two weeks after the injection stopped. Using rank ordering statistics we have estimated the most probable size of the next largest earthquake, and interestingly it is just slightly larger than the largest registered to date, $M=4.2$. Perhaps more importantly, there might be log-periodic oscillations in the seismic moment release time series, which hopefully point to the presence of precursors prior to the $M\sim4$ events. This could be encouraging in terms of a hazard perspective as it could mean that, in some cases, there might be windows of detection prior to main events.

A probabilistic assessment of waste water injection induced seismicity in central California

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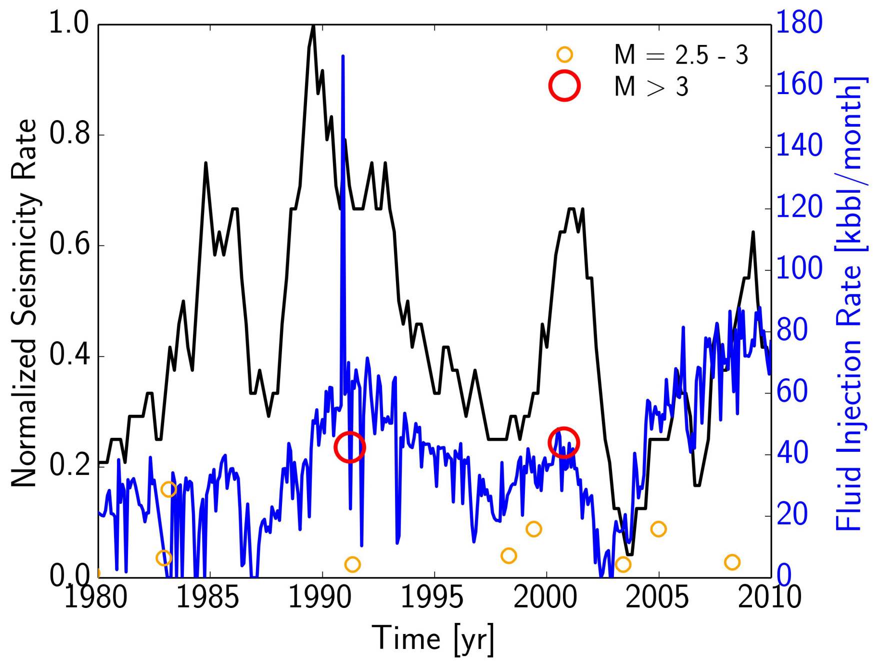
The recent, large increase in seismic activity within the central and eastern U.S. may be connected to an increase in fluid injection into deep waste-water disposal wells, since ~2001. Anomalous earthquake sequences can easily be identified in regions with low background seismicity rates, however in plate boundary regions tectonically-driven earthquake-sequences may disguise injection induced earthquakes. The present study investigates this effect. We show results from a comprehensive analysis of waste water injection in Kern County, the largest oil-producing county in California. We focus on spatial-temporal correlations between seismic and injection activity and variations in the spatial-temporal seismicity density before and after injection activity. We apply a probabilistic approach to separate induced vs. tectonic earthquakes. This approach can be applied to different regions, independent of background rates and may provide insights into the probability of inducing earthquakes as a function of injection parameters and local geological conditions.

In Kern County, most earthquakes are caused by tectonic forcing, however, waste water injection contributes to seismic activity in four different regions with several events above magnitude four. The seismicity shows different migration characteristics relative to the injection sites, including linear and non-linear trends. The latter is indicative of diffusive processes which take advantage of reservoir properties and fault structures and can induce earthquakes at distances of up to 10 km. Our results suggest that injection-related triggering processes are complex, possibly involving creep, and delayed triggering. Pore-pressure diffusion may play a larger role in the presence of active faults and high-permeability damage zones thus increasing the local seismic hazard in a non-linear fashion.



Example of a waste water injection well that showed a long-term correlation between injection rates (blue) and seismicity rates (blue) between 1980 and 2010. There were also two M>3 events coinciding with injection-rate peaks in 1990 and 2001.

Combined microseismic and geomechanical monitoring of a CCS site in Algeria

Bettina Goertz-Allmann, NORSAR; Daniela Kühn, NORSAR; Volker Oye, NORSAR; Bahman Bohloli NGI, Eyvind Aker AGR Petroleum Services AS

More than 5000 microseismic events have been detected near a pilot monitoring well at the In Salah Carbon Capture and Storage (CCS) site in Algeria using a master event cross-correlation method. Due to insufficient network geometry with only one available station for data analysis, these events cannot be reliably located. However, by using arrival angle information and S-P traveltime differences, we can distinguish events between four distinct clusters (see Figure). Three of these clusters correlate with injection rate and wellhead pressure, and can thus be attributed to being injection-related.

Analysis of wellhead data suggests that the reservoir fracture pressure has been exceeded occasionally during the injection period, each time accompanied by increased microseismic activity within clusters B, C, and D. However, cluster A shows no obvious correlation to pressure changes in the reservoir. Of particular interest in this context is a more accurate depth location of the seismicity, which may tell whether deformation was confined to the reservoir, or reached into or above the cap rock. Despite the inability to properly locate events with a non-existing aperture from one station only, we can constrain the event depth using a converted phase from a known strong impedance contrast in the overburden. Ray tracing of direct and converted phases reveals that cluster A is located at a significantly shallower depth than the other three clusters, and must be located above the reservoir injection interval. This is further corroborated by the fact that significant shear wave splitting of up to 5 percent is only observed at clusters B, C, and D, but not for the shallower cluster A, consistent with anisotropy at the reservoir and lower cap rock level.

The lack of correlation to the injection history and *b*-values close to one for cluster A indicate that the seismicity may be tectonic in nature and could be associated with re-activation of pre-existing weakness zones, rather than being injection-induced.

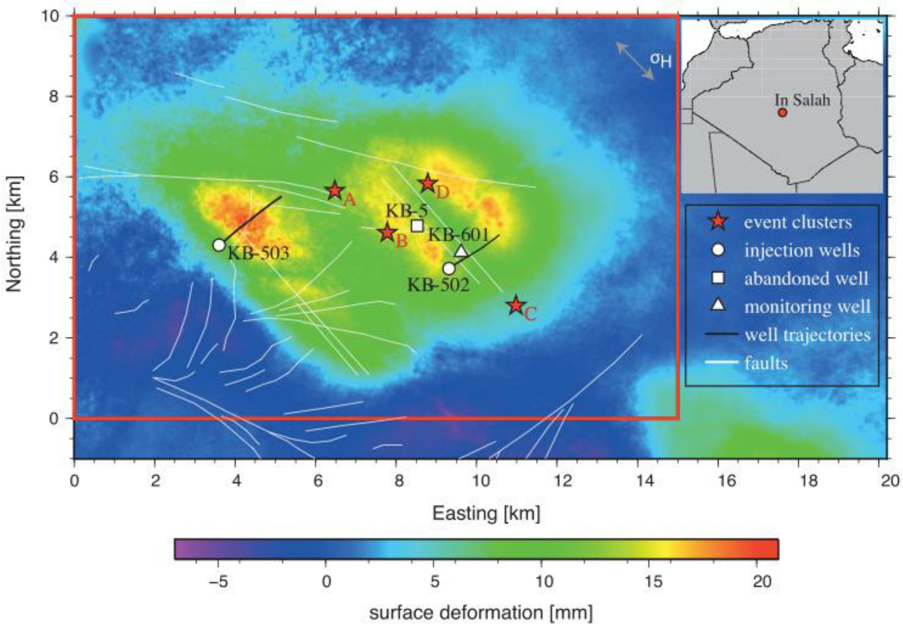


Figure: Krechba field, In Salah, Algeria showing the location of two horizontal CO_2 injection wells (KB-502 and KB-503), and the vertical microseismic monitoring well (KB-601). Microseismic event clusters A–D are shown by red stars. Faults mapped by 3-D seismic are shown down to a depth of 2000 m (white lines). The direction of the maximum horizontal stress σ_H is indicated by the grey arrow. The background color indicates the observed surface deformation due to CO_2 injection (data obtained from Tele-Rilevamento Europa TRE).

Changes in the characteristics of induced seismicity due to long-term fluid injection at The Geysers geothermal field: Implications to fracture generation mechanism and seismic hazard.

Grzegorz Kwiatek[1], Patricia Martínez-Garzón[1], Marco Bohnhoff[1,2], Georg Dresen[1,3] Hiroki Sone[1], and Craig Hartline[4]

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In this study we analyze changes in physical and statistical characteristics of induced seismicity recorded during a long-term fluid injection and production project in the northwestern part of The Geysers geothermal field, California. For this purpose, a distinct cluster of seismicity related to the injection operations at Prati-9 and Prati-29 system was investigated. The injection at Prati-9 well started in Sep 2007 with injection rate as high as 4000m^3/day occurring during winter periods. In spring 2010 another well, Prati-29 started operating at similar injection rates resulting in doubling the amount of fluid injected in the investigated area. Until spring 2012, no production of steam was performed in the vicinity of Prati-9/Prati-29.

Between 2008 and 2014, more than 1814 events occurred in the vicinity of Prati-9 and Prati-29, as reported in Northern California Earthquake Data Center (NCEDC). The original NCEDC catalog was extensively refined. First, the double-difference relocation technique was applied resulting in significant improvement of location precision. The original FPFIT focal mechanism were recalculated using the software HASH taking into account updated hypocenter catalog. The seismic moment, static stress drops and apparent stress were calculated using the spectral fitting method and then refined using spectral ratio technique (Kwiatek et al., Geothermics 52, 2014). The applied methodology resulted in a significant improvement in the quality of source parameters allowing for a high-resolution analysis of long-term changes in the seismic response due to technological operations.

The calculated source characteristics were used together with stress inversion data and other statistical and spatial parameters such as b-value, D-value, maximum magnitude, cumulative injection and production data and GPS observations to investigate the effects of long term fluid injection and later extraction on the behavior of seismicity in Prati-9/Prati-29 system. We found a 30 times lower cumulative moment release at Prati-29 in comparison to Prati-9 despite of comparable injection rates. The static stress drop of events in the vicinity of Prati-29 was found to be remarkably lower. We found a general deepening of seismicity with time as well as transition in dominant focal mechanism from normal faulting at the shallower depths to strike slip faulting at the bottom of the reservoir. Also, larger events were found to occur at greater depths. The b-values, D-values were found to weakly decrease with time, accompanied by a slight increase in static stress drop, apparent stress and a significant decrease in relative stress magnitude.

The results are discussed in the context of potential long term changes in the physical mechanism leading to the occurrence of induced seismicity. It was recently found (Martínez-Garzón et al., Geophys. Res. Lett. 40, 2013; J. Geophys. Res., 2014, in press) that the influence of the different physical mechanisms inducing seismicity during fluid-injection varies with different injection rates, being the thermo-elastic effects dominant and pore pressure increase significant during periods of high injection rates. Here, we found that apart from short-term changes there is a long-term (2008-2014) trend in various characteristics of induced seismicity. These changes are attributed to the intensive fluid injection with practically no production in the first four years. This lead to the significant increase in the amount of fluids persistently present in the vicinity of Prati-9 and Prati-29 system. A discussion in the framework of relation between maximum magnitude and cumulative volume injected (McGarr, J. Geophys. Res. 119, 2014) and seismic hazard is also included.

Characterization of seismicity induced at variable injection rates: A case study from The Geysers geothermal field

Patricia Martínez- Garzón[1], Grzegorz Kwiatek[1], Hiroki Sone[1], Marco Bohnhoff[1,2], Georg Dresen[1,3] and Craig Hartline[4], (1) GFZ Potsdam German Research Centre for Geosciences, (2) Free University Berlin, Institute of Geological Sciences, Berlin, Germany, (3) University of Potsdam, Institute of Earth and Environmental Sciences, (4) Calpine Corporation, Middletown, California, USA

Spatial, kinematical and magnitude characteristics of induced seismicity occurring at different fluid-injection rates are investigated using a high-resolution hypocenter catalog of a prominent cluster of induced seismicity at the northwestern part of The Geysers geothermal field, California.

Studying the micro-seismicity from this cluster (M_W 1.4 – 3.1), we find that during peak-injections seismicity occurs at greater distances from the injection well, mainly aligned with the orientation of the maximum horizontal stress. In contrast, during lower injection rates seismicity concentrates closer to the injection well. This observation highlighted the potential important effect of the pore pressure increase in the distribution of the seismicity.

Analysis of focal mechanisms shows that during high injection rates the percentage of strike-slip and/or thrust faulting events increases. The stress tensor inversion technique revealed that the orientation of the principal stress axis moves by approximately 20° during high injection rates and returns to its original position after the peak-injection, confirming the close relation existing between fluid-injection and reservoir stresses. The relative stress magnitude is also increasing during high injection rates. Lastly, the *b*-value decreases during peak-injections, suggesting the increase in differential stresses at the reservoir during these periods.

It is here suggested that the observed differences in the seismicity characteristics at different injection rates could be related to variable influence of physical mechanisms inducing seismicity. Prior to peak-injections, the seismicity might be predominantly connected with the thermal fracturing of the reservoir rock given the high encountered reservoir temperatures. However, during peak injections, the limited pore pressure increase around the open hole section (~1MPa) may play a significant role. By estimating the reservoir permeability and the characteristic diffusion lengths of the heat and the pressure, we confirm that the pore pressure reaches significantly greater distances from the injection well than the heat diffusion.

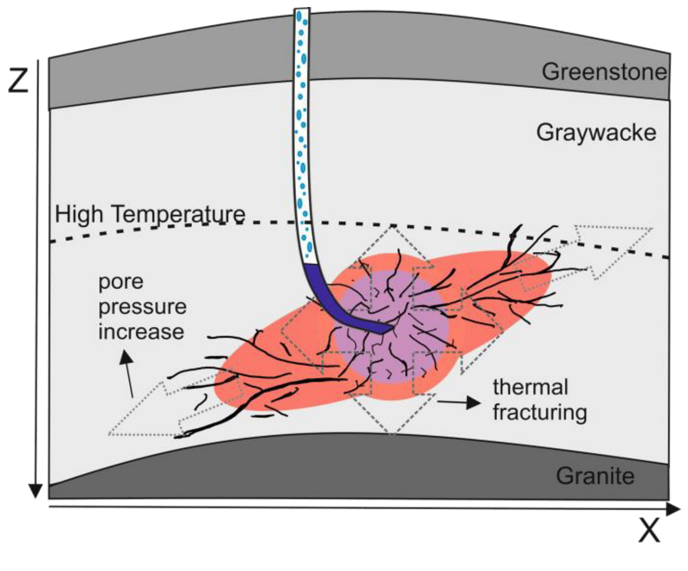


Figure 1: Conceptual sketch illustrating the characteristic lengths of the heat and pore pressure diffusion from one injection well at The Geysers geothermal field

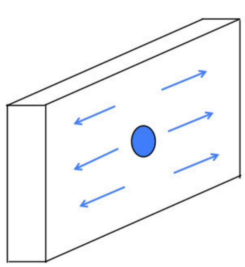
Thermal Stress as a Mechanism for Injection-Triggered Seismicity

Jack Norbeck and Roland Horne, Stanford University

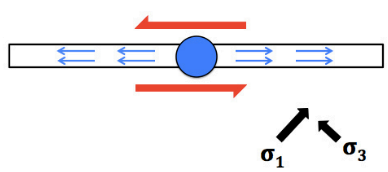
The Rangely Oil Field experiments in the 1970's proved that seismicity can be a consequence of fluid injection into the subsurface, and that the rate of seismicity could potentially be correlated to injection rates and pressures. Since then, the vast majority of analyses of injection-triggered seismicity have focused on the most intuitive physical mechanism: increased fluid pressure in the fault zone leading to a reduction in compressive effective stress and an associated reduction in frictional resistance to shear failure. This simple model provides a good starting point, but cannot fully explain observations at several field sites. As a notable example, wastewater disposal at the Rocky Mountain Arsenal in Colorado began triggering a significant number of seismic events in 1962, shortly after injection was commenced. The injection wells were ordered to be shut-in starting in February 1966, but seismicity continued for over one year following shut-in. In fact, the three largest events (M 4.8, 5.1, and 5.3) occurred in 1967 following shut-in of the injection wells. Similar observations were made during stimulation of a geothermal well in Basel, Switzerland in 2006, where the largest events were observed following cessation of injection. The diffusion process that governs fluid flow would tend to reduce pressures after shut-in, and therefore faults would generally be expected to stabilize. Other mechanisms may perhaps play important roles in triggered-seismicity.

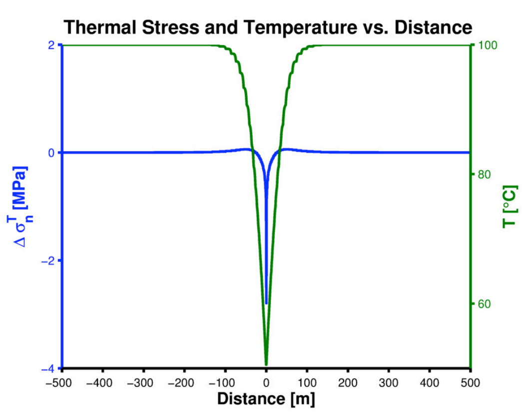
One process that could continue to generate seismicity following shut-in is thermally-induced stress due to cooling of reservoir rock. Pressure diffusion occurs over extremely short time scales relative to thermal diffusion, so it is likely that if significant thermal stresses develop during injection then they may persist long after pore pressures subside. In this work, we used numerical modeling to investigate the relative influence of fluid pressure transients, poroelastic stress, thermal transients, and thermoelastic stress in generating post shut-in seismicity. In the model, fluid flow, heat flow, and elasticity were simulated in a fully coupled poro-thermoelastic framework. Faults were represented explicitly using an embedded fracture modeling strategy. A rate-and-state description of friction evolution on the fault surfaces allowed for the simulation of the earthquake nucleation, rupture, and arrest processes. Fluid flow and heat flow calculations were performed with a finite volume method. Mechanical deformation of fractures, poroelastic stresses, and thermoelastic stresses were calculated using a hybrid boundary element and finite element method.

In this poster, we present the results of simulations of injection of cool fluid into a fault that is well-oriented for shear. The fault is surrounded by permeable matrix rock. We illustrate the interplay between pore pressure buildup in the fault, fluid leakoff into the surrounding rock, poroelastic stress, and thermoelastic stress. We identify the factors that lead to dominant behavior of each individual mechanism.



$$\sigma_n' = \sigma_n^r - p^f + \Delta\sigma_n^T + \Delta\sigma_n^P$$





Fault reactivation by fluid injection near Landau and Insheim, Upper Rhine Graben, Germany

Joachim Ritter, Michael Frietsch, Laura Gaßner, Joern Groos, Michael Grund, & Jens Zeiss

Karlsruhe Institute of Technology (KIT), Geophysical Institute, Germany, joachim.ritter@kit.edu

We study the impact of fluid injection into the uppermost crust in the area of Landau and Insheim, two neighboring towns in the Central Upper Rhine Graben, Germany. Since 2006 micro-earthquakes ($M_L \leq 2.7$) occur in this area. These events are related to the injection of fluids into 2,500-3,500 m deep boreholes. Within the MAGS project (www.mags-projekt.de) the seismicity was monitored with a dense network of recording stations and the seismic waveforms were analyzed in details. The complex 3-D geological structure complicates the application of 1-D methods, and tests were done using 3-D seismic waveform modelling with the SOFI3D FD method. Between 2006 and 2013 about 2,000 events were detected with cross-correlation analyses, although the signal amplitudes are quite low and the noise level in the study area is high. A subset of the events was localized with an absolute (HYPOSAT) and relative (hypoDD) method. The determined hypocenters are aligned along discrete elongated structures which are interpreted as preferred rupture zones. Fault plane solutions, determined with FOCMEC, indicate normal and strike-slip shear mechanisms. The preferred strike of the faults is NNW-SSE to NNE-SSW (Gaßner et al., 2014) which is similar to the regional maximum horizontal stress direction (NNW-SSE) and known faults related to the Cenozoic rifting. The study of seismic shear wave anisotropy indicates a fast polarization direction which is also aligned in NNW-SSE direction (Frietsch et al., in print). This azimuth-dependent anisotropy as well as the other seismological and tectonic models are consistent with fluid-filled faults oriented in NNW-SSE direction which are (re-)activated by fluid injection at depth.

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Frietsch, M., Groos, J.C. & Ritter, J.R.R., in print. Detection and delineation of a fracture zone with observation of seismic shear wave anisotropy in the Upper Rhine Graben, SW Germany. Pure and Applied Geophysics, DOI: 10.1007/s00024-014-0899-3.

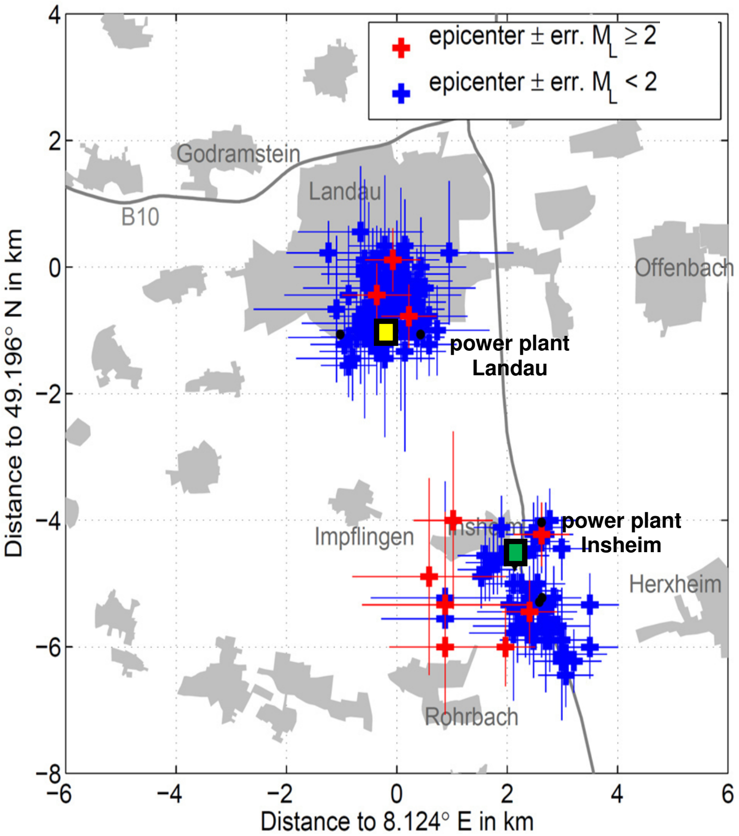

Fig.: Map with epicenters location (north: Landau seismic volume, south: Insheim seismic volume). 2-σ uncertainties are shown together with production and injection wells (black dots).

Detection and location of induced earthquakes at the Landau and Insheim geothermal reservoirs, SW Germany

Bernd Schmidt, LER Mainz; Ulrich Wegler, BGR Hannover; Andrea Brüstle, LER Mainz; Margarete Vasterling, BGR, Hannover; Tom Richter, BGR Hannover

The tertiary Upper Rhine Graben is the region with the highest temperature gradient in Germany. Since 2007 at Landau and since 2012 at Insheim (5 km south of Landau) two combined heat and power plants are running in the western part of the central Upper Rhine Graben , where the graben is divided in numerous small blocks with various subsidence rates. The reservoirs are situated in the lower sediment fill and the upper crystalline basement. Both deep geothermal reservoirs are Hot-Wet-Rock systems with a doublet configuration. Production rates are up to 70 l/s at Landau with temperatures of 155°C and up to 85 l/s at Insheim with temperatures of 165°. In 2009 two seismic events of M_L 2.4 and 2.7 and six minor seismic events were felt at the city of Landau and the surrounding area. The earthquakes were located in the region of the power plant at depths of the geothermal reservoir. The hydraulic stimulation of the Insheim reservoir in April 2010 also caused two seismic events of M_L 2.2 and 2.4, respectively, which were felt at the Earth's surface. As a consequence the local seismic monitoring network of the company was densified by an additional scientific network of 22 surface and 2 borehole stations deployed and maintained by the Karlsruher Institute of Technology (KIT) and the Federal Institute for Geosciences and Natural Resources (BGR). One goal of the 'Microseismic Activity of Geothermal Systems' project (MAGS, 2010-2013) was to record and study the microseismicity of the Landau and Insheim deep geothermal reservoirs

Since October 2013 the follow-up project MAGS2 is focusing on the study of a potential interaction of the observed microseismicity between the two geothermal systems. A surface seismic network of 12 surface stations with a station spacing of about 5 km is operated by BGR. All stations are deployed within the graben structure on sediments. The network is completed by 3 borehole stations, 2 of them operated by the local seismological survey of Rhineland-Palatine (LER) and 1 borehole station jointly operated by LER and the industrial partner. The installation of an additional borehole station is planned by LER in 2015. The continuously recorded waveform data of the entire network is transmitted in real-time to BGR. The event detection is done by defining master events from well-located observed events of each reservoir and cross-correlating the envelopes of these master events with the ones of the real time waveform data. This cross-correlation event-detector has already been developed as a SeisComP3-module during the MAGS project. The manual analysis of the automatically detected events is done by LER with the SeisComP3 software. Until now the seismic clouds of the Landau and Insheim reservoirs are clearly separated. The small network extension of less than 20 km and the unsolidated sediment-fill of the Upper Rhine Graben make a standard determination of the local magnitude impossible. Therefore a relative magnitude is determined from the amplitude of the master event and the detected event. During the first 12 months since the beginning of the project in October 2013 in total 89 per cent of the 227 detections were triggered correctly as induced earthquake of the Landau or Insheim reservoir as well as for quarry blasts.

It is planned to extend the applied detector by automatically generated shake maps. As the modelling of ground shaking at the surface is based on detailed velocity and attenuation models, intrinsic and scattering attenuation of observed shear waves are determined in the frequency range from 2 to 50 Hz. The inversion is performed by fitting Green's functions of the acoustic radiative transfer theory to the observed energy densities at the station sites.

Real time detection and traffic light systems for hydraulic stimulations

Ulrich Wegler, BGR, Margarete Vasterling, BGR, Jan Becker, gempa GmbH, Carsten Dinske, FU Berlin

In order to mitigate the risk associated with induced seismicity caused by hydraulic stimulations in deep geothermal systems so called traffic light systems (risk management plans) are used. These systems consist of a local seismic monitoring and an estimate of the current seismic hazard based on observed induced seismicity. The current hazard is compared to threshold values. Measures to reduce the seismic hazard (e.g. reducing the flow rate) specified in the risk management plan are taken, if thresholds are exceeded.

In order to improve such traffic light systems micro-seismic events must be reliably detected and assigned to a geothermal reservoir in real time. In Germany geothermal power plants are generally built close to heat consumers, that is close to densely populated areas. As a consequence seismic records are generally noisy and standard STA/LTA trigger would cause many false detections. Therefore, we established a detector based on a cross-correlation of the real time data with known master events. To guarantee a sufficient similarity of events with slightly different locations and source mechanism we use the envelope of the seismic traces instead of the seismic traces themselves. The cross-correlation is computed in two steps: First, we compute a normalized trace cross-correlation for all traces of the network. The condition for a detection is, that a certain percentage of all trace cross-correlations exceed a threshold value. Second, we compute a normalized network correlation, which also takes into account the relative amplitudes between different stations. If the network correlation also exceeds a specified threshold, an event detection is released. An accurate location is not necessary for our traffic light system and we just assign the location of the detected event to the location of the master event and so to a specific geothermal reservoir. The magnitude of the detected events is also computed relative to the master events using relative amplitudes. The detection algorithm is implemented as a module in the real-time earthquake monitoring software SeisComP3 and its output is an automatically generated earthquake catalogue. We tested the automatic detections against a manually evaluated earthquake catalogue of the Landau/Insheim geothermal field. The magnitude of completeness of the automatically generated catalogue is $M_C = 0.2$ using our current parameters, where we do not have any wrong detections caused by noise after one year of automatic analysis. The detector can separate three different classes of events and assign them to the Landau and Insheim reservoirs (5 km distance) as well as to Waldhambach quarry (10 km distance from the geothermal field). A few wrong detections are caused by local tectonic earthquakes outside of the geothermal reservoirs. This problem could be solved in the future by using some of these local tectonic earthquakes as additional master events.

Additionally to improving event detection, we also developed a new real time method for seismic hazard estimation. Standard traffic light systems use the largest recorded magnitude or peak ground velocity to estimate current ‘seismic hazard’ caused by induced earthquakes. We developed a real time technique that computes the probability of exceedance for an undesired magnitude using a statistical analysis of recorded micro-seismicity. Based on the in real time generated earthquake catalogue, we compute the magnitude of completeness, the b-value of the Gutenberg-Richter law, and the so-called ‘seismogenic index’. These three quantities are updated in real time, if more induced earthquakes are detected. Using the flow rate of the hydraulic stimulation, which we assume to be recorded in real time as well, we calculate the expected seismicity for the next hours. In particular, we compute the probability of exceedance for a predefined critical magnitude. The value is permanently updated and compared to predefined threshold values of the traffic light system. Additionally to the scenario of a continued stimulation with the current flow rate, we also consider the case of an immediate shut-in. For this scenario the probability of exceedance is computed using a modified Omori law. The developed algorithm is also implemented in SeisComP3 including a graphical user interface and it can be combined with the above described detector. In contrast to the detector, which has been running in real time using Landau/Insheim data since one year, the traffic light algorithm has only been tested in playback mode simulating a real time scenario so far. For example, using data of the Basel Deep Heat Mining project and selecting a probability of exceedance of 60 percent for a critical magnitude of $M_L = 2.7$, our traffic light algorithm turns from green to amber four hours before the first magnitude 2.7 earthquake in Basel, and it turns to red two hours before this event.

Abstracts Posters

Session 3

Modeling of Induced Seismicity
Numerical Modeling, Geomechanical Aspects, and Physical Constrains

Dynamic rupture modeling of injection-induced seismicity

Loes Buijze, TNO Utrecht, The Netherlands, Gerd-Jan Schreppers, TNO DIANA, Bogdan Orlic, TNO Utrecht, The Netherlands

Fault reactivation and induced seismicity due to pore pressure changes are often modeled using static numerical modeling. Whereas these static models may capture in great detail the injection-induced stress changes and the onset of fault reactivation, the post failure behavior is not modeled in a realistic manner, since for example effects of dynamic weakening and inertia are not taken into account. In our research, we investigate the dynamic rupture characteristics of injection-induced seismicity in dynamic models with DIANA, a general-purpose finite element simulator. We model a simplified 2D fault-bounded reservoir, into which fluids are injected, increasing the pressure on the fault and inducing a seismic event. We model friction on the fault with rate-and-state friction, where friction is a function of both slip velocity and time. We analyze the effects of the initial stress state of the fault, fault heterogeneity and friction parameters on the rupture characteristics (e.g. the slipped length, displacements and velocities).

Testing and comparing forecasting models for fluid-induced seismicity

Flaminia Catalli[1], Sebastian Hainzl[1],Torsten Dahm[1], and Valentin Gisghig[2]

[1] GFZ-Potsdam, [2] ETH Zurich

Understanding and eventually forecasting the behavior of induced seismicity in space, time and magnitude is a major task for the geothermic community nowadays. A reliable prediction of fluid induced seismicity in geothermal fields could help reducing the related nuisance and risk, thus favoring also the acceptance of such alternative source of energy by local populations.

Some forecasting models, based on the assumption that earthquake triggering for induced seismicity is based only on pore pressure diffusion (under different assumptions, as for example considering a linear or non-linear problem), have already been applied and reproduced the main features of observed seismicity in some cases (e.g. *Shapiro et al.*, 2010; *Goertz-Allmann and Wiemer*, 2012; *Gishig and Wiemer*, 2013; *Hakimashemi et al.,* 2014). Here we propose a thorough and comparative test of three kind of such models for induced seismicity, taking also into account for the possible influence of earthquake interactions during and after the injection of fluids (e.g. *Catalli et al.*, 2013). We perform a synthetic test, based on a set of possible injection scenarios, about modeling expected induced seismicity by means of: 1) a geomechanical stochastic seed model (GSSM, *Gishig and Wiemer*, 2013); 2) a threshold triggering model (e.g. Shapiro et al., 2010), and 3) a rate-and-state model (*Dieterich*, 1994) based on Coulomb triggering. We test the three proposed methodologies set up on a common pore pressure diffusion, which performs as the stressing history for possible triggering in time, perturbed also by event interplays. This common basis for the three models allows one to identify similarities and differences between the approaches. The three methodologies are yet independent from the geomechanical model used for the reservoir and it allows also to test different kind of pore pressure models (e.g. fully coupled or not; in 2 or 3D; linear and non-linear).

The final task of our study is evaluating the performance of each model under different initial assumptions on the fluid flow trend and relative pressure diffusion; we aim to understand which model might be more robust and reliable in terms of predicting: 1) the number of events; 2) the spatio-temporal growth and pattern of the seismic event density around the well and at further distances; 3) the magnitudes distribution of triggered events.

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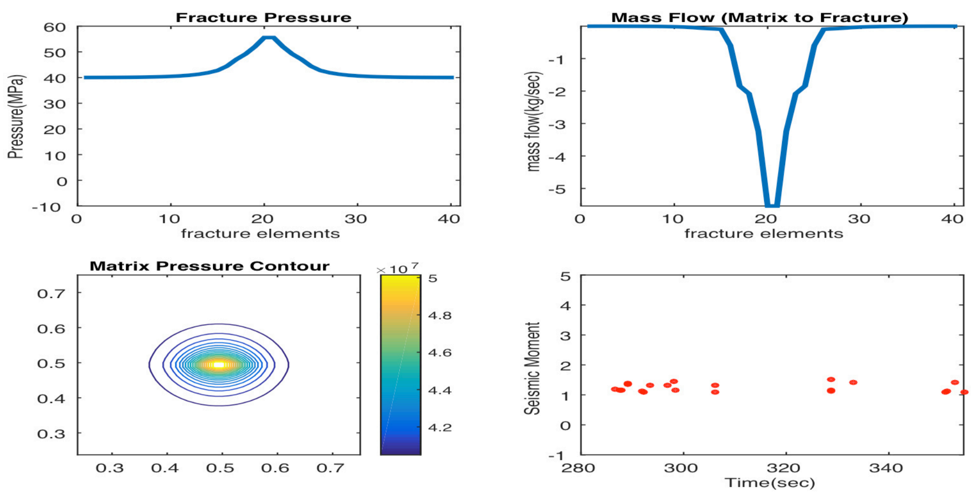
Numerical modeling of injection induced seismicity in a damaged rock domain with fracture manifolds

Rajdeep Deb and Patrick Jenny, ETH Zürich

The work focuses on developing a numerical model to study the effect of induced seismicity due to fluid injection in a fractured domain. A finite volume method based numerical model is developed to capture the failure events in a stressed domain and the subsequent effect on the fluid pressure and volume along the fractures. The failure criterion is based on the static/dynamic friction law of Coulomb friction forces and the slip solution along with elastic displacements of the domain are calculated for discrete volume segments. A subsequent evolution of the pressure field due to failure induced opening of fractures is also obtained. The aperture changes along the fracture manifolds are calculated as function of shear dilation slip solutions. The change in fracture volume due to shear dilation is modeled using a time dependent volume change equation, which is characterized by a timescale used. This lead to a stable numerical scheme without having to resolve the geo-mechanical timescale.

Numerical studies of enhanced geothermal systems (EGS) requires efficient modeling and simulation of the coupled solid and fluid mechanics in the reservoirs. Geothermal systems are natural heat exchangers, which depend on fluid flow paths through the rock and heat exchange between fluid and rock. Rock mechanics obviously plays a key role in creating new flow paths, and therefore a first objective is to obtain a physically accurate numerical modeling to describe the geo-mechanics. Typical EGS reservoirs can be approximated by an elastic medium with a high fracture density. The fluid injection in a geothermal domain decreases the compressive normal stress on the fractures which results in a small increase of fracture volume and aperture and can trigger shear failure along the fractures. The shear failure causes the fracture planes to slip with respect to each other along the direction of shear traction forces. This leads to a corresponding increase in aperture of the fracture manifolds which is much larger compared to the tensile opening of fracture aperture due to pressure. The increase in fracture aperture leads to increased permeability and the increased volume.

In this talk, an accurate and efficient solution approach for shear induced slip calculations and the corresponding stress distributions is presented. The method is coupled with a fluid flow solver for discrete fracture networks. The rapid change in fracture aperture and volume due to the shear induced failure is accounted for by a timescale required for the fluid to occupy this volume and it is responsible for a temporal low pressure peak around the failed fracture segment. The figure below presents numerical results along a single fracture in a damaged matrix exposed to shear and normal stress with an injection well at the center. Shown are pressure distribution along the fracture with its maximum at the injection well, mass flow from the fracture into the matrix, pressure contours in the damaged matrix around the fracture, and the history of seismic events and their magnitudes.



Pressure front interacting with a rate-and-state fault of heterogeneous permeability

Dublanchet Pierre, Karvounis Dimitrios, Rinaldi Antonio P., Stefan Wiemer
Swiss Seismological Service (SED), ETH Zürich

Many induced earthquake sequences could be seen as the rupture of brittle asperities along a fault zone, in response to fluid pressure changes generated by an injection at depth. Furthermore, the relocation of seismicity shows that these brittle patches only cluster on particular regions of the fault zone, which indicates that other portions of the fault are either creeping or not activated during the injection. This shearing behavior indicates heterogeneous permeability conditions within the fault zone.

Here, we investigate the injection-induced seismic response of a heterogeneous fault plane featuring brittle asperities with low permeability embedded in higher permeability and ductile matrix. We first simulate the fluid flow and pressure evolution with well-known hydrogeological numerical simulators, which account for the heterogeneous permeability caused by the presence of asperities. We account for two different scenarios: the first case the injection occur far from the fault zone, with the fluid and pressure propagating in a porous medium (TOUGH2); in the second scenario we account for an injection close to the fault zone, and then we account for the fluid flow that may occur within the fault zone by performing simulations with a discrete fracture simulator (HFR-Sim). In both cases, we simulate heterogeneities in fault permeability, defined by a given distribution of asperities.

In order to get the seismicity associated with the simulated injection in the two scenarios, we modeled in a second step the fault as a planar rate-and-state frictional interface, where brittle asperities are represented as velocity-weakening unstable patches embedded in a velocty-strengthening stable region. We used the pressure history generated by the hydrogeological models as a mechanical loading of the interface, and we computed the slip history of the asperities and the stable matrix.

This coupled modeling approach allows to compute the seismicity generated by a localized fluid injection, and to investigate the relative importance of static stress transfers and aseismic stress transfers in the triggering of seismicity.

A coupled fluid flow–seismicity model for real-time assessment of induced seismic hazard and reservoir creation

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2: Swiss Seismological Service (SED), ETH Zurich

New induced seismicity forecast models are currently being built and calibrated to become part of a real-time hazard assessment tool – the Advanced Traffic Light System ATLS. The models that currently are able to reproduce event numbers and statistics of observed induced seismicity sequences range from basic statistical models to so-called hybrid approaches. In the latter, seismicity is triggered by transient pressure changes modelled by linear or non-linear pressure diffusion models. A severe limitation of the current hybrid models is their loose coupling between seismicity and fluid flow, i.e. they include only one-way coupling from pressure to seismicity, but ignore the feedback of seismicity on the permeability field. We propose a new equivalent continuum fluid flow approach, in which seismicity is triggered by pressure diffusion on potential earthquake hypocenters randomly distributed in space. In addition, two-way coupling is enabled by enhancing permeability in the mesh cells intersected by the source area of the triggered earthquakes. Upon triggering the induced events are assigned a magnitude randomly drawn from Gutenberg-Richter distribution with a pre-defined b-value. The earthquake catalogues thus produced by a stochastic process exhibit a realistic statistical distribution. By enhancing permeability in dependence of slip that is estimated from magnitude and standard earthquake scaling laws, the model yields not only estimates of seismic hazard, but also of the degree of reservoir permeability enhancement obtained by the spent seismic hazard. In the framework of a real-time traffic light system, such a model would not only inform on the current seismic hazard, but also if the required reservoir properties have been achieved. The traffic light system could then be operated with two stop criteria: one based on seismic hazard, the other on based on reservoir size and properties. Here, we present the model procedure along with first results from joint calibration against induced seismicity data as well as wellhead pressure and flow rate as observed during the stimulation at the Basel EGS project in 2006.

Forward Induced Seismic Hazard Assessment – FISHA Application to the Synthetic Seismicity Catalogue by Discrete Element Fluid Injection Modeling

Amir Hossein Hakimhashemi, Jeoung Seok Yoon, Arno Zang, Oliver Heidbach, Gotfried Grünthal, GFZ Potsdam

The Forward Induced Seismic Hazard Assessment – FISHA (Hakimhashemi et al. 2014a,b) is a general workflow which links the output of hydromechanical-numerical models of geothermal reservoirs, either in terms of seismicity catalogue (Hakimhashemi et al. 2014a) or in the form of spatiotemporal changes in the stress field (Hakimhashemi et al. 2014b), to a time-dependent probabilistic seismic hazard assessment in terms of the time dependent occurrence rate of the Seismic Events of Economic Concern – SEECo. SEECo refer to the seismic events of low to moderate magnitudes which may not be destructive but can cause economic losses due to damage to the infrastructure (see also Grünthal, 2014). Therefore, the FISHA has the capability to a priori test different stimulation/production strategies and to develop a priori knowledge about how the reservoir should be treated to mitigate the risks associated with SEECo.

This study tests the FISHA using the outputs of the fluid injection modeling, in the form of synthetic seismicity catalogue. Fluid injection modeling used in this study is prepared by Particle Flow Code 2D (PFC2D, Itasca). Fluid injection modeling is done on a granitic geothermal reservoir with an inclined through-going fault zone and subjected to different stress regimes (Yoon et al. poster presented in the workshop). For all modeling cases tested synthetic seismicity catalogues are produced and analyzed by the FISHA concept. The synthetic catalogues include the occurrence time, the coordinated hypocenter as well as the moment magnitude for the events. These are used to calibrate the magnitude completeness Mc, as well as the parameters of the frequency-magnitude relation, i.e. *a* and *b*. Using these parameters, time dependent occurrence rate of SEECo is computed for different modeling cases and prediction/assessment on the potential risks associated with occurrence of SEECo are addressed. Finally the results according to different scenarios are analyzed and compared in order to assess in which geological and operational settings the risks associated with SEECo would be the highest.

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Developing a Test Bench for Induced Seismicity Modelling in Deep Geothermal Energy Projects

Eszter Király, J. Douglas Zechar, Valentin Gischig, Dimitrios Karvounis and Stefan Wiemer, Swiss Seismological Service, ETH Zürich

The decision to phase out nuclear power in Switzerland by 2034 accelerated research on deep geothermal energy, which has the ability to contribute to long-term energy resources of the country. Induced seismicty is a necessary tool to create an enhanced geothermal system; however, potential seismic hazard poses a major challenge to the widespread implementation of this technology. Monitoring and controlling induced seismicity with warning systems requires models that are updated as new data arrive and that are cast in probabilistic terms. Our main question is: is it possible to forecast the seismic response of the geothermal site during and after stimulation with models based on observed seismicity and hydraulic data? To answer the question, we build a seismicity modeling test bench to explore the predictive performance of various stochastic and hybrid models. The goal is to find the most suitable model or model combination for forecasting induced micro-seismicity and unexpected events in geothermal reservoirs.

We consider the Basel 2006 and the Soultz-sous-Forêts 2004 stimulation datasets and generate forecasts of seismicity in the next six hours. We explore two models of different complexity: (1) a 1D hydraulic model coupled with a stochastic seed model based on pore pressure diffusion with irreversible permeability enhancement; and (2) four variants of a 3D "Shapiro" model which combine estimates of seismogenic index with a spatial forecast based on kernel-smoothed seismicity and temporal weighting. For both models, hydraulic and seismic parameters are calibrated against data from a learning period (starting at the beginning of injection) every six hours. We assess the models using metrics developed by the Collaboratory for the Study of Earthquake Predictability (CSEP): we check the overall consistency of forecasts with the observations by comparing the number, magnitude and spatial distribution of forecast events with the observed induced earthquakes. We also compare the models with each other in terms of information gain, allowing ranking with respect to a chosen model.

3D modeling of fault reactivation during CO_2 injection

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Injection or withdrawal of fluid at depth may trigger felt seismicity. Such human-induced seismicity is a key environmental concern related to exploitation of natural underground resources. Thus, understanding how to avoid triggering felt earthquakes plays a crucial role in the success of underground anthropogenic activities, such as CO_2 geological storage.

Previous 2D numerical results showed that such undetected faults could produce felt seismic events, whose magnitude is only limited by the size of the fault itself. However, 2D models overestimate overpressure acting on the fault. Thus, 3D models are necessary to reproduce the actual overpressure evolution.

In this work, we conduct 3D model simulations of injection-triggered fault reactivation. We analyze two different cases of injection—through (1) a vertical and (2) a horizontal well. Simulation results for a vertical well show the fault pressurizing faster and more locally than the case for a horizontal well, resulting in a slightly smaller seismic event. For a horizontal well, the pressure is distributed over a wider area along the fault, which requires a longer time to reactivate, but results in a slightly larger event. Fault reactivation also produces changes in damage-zone and fault-core permeability, allowing the CO_2 to leak at shallower depths. Although the calculated fault permeability enhancement is similar for the two cases, results show a slightly higher leakage rate for the vertical well in the region close to the well itself, while the leakage resulting from injection through a horizontal well is smaller, but more widely distributed.

Evolution of pore fluid pressures in a stimulated geothermal reservoir inferred from earthquake focal mechanisms

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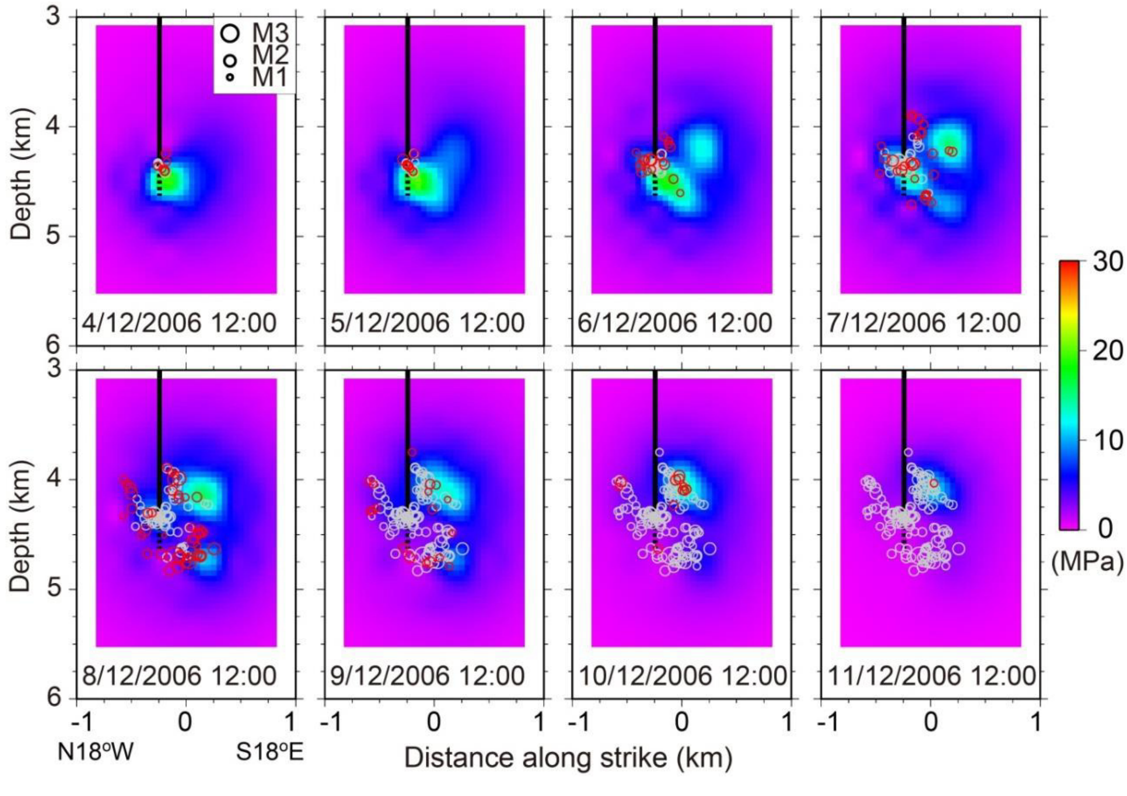
We developed an inversion method to estimate the evolution of pore fluid pressure fields from earthquake focal mechanism solutions. Application of the method to induced seismicity in the Basel enhanced geothermal system in Switzerland shows the evolution of pore fluid pressure in response to fluid injection experiments. For a few days following the initiation of the fluid injection, overpressurized fluids were concentrated around the injection well and then anisotropically propagated within the reservoir until the well was shut in and bled off. Subsequently, the pore fluid pressure in the vicinity of the well drastically decreased, and overpressurized fluids became isolated in a few major fluid pockets. The pore fluid pressure in these pockets gradually decreased with time. The pore fluid pressure in the reservoir was less than the minimum principal stress at each depth, indicating that hydraulic fracturing did not occur during the stimulation. This suggests that seismic events may play an important role in promoting the development of permeable channels, particularly southeast of the borehole where the largest seismic event (M_w 2.95) occurred. This is not directly related to a drastic decrease in fault strength at the hypocenter, but rather to positive feedback between permeability enhancement and elastic/poroelastic stress loading from slipping interfaces.



Spatiotemporal evolution of pore fluid pressure in the Basel EGS. The red and gray circles denote seismic events within the time interval half day before and after the time indicated in each panel and the earlier events. The thick black solid and dashed lines denote the borehole and the open hole section.

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2. Deichmann, N., T. Kraft, and K. F. Evans, Identification of faults activated during the stimulation of the Basel geothermal project from cluster analysis and focal mechanisms of the larger magnitude events, Geothermics, doi:10.1016/j.geothermics.2014.04.001, 2014.

Rate-and-State Model of Induced Seismicity

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One of the recent seismic activity models is based on the suggestions, that earthquakes are related with unstable sliding of the Earth crust blocks along tectonic faults (Brace, Byerlee, 1966), and that the sliding is governed by friction law of rate-and-state type with the friction dependent on the rate of the sliding (Dieterich, 1992). Usually, one-parametric type of friction dependence on the rate is considered, which corresponds to one characteristic size of the fault surface roughness. Following the works by Hobbs, 1990, Perfettini, Campillo, 2003, we suggest that the seismic processes can be described by rate-and-state equation with two-parametric dependence of friction on the sliding rate:

$$\tau = \tau^* + A\, ln(v/v^*) + \theta_1 + \theta_2$$

where v^* - parameter, τ^* - critical stress, which can be changed by fluid injection and can be written as

$$\tau^* = C + \mu(\sigma - p)$$

where C - cohesion coefficient, μ - coefficient of friction, p - pore pressure, σ- normal stress; θ_i - state variable, which characterizes the state of the sliding surfaces, and which evolution over time is determined by the equation:

$$\dot{\theta}_i = -\frac{v}{L_i}\,[\theta_i + B_i ln(v/v^*)]$$

here L_i - characteristic dimensions of the roughness of sliding surfaces, $i = \overline{1,2}$. Values of the constants v^*, A, B_i, τ^*, L_i were taken from experiments of Gu et al, 1984. An increase of the pore pressure due to injection will lead to decrease of critical shear stress, which can lead to changes in seismic regime.

In the proposed paper, the rate-and-state two-parametric equation solutions are considered under fluid pore pressure increase on 5 - 50 MPa. The obtained solutions were analyzed by means of Grassberger-Procaccia method, variation of correlation dimension and embedding space dimension due to fluid pore pressure change were considered. It was found that change of the critical stress from 5 MPa to 50 MPa resulted in change of correlation dimension and embedded space dimension from 1.1 to 2.5 and from 3 to 5, respectively. In the range of the critical stress from 5 MPa to 30 MPa the correlation dimension increases linearly with critical stress increase; at higher values of the critical stress there is a tendency of saturation of the correlation dimension dependence on the critical stress.

The same procedure of analysis was applied to data on seismicity in The Geysers area and Romashkino oil field. It was found, that in both cases the decrease in correlation and embedding space dimensions are observed after increase of injection volumes (in The Geysers case) and beginning of the oil field intensive flooding (in Romashkino case).

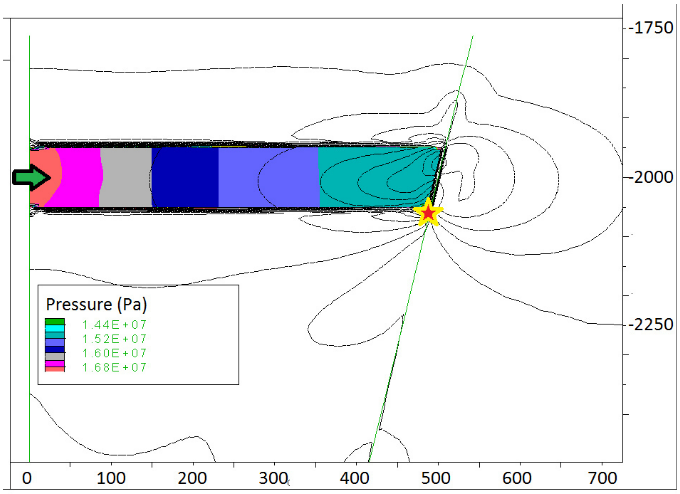
The aim of further research is to study the minimal values of the pore pressure variations that can change the state of seismic activity. We plan to investigate the solutions of the rate-and-state equation with more realistic parameters than obtained in laboratory experiments.

Fault reactivation due to fluid injection: fault friction and slip distance

Luca Urpi, University of Utrecht

Fault reactivation may happen due to fluid injection performed for various activities, among them CO_2 sequestration, gas storage, waste water disposal and engineered geothermal system.
Static stress and pressure perturbation due to the fluid injection may cause different scale earthquake phenomena, from instrumental recorded micro-seismicity to triggering of human-felt events.
The excessive load originated either by reduction of the normal stress acting on a plane of weakness or by increase in shear stress can therefore trigger rupture. If the plane of weakness is a fault, this may generate an event strong enough to be felt by the general population. However, when the rupture starts, the amount of slip, the slip velocity and the stress drop are all strongly depending on the evolution of frictional properties.
Moreover, not all rupture are seismic, since slip may also happen aseismically. Stick–slip frictional instability are associated at the laboratory scale experiment with velocity weakening process, while in numerical investigations the rate-and-state dependent friction law, empirically derived, can explain some pre-seismic and co-seismic observed behavior. To investigate the evolution of frictional parameters depending on slip velocity from the modelling point of view, the dynamic of the rupture process must be taken into account.

A numerical model has been developed to take into account for co-seismic variation of frictional properties. Scope of the model is to highlight the difference in response from a reactivated fault that may arise from different frictional behavior, for an idealized CO_2 storage scenario. The reservoir, confined within impervious rock units, is composed by a porous rock mass laterally bounded by a fault. The fault is hydraulically connected to the fluid hosting unit.
The numerical analysis is based on fully explicit sequential coupling between a multiphase fluid flow and a hydromechanical finite element calculation code. When the system conditions approaches failure, the simulation is performed in a fully dynamic mode.
The coupling allows simulating change in permeability due to stress/strain change, as well as triggering the slip on the fault, by direct pressurization and reduction of normal stress on the failure plane, or by reservoir associated stress changes.
Interface elements have been used to include the constitutive law characterizing the frictional behaviour of the fault.
The change in friction with different slip velocities has been derived from laboratory results.
Velocity- and strain-dependent frictional behavior of different patches of the fault influence the system evolution, resulting in larger or smaller slip length for the same injected volume.



Pressure distribution in the reservoir at the moment rupture is triggered on the almost vertical normal fault.

Induced seismicity due to anthropogenic activities: When does it happen (and when not)?

Mirko van der Baan, Himanshu Barthwal, Frank J. Calixto, Fernando Castellanos, Vincent Roche

University of Alberta, Edmonton, Canada

Over the last several years there has been significant public interest in possible increased earthquake hazard due to anthropogenic activities. For instance, Ellsworth (Science, 2013) finds that the number of earthquakes with magnitudes > 3 recorded in the US midcontinent has been essentially constant between 1970 and 2000. Yet, from 2010 onward the number of events per year has dramatically increased, with a deviation in trend already visible from 2003-2005 onward. The increase in earthquake rates coincides roughly with the trend reversal in oil production in the US Midwest. This raises the question if there is a causal link between increased hydrocarbon production, possibly due to increased hydraulic fracturing and waste-water disposal, and concurrent changes in seismicity rates.

Frohlich (PNAS, 2012) compares recorded seismicity in the Barnett Shale, Texas, with locations of detected seismicity. Some of the detected seismicity occurs nearby select wells in the East with large disposal volumes, yet seismicity is generally not related to known regional faults. Conversely, no seismicity occurs in the western part of the region, despite an abundance of injection wells. This raises the question under which circumstances fluid injection may increase the risk of felt seismicity and when not, since a correlation seems to be rather an exception than a general rule.

Geomechanical modeling using discrete element models (Roche and Van der Baan, JGR, submitted) shows that horizontal stresses are not a simple function of depth, but can change significantly from layer to layer. This means that failure may be counterintuitive with either weaker or stronger layers predicted to fail first, casting doubt on simple Mohr circle analyses, which generally assume homogeneous rocks and stress profiles. Comparisons with recorded microseismicity due to hydraulic fracturing treatments confirm these conclusions.

Castellanos and Van der Baan (GJI, submitted) study recorded microseismicity in an underground mine. They address three key questions: Where is the seismicity located? Why does it occur in these locations and not somewhere else? And what specifically triggers their occurrence? They conclude that for microseismic activity to occur two conditions should be met: 1) a favorable stress state in the neighboring area exists, and 2) unless the in situ static stresses exceed some critical threshold, an additional dynamic triggering mechanism must be present. The microseismicity in this mine occurs predominantly near one shaft and in the center of the tunnel network. Castellanos and Van der Baan (GJI, submitted) thus postulate that the hoop stresses around this shaft and the potential for subsidence due to the existence of the tunnels creates a favorable initial stress state. This is confirmed by the stress analysis of Barthwal and Van der Baan (in preparation). On the other hand, a correlation of detected microseismicity with rock removal implies however that the in situ static stress field is not sufficiently developed to create failure and a dynamic triggering mechanism is also required. Yet, in their study, it is not blasting but rock transportation that seems to dynamically trigger microseismicity.

Anthropogenic activities may lead to brittle failure of rocks, causing acoustic emissions. Many current investigations focus on particular wells or observations, where a positive correlation may exist between human activity and induced seismicity. While these are important and insightful observations, it does not explain when there may be an increased risk and more likely when not.

Performance comparison of surface and downhole monitoring systems in complex velocity models using synthetic waveforms

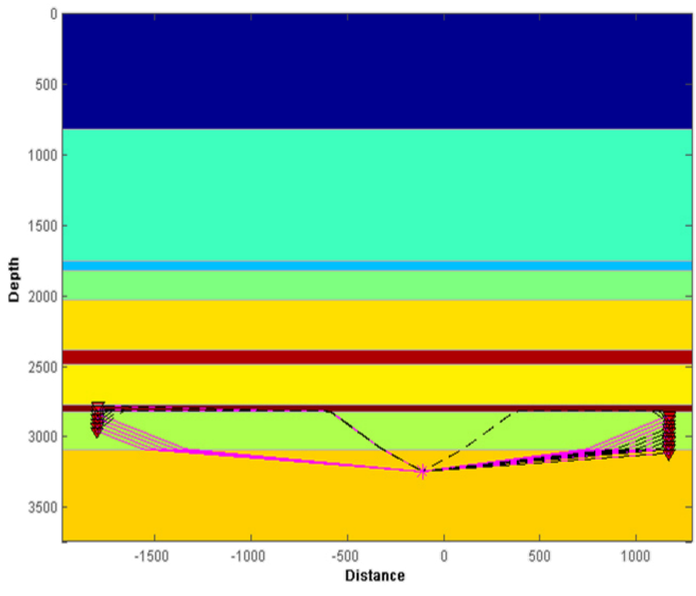
Andreas Wuestefeld, NORSAR; Kamran Iranpour, NORSAR

Considerable controversy exists in the scientific community on the benefits and disadvantages of both downhole and surface monitoring systems. While downhole systems generally show a better signal-to-noise ratio, the consensus is that stacking of large numbers of surface stations could overcome this limitation. At the same time, surface networks are more cost-effective and can cover a larger area of interest, not limited by the availability of observation wells.

Locating microseismic events strongly depends on the accuracy of theoretical arrival times. These determine the move out and eventually residual times used in the location inversion. Complexities in the model, especially high-velocity layers, introduce complex wave forms, such as head-waves. When identified correctly, these phases add constraints to the inversion and thus help to provide better location accuracy. Often the cap-rock above a reservoir is a high-velocity layer, resulting in head-waves. This renders it difficult to accurately differentiate the depths of events at the boundary of reservoir and cap rock. Accurate locations are however necessary for distinguishing whether these events occurred in the reservoir or in the caprock, which is critical information for early-warning of potential cap-rock failure.

We here compare the capabilities of downhole and surface systems by using synthetic waveforms. That way, we simulate the full acquisition and processing workflow while having control over noise levels, event location, and source parameters. Also, the inherent uncertainty of a (complex) velocity model is eliminated.

Our model consists of 2 vertical observation wells with 8 sensors within a reservoir. Above the reservoir is a comparatively thin (70 m) high-velocity layer. Additionally, we simulate a surface sensor network of 200 geophones. Microseismic events are simulated at characteristic positions within the reservoir, within the high-velocity cap-rock and above and below the reservoir. Standard processing techniques for downhole and surface networks are used independently to first detect and then locate the simulated event locations. Also, estimates of source parameters (magnitudes) are made. In the downhole case we also compare location routines allowing for head-waves and direct-wave arrivals only, respectively.



Theoretical ray paths from a microseismic event to two downhole receiver strings placed in a synthetic model (black: head-waves; magenta: direct waves). The event is placed below a simulated reservoir of lower velocity. Depending on the event location, head waves will travel through the thin cap-rock of higher velocity (color background: P-wave velocity model).

Discrete Element Modeling of Fluid Injection Induced Seismicity and Fault Zone Slip

Jeoung Seok Yoon, Amir Hakimhashemi, Arno Zang, Günter Zimmermann, Oliver Heidbach, GFZ Potsdam

Occurrence of relative larger magnitude seismic events induced by fluid injection in Enhanced Geothermal System (EGS) development, e.g. the Mw=3.2 event in 2006 in Basel EGS, has initiated an on-going debate on the potential risk in EGS development by fluid injection. In order to better understand the physics behind and to enable prediction of occurrence of larger magnitude events by fluid injection, various modeling tools have been developed. As one of many modeling methods, this numerical modeling study presents 2D discrete particle joints model by Particle Flow Code 2D (Itasca).

The objective of the study is to investigate evolution of seismicity and slip of fault zone induced by a nearby fluid injection. Injection of fluid into a geothermal reservoir with granitic rock mass properties and with an inclined through-going fault zone is tested. The physics of the fault zone behavior is modeled explicitly by combination of fault core fractures and damage zone. The reservoir model is in 2D and generic but its parameters are adapted to the setting of the geothermal reservoir rock mass in Soultz-sous-Forêts (France) and Basel (Switzerland).

We investigate numerically how fluid injection at different locations under different stress regimes affect the characteristics of the induced seismicity in terms of (i) shape of the evolution cloud, (ii) frequency-magnitude distribution, (iii) slip potential of the fault zone, (iv) spatial and temporal changes in the Gutenberg-Richter *b* value in relation to occurrence of larger magnitude seismic events.

Preliminary modeling results show that fluid injection at 200 m distance from the fault zone centre induces seismicity within the fault damage zone and slip of the fault fracture by small amount of fluid pressure perturbation (0.01<Pf<0.1 MPa). The modeling result shows that after the well shut-in the pressurized fluid migrates into the fault damage zone and reduces the frictional strength of the core fractures. Movement of the fault zone, therefore, is triggered which led to a seismic events of which the magnitude is larger than those induced by the fluid injection. Magnitude-frequency distributions of the seismicity catalogue shows progressive transition from a fracture dominated characteristics (lower magnitude events, high b-value) to a fault related characteristics (larger magnitude events by fault slip, low b-value) as the pressurized fluid migrates into the fault zone and causes slip of the fault fractures by reducing their frictional strength (Fig.1).

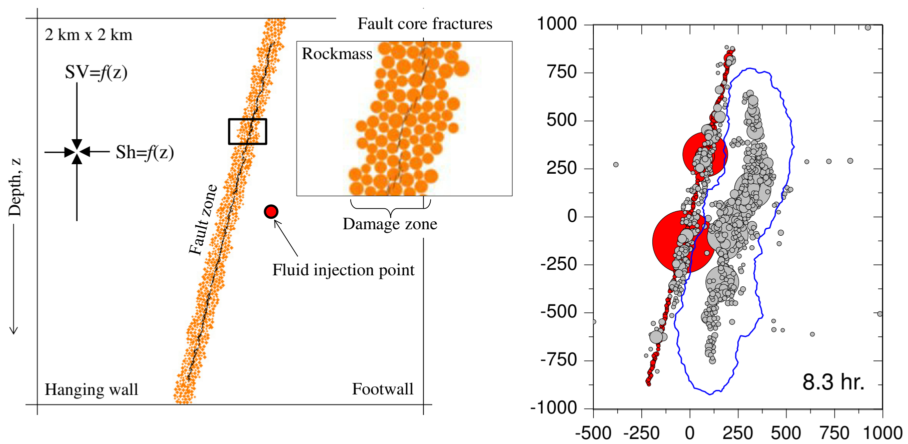


Fig.1. (Left) Geothermal reservoir model in 2 km x 2 km size with though-going fault zone (damage zone + fault core fractures) and subjected to normal faulting stress regime (SV>Sh) with both stress components varying with depth. (Right) Induced seismic events by fluid injection (within the 0.01 MPa fluid pressure contour, blue) and seismic events in the fault damage zone (gray) and the fault core fractures (red) triggered by the fluid injection, beyond the 0.01 MPa fluid pressure contour (blue).

Abstracts Posters

Session 4

Scaled Experiments
Underground Labs, Petrophysical Labs

Earthquake source parameters and scaling relationships at The Geysers geothermal field, California

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Understanding induced seismicity in a geothermal system can help to characterize the geometry, extent and conditions of the reservoir, and to assess the potential seismic hazard associated with field operations. Here we present the results of source parameters' analysis of induced seismicity at The Geysers geothermal field in Northern California recorded from 2007/07/26 through 2011/10/30. We have originally analyzed the P- and S-wave displacement spectra of 1274 micro-earthquakes, in the seismic moment range $1x10^9$ – $1x10^{15}$ Nm, recorded at the dense Lawrence Berkeley National Laboratory Geysers/Calpine (BG), surface seismic network, to estimate source and attenuation parameters. However, the natural frequency of instruments and the signal-to-noise ratio limited our analysis to a total of 266 micro-earthquakes having seismic moments in the range $1x10^{10}$ – $1x10^{12}$ Nm. To study seismic source parameters we have used a parametric modeling approach, which is combined with a multi-step non-linear inversion strategy (Zollo et al., 2014) that allows to jointly invert source and attenuation parameters, together with site/station correction.

We determined seismic moments, source radii and static stress drops from P-wave and S-wave displacement spectra assuming a four-parameters spectral model and a constant-Q attenuation factor to account for anelastic attenuation. We observe a self-similar scaling of the estimated source parameters in the whole investigated seismic moment range, with a nearly constant Madariaga (1976) static stress-drop of 1.74(0.79, 3.83) MPa (Figure 1a). We also found that stress-drop varies with depth delineating the seismogenic layer between the average and maximum depth of the injection wells located in the study area.

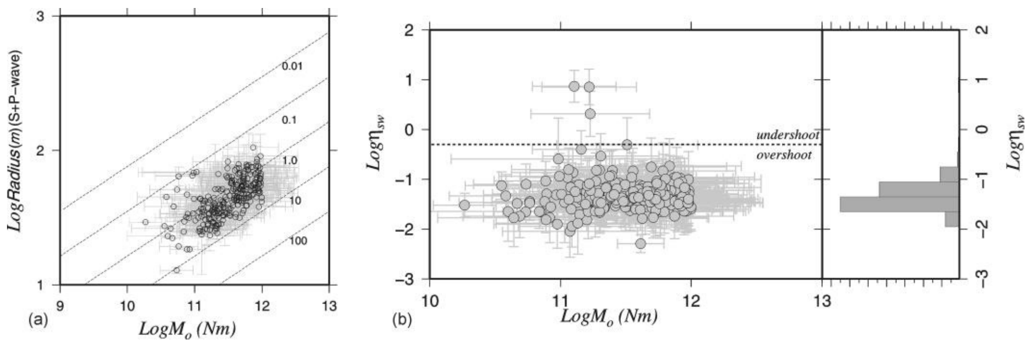


Figure 1. Panel a: Madariaga (1976)' source radius as a function of the seismic moment (in log-log representation) and associated uncertainties. Dashed lines refer to the theoretical constant stress-drop values expressed in MPa. Panel b: Savage–Wood seismic efficiency *vs* seismic moment (in log-log representation) and histogram of the observed values.

The results of the analysis indicate that a constant Q model can be used to represent the anelastic attenuation in the investigated volume. We found median P and S quality factors equal to Q_P=75 (53,104) and Q_S=65 (44, 96), respectively (the 68.8% confidence intervals are given in parenthesis), which provide a Q_S/Q_P ratio close to unity (median value Q_S/Q_P =0.9±0.2). For the seismic source, we found that the mean value of the high-frequency fall-off parameter γ for both P- and S- wave is consistent with the ω-square source model. A nearly constant apparent stress τ_a of 0.073 MPa, 68.8% confidence interval given by (0.027,0.197) MPa, as measured by seismic energy, is observed in the whole analyzed seismic moment range. The median values of the S-to-P corner frequencies (f_c^P/f_c^S=1.52) is consistent with the dynamic model of an expanding circular crack at a constant stress drop scaling. The distribution of the estimated Savage-Wood seismic efficiency –η_{SW} median value of 0.04 (0.02, 0.1) – indicates a rather small radiation efficiency (Figure 1b) suggesting that a large positive dynamic overshoot could be the dominant mechanism the micro-earthquake fractures in the volume investigated in the present study.

Small-scale Reservoir Stimulation Experiments in the Deep Underground Laboratory at the Grimsel Test Site

Authors: Valentin Gischig, Joseph Doetsch, Mohammadreza Jalali, Claudio Madonna, Florian Ammann, Swiss Competence Center for Energy Research - Supply of Energy (SCCER-SoE), ETH Zürich

As a response to the Swiss government decision of fading out nuclear power by 2034, research and development in GeoEnergy has become a major topic in the Swiss energy research. As part of the work-package one of the newly-founded Swiss Competence Centre for Energy Research – Supply of Electricity (SCCER-SoE), we are currently planning a small-scale stimulation experiment in the Grimsel Test Site (GTS) – the rock laboratory dedicated to research on nuclear waste depositories and run by NAGRA. The granitic rock mass at the GTS has similar characteristics to those expected at potential enhanced geothermal system (EGS) sites in the deep underground (ca. 4-5 km) of the Swiss Plateau, and thus can act as a proxy for potential future EGS sites. The objectives of the experiment are to explore 1) the interaction of hydro-fractures with the natural fracture system, 2) permeability and connectivity enhancement resulting from hydro-fracturing and hydro-shearing, 3) stress and pressure changes associated with stimulation and 4) induced seismicity characteristics during different stimulation procedures. The GTS rock laboratory provides favourable conditions for such an experiment, because low fracture density and the wealth of information available from previous experiments allow construction of a near-deterministic rock mass model. Hence, the small scale and clear geological conditions provide us with maximum control on boundary conditions and evoked processes, the possibility to design an optimal monitoring system, and, at the same time, ensure that risk related to induced seismicity is low.

The experiment comprises a rock mass volume of a few tens of meters in diameter that includes both intact rock as well as rock that is dissected by pre-existing sub-vertical fault zones. In a sub-vertical injection borehole, stimulation is performed in short packed intervals that include either intact rock, where hydro-fractures are created, or natural faults along which hydro-shearing is induced. Due to the proximity of the intact rock portions to natural faults zones, interaction between hydro-fractures with the natural fractures is expected. Fans of both sub-vertical and sub-horizontal boreholes distributed around the experiment volume contain a comprehensive monitoring system that records hydraulic processes (e.g. transient pressure changes), mechanical processes (e.g. stress, deformation and fracture dislocation) as well as induced micro-seismic activity during and after stimulation. Induced and natural micro-seismicity will be monitored using a multi-scale approach, consisting of seismological surface stations, rock-laboratory scale installations and experiment-specific monitoring in nearby boreholes. In addition, rigorous hydraulic characterization and characterization of the stimulated rock mass by means of geophysical imaging are performed before and after stimulation. Hence, the experiment is designed such that stimulation processes – like fracture propagation and interaction, seismic and aseismic slip front propagation, shear dilatancy, and the resulting enhancement of permeability and fracture connectivity – are recorded in a dataset that is unique in induced seismicity research and could not be obtained from stimulation experiments in inaccessible deep reservoirs typically targeted for EGS.

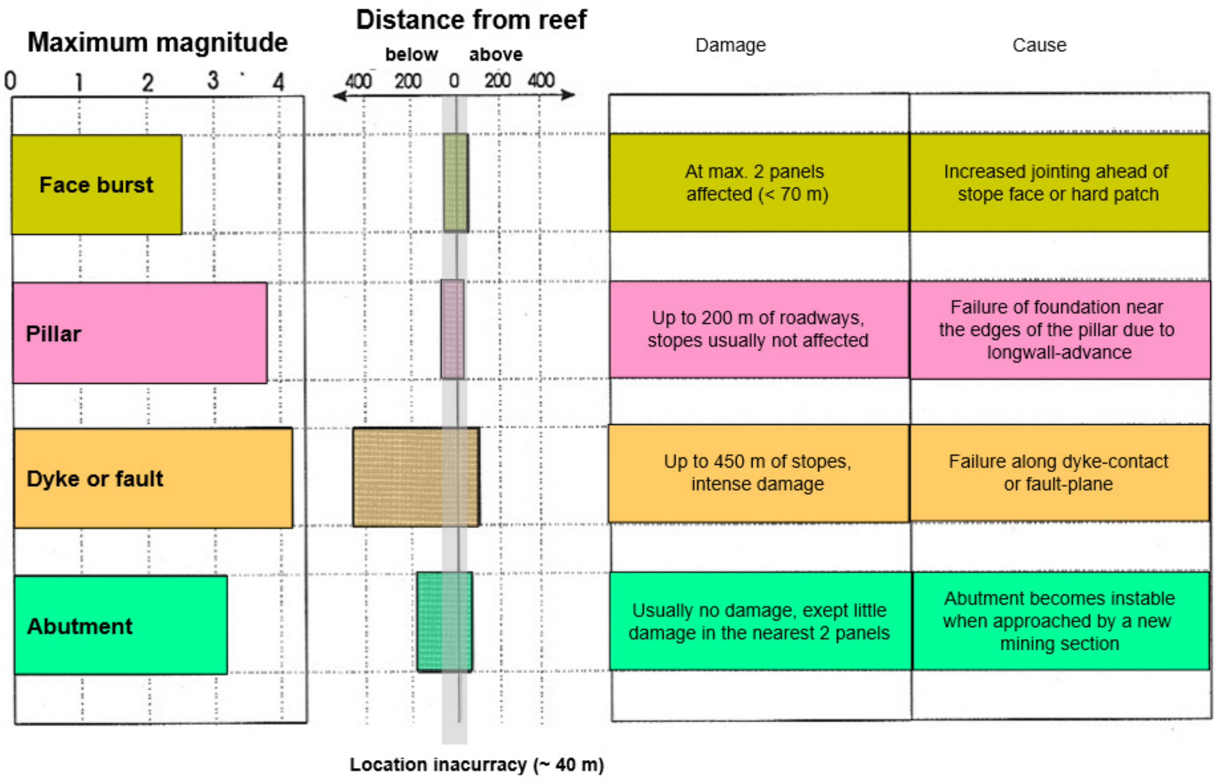
In this contribution, we outline the experiment design and discuss our choice of geometry, monitoring strategies, characterization procedures and injection protocols. We further present results from pre-experiment investigations, such as the (hydro-)geological model extracted from NAGRA reports, stress field characterization, seismic monitoring network design, and preliminary results from geophysical imaging.

Rockbursts at Great Depth

Wolfgang A. Lenhardt, Zentralanstalt für Meteorologie und Geodynamik (ZAMG)

As mining progresses to greater depth, the stress regime changes, whereby vertical stresses become dominant and stress concentrations around mine openings intensify. These circumstances not only increase the seismic hazard underground, but also show diversified expressions of prevailing and induced stresses brought about by creating mine openings, such as stopes.

Despite classic slips along zones of weakness, such as faults and dyke-contacts, which show clear double couple mechanisms, facebursts, pillar and abutment failures add to the complexity of seismic observations in deep mines. Facebursts, considered as a result of hard patches along the stope face, can release a limited amount of energy only due to the available strain energy stored in the ultimate vicinity of the mine opening. In contrast, pillar and abutment failures involve much larger volumes when becoming distressed during such an event. All event categories constitute a potential hazard for mining personnel and can cause considerable production losses and even damage buildings on surface, given the magnitude exceeds 3,0. Few examples from an ultra-deep mine environment are presented.



After: Lenhardt, W. A. 1992. Seismicity associated with deep level mining. Acta Montana, Series A, No.2 (88), 179-192.

In-situ Observation of Micro-crack Evolution during Large-scale Gas-loading Experiment

K. Plenkers (1), D. Dörner (1), J. Philipp (1), T. Popp (2)

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In-situ Acoustic Emission (AE) Monitoring allows to record (induced) seismicitiy in mines and underground laboratories significantly below the micro-seismicity scale. Magnitudes Mw < -4 are recorded, which corresponds to micro-damage on cm-scale. Therefore In-situ AE Monitoring allows to observe small-scale migration and deformation processes in high resolution that are often missed in other environments like deep boreholes.

We present here the results of a large-scale gas injection experiment that was conducted in the Merkers salt mine/Germany (depth interval 300m to 380m), where In-situ AE Monitoring is successfully used for the assessment of potentially induced damage processes. The main purpose of the geo-mechanical experiment was to test the gas tightness of rock salt around a wide-diameter borehole (1.3m diameter, 60m extension) that is subject to high gas pressurization (until the order of acting minimal stress).

The AE monitoring network employed consisted of twelve AE sensors sensitive mainly in the frequency range from 1 to 100 kHz, situated in four monitoring boreholes located approximately 15m from the center line of the wide-diameter borehole. Data was recorded on a fast data-acquisition system with a sampling rate of 1MHz per channel. The system developed by GMuG performed automated P- and S-wave picking as well as in-situ localization in (near) real-time and stored all waveforms of detected events.

The monitoring took place over a period of more than 2 years thus covering the rock response in all different stages of the experiment: 1) pre-excavation 2) excavation 3) partial backfill with Sorel concrete to create gas tight seal and 4) high gas-pressure loading. In total more than five million events were recorded.

In this study we present the temporal and spatial distribution of AE events recorded. During excavation and backfilling the event rate increased steeply. Up to nearly 200.000 seismic events per day are recorded. After these operations the daily event rate returns with time to a low activity rate of approximately 300 events per day. The temporal-spatial evolution of the excavation damage zone is shown as well as the migration process of heat and humidity after backfilling.

No substantial increase in AE activity was initially observed in the gas-pressurization stage when compressed air (total gas volume 50m3) was pumped stepwise into the borehole. When pressures reached 68 bars a cluster of more than 251 seismic events occurred. Whereas seismic activity in all phases before was focused on the direct vicinity of the large-diameter borehole, this cluster spread over distances up to 15m (reaching the monitoring boreholes) from the wide-diameter borehole within an approximately 2m-thick zone. The seismic cluster was accompanied by a brine and gas break-through to two of the monitoring boreholes and a significant drop in pressure.

The fluid outflow as well as the pressure decrease stopped after 14 days, when gas pressure reached back 56 bars. No evidence for the formation of a macro-fracture was found, which clearly contradicts to a gas-frac scenario in salt. The cluster activity before the breakthrough is interpreted as the result of changes in permeability owing to increased connectivity of micro-cracks.

Abstracts Posters

Session 5

Risk Governance, Societal Acceptance, and License to Operate

Risk pre-assessment phase for deep underground laboratory: hazards, consequences and dependency mapping

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A comprehensive risk governance framework is vital for decision making under deep uncertainty and risk management related to enhanced geothermal systems, including the induced seismic risks. Development of such a risk governance framework is one of the integrative activities of the new Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE). The SCCER-SoE has been established to develop basic research and innovative solutions in the domains of GeoEnergies (enhanced geothermal systems and carbon capture and storage) and HydroPower.

As described by Renn (2008) and the International Risk Governance Council (2005), the risk governance process is composed of four consecutive phases: pre-assessment, appraisal, characterization/evaluation and management. In all of these phases, risks are approached from the natural sciences and engineering perspective and from the perspective of social sciences and societal decision making (Krütli et al., 2010). Risk communication accompanies all four phases. This risk governance framework starts with the pre-assessment phase, where the risk problem is framed and defined, analyzing what risks need to be analyzed in detail in next phases. Perspectives of the societal actors, such as scientific community, governments and general public, need to be combined in order to integrate expertise and values-based perspectives of the practitioners.

In this context, this study serves two purposes. First, it briefly introduces the comprehensive risk governance framework that is being developed for GeoEnergies and HydroEnergies within SCCER-SoE. Second, it presents in more detail the approach for the risk pre-assessment phase, where the relevant and important risks for further appraisal are analyzed. The approach is illustrated with the case of the deep underground laboratory (DUG Lab) in Grimsel, Switzerland. DUG Lab is the site for stimulation and circulation experimental research and aims to collect data on induced seismicity related to deep geothermal systems. Risk pre-assessment phase for DUG Lab focuses on hazards, consequences and dependency mapping.

For hazards, consequences and dependencies mapping, a set of Hazards, *H*, a set of Consequences, *C*, and a set of dependencies, *E* are identified. The latter ones can be interlinks between elements of different sets *H* and *C* and/or intralinks between elements of one set. Starting from a selection of elements of *H*, *C* and *E*, a graph is mapped out. For DUG Lab, this assessment is conducted on the basis of internally available expert knowledge from different disciplines, involved in the SCCER-SoE program and on the basis of literature overview. The experts of SCCER-SoE are asked to select subsets of *H*, *C* and *E*. In this manner, a collection of graphs is identified. Different graphs represent different frameworks for the same task; a big dispersion in the network shape and topology leads thus to larger model uncertainty reflecting disagreement or lack of knowledge of the problem. On the other hand, a small dispersion of the graph structure indicates a good understanding of and general agreement on the model, which translates into a smaller model uncertainty.

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Abstracts Posters

Session 6

Monitoring and Analysis of Induced Seismicity

4D imaging of elastic/anelastic medium properties: application to the Geyser geothermal area

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In this study we present innovative tools for 4D (space and time) seismic monitoring of complex fault systems and of the embedding medium, with an application to The Geyser geothermal field in California, USA.

Crustal faults are complex natural systems whose mechanical properties can evolve with time due to short-term changes in the local stress field, temperature or fluid percolation. Reliable monitoring and studying of the physical processes that can trigger earthquakes along a segmented fault system require an accurate knowledge of the geological medium in which the earthquake fractures develop. The reconstruction of the medium properties in terms of elastic/anelastic rock properties can be performed through the seismic *imaging* by modeling the body-wave arrival times. In particular, to locate induced seismicity and characterize the geometry and conditions of the reservoir in a geothermal system, the modeling of space-time evolution of the seismicity is very important.

We propose to recover the medium properties by using two different approaches. The first approach includes the analysis of temporal variations of the near-station/source V_P/V_S ratio and of P and S arrival-time residuals. Both the analyses use the arrival times of the P and S phases (possibly measured by waveform cross-correlation) and allow detecting average, large-scale changes in elastic medium properties. The second approach is based on the 3D seismic tomography that allows to image crustal heterogeneities (i.e. the position, extension and intensity of anomalies) using local earthquake data. In particular, very striking results for the P- and S-wave velocity models can be obtained by performing a simultaneous inversion of P- and S-wave arrival times to estimate the event location coordinates, the origin times, and P- and S-wave velocities at the nodes of a 3D discretized volume. The anelastic imaging can be obtained in terms of Q_P and Q_S attenuation models, through the attenuation tomography technique. In fact, starting from the observed $t*$ (i.e., the ratio between travel-time and quality factor Q) it possible to perform a linear inversion, following a scheme very similar to the tomographic inversion in velocity.

Possible time variations of the seismic properties of the propagation medium can be observed, through the time-lapse tomography, consisting in applying the three-dimensional tomography at consecutive time-windows (epochs). In order to use this technique a proper temporal subdivision of the seismic catalogue is critical. This is because differences in the acquisition layout may significantly perturb the retrieved velocity images. For this purpose, we performed a preliminary analysis aimed at providing a 3D average velocity model and its resolution. These results represent the benchmark for the analysis of tomography resolution in the individual epochs.

The adaptive selection process of the temporal duration of an epoch consists in selecting a time window and uses the relative arrival-time data set to perform a 3D tomography. For each epoch, the result is evaluated and compared with the resolution obtained for the 3D average model. The optimal time-window length and acquisition layout are chosen in order to guarantee the same resolution level in each of the selected time-lapses. Since earthquakes location provides primary information on the geometry of the structures on which they are generated, we propose to apply a probabilistic approach in a 3D propagation medium to obtain accurate hypocenter location (accuracy from tens to hundreds of meters).

The methods described above will be applied to The Geysers geothermal field, an enhanced geothermal system, which has been actively exploited since the 1960's and it is now the most productive geothermal field in the world. With increasing field development also the seismicity increased in the area. For the present studies we compiled a waveform database of 15476 events recorded at Lawrence Berkeley National Laboratory Geysers/Calpine stations between 2007/07/24 and 2011/10/30, and associated to earthquakes in the catalog of the Northern California Earthquake Data Center (NCEDC).

Velocity ratio variations in the source region of earthquake swarms revisited: application to 2011 and 2014 sequences in West Bohemia using waveform cross correlations

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Crustal earthquake swarms are an expression of intensive cracking and rock damaging over periods of days, weeks or month in a small source region in the crust. The localized stressing of the crust is often associated with fluid or gas migration, possibly in combination with pre-existing zones of weaknesses. Dahm and Fischer (2013) have applied the so-called double-difference Wadati method (see also Lin and Shearer, 2007) to the arrival times of mid-crustal earthquake swarms of 1997, 2000 and 2008 in West Bohemia. This robust method enables to estimate the velocity ratio between *P*- and *S*- waves (v^P/v^S-ratio) in the source region of an earthquake activity. A strong temporal decrease of v^P/v^S down to 1.4 before and during the main activity of the swarms, and a recovery of v^P/v^S to background levels at the end of the swarms was found. The anomalies were interpreted in terms of the Biot-Gassman equations, assuming the presence of oversaturated fluids degassing during the beginning phase of the swarm activity.

In this study we extend the analysis to the recent earthquake activities: swarm 2011 and three mainshock-aftershock activities of 2014. In order to achieve higher accuracy and more detailed resolution in time and space we use delay times between pairs of events derived from waveform cross-correlations. We find that both these seismic sequences are accompanied by temporal decrease of v^P/v^S
ratios, which are localized in space. This indicates possible presence of gas phase in the fault zone during rupturing and points to localized fluid movement at depth during the swarm generation, which could be related to the triggering mechanisms of earthquake swarms in question.

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Magnitude-frequency distribution of induced and tectonic seismicity in the Upper Rhine Graben/Germany

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Seismic activity in the densely populated Upper Rhine Graben/Germany (URG) is an important issue for the public, politics, and industry. The spatial analysis of magnitude-frequency distributions of both, tectonic and induced seismicity, provides valuable information about local seismicity pattern and seismic hazard assessment.

The URG is a NNE-SSW striking continental rift north of the Alpine mountain chain in the German-French-Swiss border region and it is one of the active seismic regions in Central Europe. Its total length is about 320 km from Basel/Switzerland in the south to Frankfurt/Germany in the north. We use *b*-value variations of the tectonic seismicity along the URG to separate four distinct sections with significant differences in earthquake magnitude distributions: the Basel region in the Swiss-France-German border region (*b*=0.83), the region between Mulhouse and Freiburg in the southern URG (*b*=1.42), the central URG (*b*=0.93), and the northern URG (*b*=1.06).

According to this separation, the geothermal power plants of Landau and Insheim are located in the transition of the central URG to its northern part. The seismic network in their surrounding detected 1.982 induced events between September 2009 and August 2013 with magnitudes as low as M_L -1.0. We analyse the *b*-value of the magnitude-frequency distribution for several periods of induced seismicity and compare it to the local tectonic activity level.

The return period of a tectonic earthquake $M_L \geq 0.0$ for an area of 10 km^2 - as it is affected by the geothermal power plants in Landau or Insheim - is three years. However, induced seismicity at the Landau site reveals within the four years of observation a seismic activity of 28 events per year with $M_L \geq 0.0$ (*b*=0.65), which corresponds to an increase of a factor 100 compared to the average tectonic activity. A similar estimation for the Insheim power plant results in even ten times higher rates for induced events $M_L \geq 0.0$ (*b*=1.15). Further analysis of the various phases of activity also reveal a strong difference in the seismic response of the two nearby geothermal sites of Landau and Insheim, that might be due to different reservoir characteristics and injection histories.

Site Effects and their Impact on Microseismic Surface Arrays

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The use of surface arrays for microseismic monitoring provides a number of advantages over downhole arrays, which are related to their azimuthal, spatial and cost benefits. Due to the greater relative distance from the source and the variable nature of the near surface, significant levels of both signal attenuation and amplification can however occur. Surface array datasets therefore require more laboured processing in order to suitably enhance the signal, sometimes requiring migration style processing in order to lower the detectability limit. Some of the benefits of greater azimuthal and spatial coverage from surface arrays include more robust source-mechanism inversion and the improved measurement of seismic anisotropy. An important component of these processes is the determination of particle motion, which requires consistent and reliable estimations of motion across the array.

Site effects, and their relationship to local geological conditions, have become an important area of study for earthquake hazard assessment. Modification of the ground motion as a result of the near-surface structure can produce frequency dependent amplification, with some studies showing cases with amplifications of a factor of 10. These effects have also been shown to be very localised, and can vary significantly across a large surface array. Several methods have been developed to assess localised site effects, with the Nakamura H/V method one of the most common approaches used. This method uses the spectral ratio of the vertical and horizontal components to estimate the fundamental resonance frequency of a site, through the assumption that the vertical component amplitude does not change significantly compared with the horizontal components.

Different methodologies to assess site effects have been used on a number of locations in order to determine the frequency dependent site effects. Inversion to compensate for these effects have been carried out and the results on particle motion considered. These results suggest that the validity of using the Nakamura H/V method to correct for the influence of localised site effects is dependent on the specific structure of the site. Compensating for these effects is shown to have an impact on particle motion, and future research will investigate the impact on different processing methods.

Analysis of sources and possible effects of anthropogenic seismicity in Argentina, Colombia and Mexico

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A new, international, inter-institutional, interdisciplinary, initiative is being developed in order to study the seismic activity manifestations in the vicinity of several hydrocarbon projects (conventional and no-conventional) in several Latin-American countries.

ASAP - **A**nalysis of **S**eismicity induced by **A**nthropogenic **P**rocesses in Latin-America and Caribbean is a new project, which main goal is the analysis of the potential relationship between earthquakes and hydrocarbon exploitation processes, in order to get a better understanding of how these processes may affect the earthquake background, trigger seismicity and change the tectonic behavior in the Latin-American region.

The principal locations of study are: Outcrops of the Vaca Muerta shales (Argentina), Outcrops of the Middle Magdalena Valley Shales (Colombia), and Outcrops of geothermal fields (Mexico).

The aspects, which make this study relevant, not only for three mentioned countries, but, in general, for Latin-America and Caribbean region, and why we are presenting the preliminary results of it here, are:

1) New records of unexpected seismic activity, which was not registered before.

2) New initiatives for exploration and production of non-conventional hydrocarbons, which are implemented in this region.

3) Close location of these kinds of exploration and production processes to urban and semi-urban centers.

4) Concern of people about the influence of this sort of processes in the lack of stabilization of sites where these processes are carried out.

5) Concern of communities about the effect of these kinds of processes on the local belongings and traditions.

6) These sorts of exploration and production processes are carried out in the whole Latin-American and Caribbean region.

ASAP Project invites other Latin-American interested institutions to join this initiative.

The 2013 M_L 3.5 earthquake sequence of St. Gallen (Switzerland): A Mesozoic fault system activated by stimulations of a geothermal reservoir

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In July 2013, stimulation operations of a potential geothermal reservoir triggered a series of earthquakes close to the city of St. Gallen, Switzerland. The sequence culminated in an M_L 3.5 earthquake, which provoked the discussion on the feasibility of hydrothermal power plants targeting fault zones in tectonically active regions such as the northern Alpine Foreland of Switzerland. In this study we apply high-precision earthquake relocation to image the response of the fault system during well operations. Absolute depths of hypocenters are calibrated by a joined interpretation of seismic velocities of the source region and a lithological model derived from borehole and 3D seismic data. Our results suggest that the M_L 3.5 event as well as the majority of microseismicity occurred on a NE-SW striking fault system in the Mesozoic sediments.

In the early phase of the sequence, microseismicity spreads over the future M_L 3.5 fault patch in immediate response to hydraulic and acid stimulations. We interpret this seismic activity as preparation-phase, in which increasing pore-pressures and chemical reactions weaken the fault gouge material. While seismicity prior to the M_L 3.5 rupture as well as its fault patch are limited to the targeted fault segment, earthquakes migrated more than 1 km beyond the segment imaged by 3D seismics in the weeks following the M_L 3.5 event. In combination with the complex spatio-temporal evolution of the sequence, we conclude that distinct pathways for fluids exist in the targeted fault system, which connect to other segments and cannot be modeled by 1D diffusion processes.

Cross-correlation traffic light systems for Induced Seismicity; an example of an operational single station detector in Ohio

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Traffic Light Systems introduced in geothermal monitoring and used for monitoring induced seismicity are now a necessary tool in monitoring waste-water injection sites where seismicity can be a concern to operators and local residents.

Examples of such systems deployed in British Columbia and Great Britain rely on dense surface seismic arrays installed over the injection regions. Sufficient density of the surface arrays allows traditional earthquake detection and location techniques to work well. However, deploying dense networks in an urban environment is expensive and time consuming and may not be necessary. In Britain and US state of Ohio, the thresholds at which operators must take action are at very low magnitudes (0.5 and 1.0 respectively) currently require a sensitive network of seismometers to achieve. Any techniques that can be used to reduce the number of stations needed, yet provide reasonable accuracy of location and magnitude will facilitate the use of seismic monitoring at waste injection sites by industry and regulators, and in turn help researchers to get a better understanding of induced seismicity.

Cross correlation detectors with template events have been used successfully to identify earthquakes where traditional STA/LTA detector methods often fail due to low signal to noise ratios. Furthermore, seismicity induced by fluid injection has shown to have remarkable similarity between earthquakes at different scales, particularly in 6 cases observed in Ohio (e.g. Friberg et al, 2014; Skoumal et al, 2014) where individual faults have been activated. This characteristic, combined with the ability to lower the magnitude threshold of detection by 2 orders of magnitude make cross correlation techniques ideal candidates for use in a traffic light system to monitor induced seismicity. In our work we have developed a near real-time single station 3-component cross correlation detector algorithm that uses a robust statistical approach to identifying events and determining magnitudes. When combined with a traditional STA/LTA detector in the Earthworm processing system, a cross correlation detector can provide a traffic light system with as few as 5 stations. In our presentation we demonstrate the use of a single station detector in two cases, a hydraulic fracturing operation and an waste water injection site in Ohio.

Microseismic monitoring in advance of geothermal projects in the northern Upper-Rhine Graben: borehole noise studies and swarm events

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The seismicity of the northern Upper-Rhine Graben and its seismic hazard have recently attracted new attention due to the potential of this region for geothermal power generation. The characterization of the natural seismicity in this region well in advance of a geothermal project is one of the main goals of the project SiMoN (Seismic Monitoring of the Northern Upper-Rhine Graben), which is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). We present new results for the microseismic activity in an area of approximately 50 km^2 by analyzing seismogram recordings from a temporary network of up to 13 broad-band stations in combination with data from permanent stations. The network was recently expanded by several borehole stations to accommodate for the relatively high noise levels in the densely populated Rhine-Main region. Systematic measurements in over 40 shallow boreholes (up to 30 m depth) in the study area were used to determine the local seismic noise and its lateral and vertical variations. Ongoing measurements in three up to 70 m deep boreholes are used to lower the detection threshold in the graben. Results of the noise measurements and their implications for a possible monitoring of induced seismicity in the area are presented.

Starting in November 2010 we have recorded a number of 195 local earthquakes within the immediate vicinity of the network with magnitudes ranging between M_L = -0.5 and M_L = 4.2. The detection threshold of the whole (surface) network is a local magnitude of approximately 1.0; the magnitude of completeness is M_c = 1.3. Since May 2014 swarm earthquakes occur southeast to the city of Darmstadt in the northern Upper-Rhine Graben. During the period from May to August 2014 we have recorded more than 110 earthquakes with a maximum magnitude of M_L = 4.2. We identified two source clusters with distinct differences in source mechanisms and spatial distribution. The hypocenters within these clusters are aligned vertically extending over a depth range from 1 to 8 km with a lateral extent of about 2 to 3 km. A depth migration with time is not obvious. In fact, this is the first time in more than 150 years that such a swarm activity has been reported within the region of the northern Upper-Rhine Graben. Historical accounts from the 19^{th} century report of over 2000 felt earthquakes between the period from 1869 to1871 with maximum intensities of VII according to the EMS-98 scale.

Feasibility of using ambient seismic noise for CCS monitoring

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Longyearbyen, on the remote Svalbard archipelago, is a closed energy system with a coal power plant fuelled by local mines, and geological structures suited for CO_2 sequestration. For this reason, it provides a unique opportunity to demonstrate the entire CO_2 production and sequestration chain. Accordingly, the Longyearbyen CO2 Lab (hosted by University Centre in Svalbard, UNIS) conducts CO_2 Capture and Storage (CCS) research since 2007. In 2010, a short-period geophone network has been installed surrounding the test injection well. During the first water injection, one event (M~1) was recorded followed by a series of aftershocks. However, later injection test did not produce any detectable microseismic events, although the pressure and flow rate exhibited a pattern that is characteristic for fracture opening, indicating potentially the occurrence of slow-slip events.

Microseismic monitoring used to infer pore pressure variations or the development of a fracture network from the spatio-temporal distribution of microearthquakes has the disadvantage of only being applicable during periods of seismic activity. Therefore, particular reservoirs, where significant deformation may occur aseismically (Cornet et al., 1997), require monitoring also during periods of seismic quiescence.

Over the last years, the estimation of the Green´s function between sensors constructed from the ambient wave field (e.g., Campillo et al., 2006), has become a standard tool for subsurface imaging. Examples include monitoring the evolution of stimulated geothermal reservoir properties using the ambient seismic field (Hillers, 2014), which has recently shown to provide critical observables complementary to microseismic monitoring.

We conducted a feasibility study to determine the applicability, benefit, and resolution power of noise-based imaging methods at the Longyearbyen CCS site. To this end, we analysed the frequency-dependent wave field properties as well as the spatial and temporal distribution of noise sources employing data recorded on the SPITS array (installed by NORSAR in 1992 and consisting of 9 broadband stations) and on a local temporary network consisting of 12 broadband stations (60 s and 20 s), installed around the CCS site from May to September 2014, covering the period of the most recent injection experiment.

The f-k analysis of continuous SPITS records, when filtered in specific slowness windows, shows distinct directional patterns with very abrupt seasonal changes: body wave phases dominate throughout the year (from southwest direction), but during the summer, a strong signal from surfaces waves invading from SSE direction becomes visible. Also the symmetry of cross-correlation functions (computed with the Whisper code; Briand, 2014) varies with time, which also may indicate a variation in the direction of noise sources. A time-domain technique to estimate relative velocity changes ("stretching technique") applied in the 1-4 Hz frequency band seems to reveal seasonal changes in medium velocity. However, Zhan et al. (2013) criticise that at the small level where temporal variations of seismic velocities are detected by ambient seismic cross-correlations, temporal variations in the properties of noise sources may also cause apparent velocity changes.

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New seismic risk assessment: evaluation of the cumulative fault area under critical state based on microseimic information

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Occurrence of induced seismicity with large magnitude is critical environmental issues associated with fluid injection for shale gas/oil extraction, waste water disposal, carbon capture and storage, and engineered geothermal systems (EGS). Studies for prediction of the hazardous seismicity and risk assessment of induced seismicity has been activated. Many of these studies are based on the seismological statistics and these models use the information of the occurrence time and event magnitude.

In this study, taking a different approach to the previous studies based on seismostatistical theory, we originally developed the risk assessment model based on the more physical information from microseismic events. We named our new model as "Slip-able area (SAA)", which means the summation of the fault areas which is under the condition to have shear slip. As the model name suggested, SAA needs the information of fault area of each seismic event. In addition to fault area, the occurrence time and hypocenter location are used for estimation SSA. This model can forecast the cumulative fault area which can release seismic energy in the near future by comparing the observed data of fault area. SSA can be transformed into the moment magnitude. Estimation of SSA can be evaluated by using the result of semi real analysis of microseimic event. Therefore, SSA model can contribute to the risk assessment of the large seismic event in short term (one or two days) or middle term (week).

SAA is described as equation (1): simple product of slipped area density and stimulated volume.

$$A_{slip}=K * V_{stimu} \qquad (1)$$

A_{slip} is the cumulative SAA, K is slipped area density, and V_{stimu} is the stimulated rock volume by fluid injection. K is estimated by the sum of fault area of the seismic events occurred within the target area. Target area and time step to determine A_{slip} are defined by the case by case and field. V_{stimu} is defined as the rock volume where permeability was enhanced by the fluid stimulation. So, V_{stimu} is estimated by distribution of the hypocenter location by counting the number of grid cubes containing at least one seismic event. Finally, A_{slip} is calculated and compared with the observed fault area. Difference between A_{slip} and cumulative observed fault area can be regarded as the fault area which will have shear slip in future.

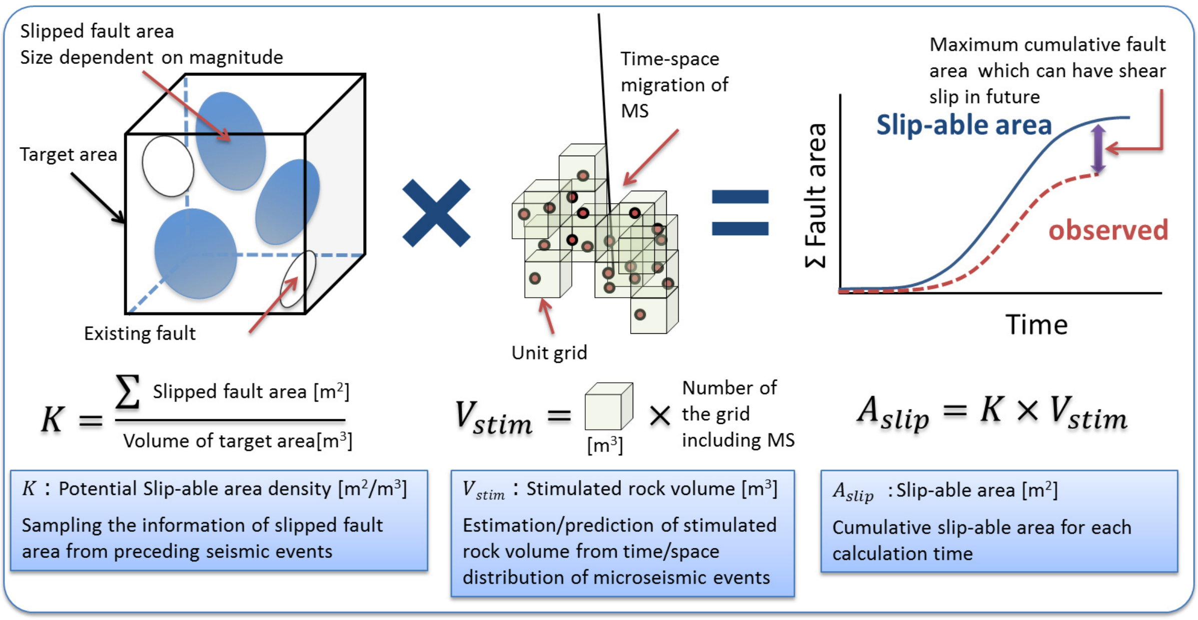

Figure 1: The concept of the Slip-able area model.

Evaluation of seismic source parameters and short-term seismic hazard for rock bursts in deep underground mines (LKAB, Kirunavaara mine, Sweden)

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A study was conducted on forty six mining-induced seismic events that occurred between 2008 and 2013 with moment magnitude between -1.8 and 2.1 in Kirunavaara Mine (Sweden) in a block with dimensions approximately 500 x 600 x 500 m at depth between 850 and 1350 m. All studied events caused damage underground. 90% of events occurred in the mine footwall. The seismic events were recorded by the underground seismic monitoring system consisting of almost 250 sensors. P- and S-wave arrivals were manually picked from the waveforms. The number of sensors that recorded the events varied between 6 and 130. The hypocenter locations and the dynamic source parameters were re-estimated using the IMS Trace software.

The seismic events were separated into non-shear events (NS) and shear (fault slip) events (FS) based on the calculated Es/Ep ratio. Fifteen of the processed events indicated to have a non-shear source mechanism with Es/Ep ratio less than 10, ranging between 1.2 and 8.9. The remaining thirty two events indicated a fault slip source mechanisms with an Es/Ep ratio ranging between 11 and 126. The moment magnitude of the NS events varied between -1.2 and 1.7. Comparatively larger values for the moment magnitude were obtained for the FS events, between -1.3 and 2.1. The source radius for the NS events varied between 4 and 65 m, and for FS events between 3 and 110 m. The stress drop for the NS events varied between 0.08 and 2.2 MPa, and for the FS events between 2.1 and 11.0 MPa. The NS events were distributed randomly throughout the studied volume but the FS events were concentrated in a comparatively small area.

Twenty five out of all studied events were selected for further seismic hazard back analysis to evaluate the merits of the short-term seismic hazard indicators (precursors) and their potential application for early warning using the MxRap software. The temporal variations of indicators like: Energy Index (EI), Cumulative Apparent Volume (CAV), Seismic Activity Rate (SAR), Apparent Stress Frequency (ASF) and Cumulative Seismic Moment (CSM) calculated for the seismic events one week before the seismic event within the focal sphere defined by the source radius, were studied. The results showed a very good agreement between the expected and actual behavior of the indicators for 23 events. For two of the events the behavior in ASF was not as expected but this could be due to the fact that some of the orepass events were not filtered out completely and remained within the focal sphere. The changes in the parameters (indicators) behavior started 5 days before the studied event occurred and 3 days before they showed more prominent behavior. The EI and CAV parameters were found to be very good indicators 5 days before events in most cases. The possible relationship between the seismic events with blasts shortly before the seismic events was investigated.

The results from this study will be used for further improvement of the short-term hazard estimations and early warning system in the mine.

Ahtomatic P- and S-phase travel-time determination of induced events based on an AR-AIC-Costfunction approach

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Dr. Ludger Küperkoch, Bestec GmbH, Landau

The rapid automatic travel-time determination is essential for the quick and consistent processing of large datasets and precise event localizations. Various automatic picking algorithms have been proposed since the 1970s of which classes can be separated. The earliest attempts are based on the envelope of the waveform and the short-term-average to long-term-average (Allen [1978], Baer & Kradolfer [1987]). Since the 1980s and 1990s several publications proposed automatic picking with autoregressive-prediction and the Akaike-Information-Criteria (Tjøstheim [1975], Takanami & Kitagawa [1988], Küperkoch et al. [2012]), higher-order-statistics (Saragiotis et al. [2002], Küperkoch et al. [2010]) cross-correlation (VanDecar & Crosson [1990]) and combinations of these (Bai & Kennet [2000]). The picking algorithms have been tested and applied on teleseismic and regional scales. Furthermore it is applied in the context of the MAGS2-project on data of a dense network monitoring the induced seismicity in the deep geothermal reservoirs of the power stations Landau and Insheim. Precise localizations and further characterizations of the events are crucial for a better understanding of the reservoirs and its dynamics. Thus, for the processing and re-processing of the database a precise, quick, automatic picking algorithm is the first essential step.

In this work a picking algorithms is proposed which identifies the phase with the AIC calculated on the characteristic function, which is the autoregressive-prediction-error of the waveform. It further provides precise picks by a cost function consisting of the characteristic function and side conditions. Furthermore, an automatic evaluation of the pick qualities is implemented. This is essential to identify imprecise picks in waveforms with low signal to noise ratio or no visible phases from reliable picks.

For the application on a dataset of 437 induced events recorded at 11 stations of the local network, the algorithm determines 1012 good quality P-phase- and 914 good quality S-phase travel-times. These automatic P-picks show an average residual travel-time to the manual picks of 0.04s and a standard deviation of 0.1s. In total, the automatic S-picks are not biased compared to manual picks and the standard deviation of the residuals to manual picks is 0.15s. Thus, for this dataset the automatic P- and S-picks are consistent and of a high precision such that they can be used for further event characterization procedures.

The automatic picking procedure is furthermore applied on the whole dataset around the Insheim reservoir and the events are re-localized with the automatic determined travel-times. Results of this automated processing and a comparison to the manual processing results are shown.

Tremor mapping at the Groningen field

Elmer Ruigrok, Hanneke Paulssen and Jeannot Trampert: Utrecht University

The Groningen gas field is a giant natural gas accumulation in the northeastern part of the Netherlands. The gas is present in a reservoir at a depth of about 3 km. The gas-filled sandstone extends about 45 by 25 km laterally and 140 m vertically. Decades of production have led to significant compaction of the sandstone. The (differential) compaction is thought to reactivate existing faults and therewith to be the main driver of induced seismicity (NAM, 2013).

The current seismic network (Fig. 1) has been designed to detect and locate all (impulsive) events with $M_L>1.5$ (van Eck et al., 2006). Precise location is difficult due to a complicated subsurface. Amongst others, the induced wavefield is perturbed by a heterogeneous salt layer on top of the reservoir. Likely due to unprecise location, the current hypocentre estimates do not clearly correlate with a well-known fracture network (Kraaijpoel and Dost, 2013). Our current research focuses on detecting also the non-impulsive seismicity and finding preferential locations of these tremors. This could lead to identification of the reactivated faults.

High-resolution location could be achieved by using (complete) Green's functions between potential source positions and receivers. For travel paths through the overburden (the subsurface above the reservoir) such Green's functions could be estimated from available surface seismic data. However, most receivers have a much larger lateral than vertical distance to a reservoir-depth source. Consequently, preferred travel paths are refractions over high-velocity layers below the reservoir. Yet, the subsurface below the reservoir is poorly known. Therefore, we start with a pragmatic detection and localization scheme. From past seismicity we assimilate one average shotgather and determine from it the average slowness of the most energetic refraction. Next, we crosscorrelate day-long recordings over the network. Surface waves and other unwanted arrivals are suppressed by cross-component crosscorrelations (van Wijk et al., 2011), bandpass frequency filtering, and taking advantage of borehole array measurements. Subsequently, we map the crosscorrelation-derived traveltime differences to space, using the dominant refraction slowness and apply an imaging condition. This yields day-maps of seismic activity, including both tremor and transient sources. These maps are compared with conventionally located seismicity and known fault networks. We discuss the resolution and detection threshold for the new maps.

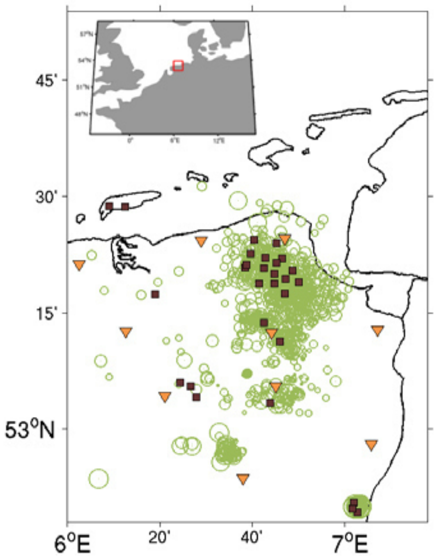

Fig. 1: Map of the Groningen area with locations of induced seismicity (green circles, source KNMI), geophones (orange triangles) and accelerometers (purple squares). The inset shows NW Europe with the Groningen area indicated with a red rectangle.

Acknowledgements

We kindly acknowledge the Royal Netherlands Meteorolgical Insititue (KNMI) for providing us with the field data.

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Swarm or induced: Comparing natural and induced seismicity at the Coso geothermal field

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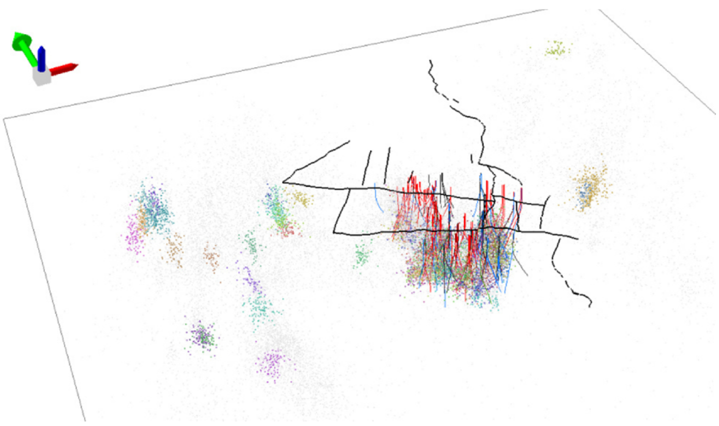
Increased levels of seismicity coinciding with injection of reservoir fluids have prompted the demand for methods to distinguish induced seismicity from natural seismicity. Discrimination between induced and natural seismicity is especially difficult in areas that have high levels of natural seismicity, such as the geothermal fields at the Salton Sea and Coso. Both areas show swarm-like sequences which are thought to be connected to deep fluid flow. Therefore, swarms often have spatio-temporal patterns that resemble fluid-induced seismicity, and might possibly share other characteristics.

The Coso geothermal field is one of the most seismically active areas in California, with most of its activity occurring as seismic swarms. Here we analyze clustered swarm seismicity surrounding the produced reservoir and compare it to induced seismicity adjacent and below the geothermal wells. We perform a cluster analysis, based on the inter-event distance, in a space-time-energy domain to identify notable earthquake sequences. For each event, the closest previous event is identified and categorized. If this nearest neighbor's distance is below a threshold, the event is included in the cluster as a child-event to this nearest neighbor and called the parent event. If it is above the threshold, the event begins a new cluster.

We apply this method to three different catalogs: a two-year microseismic survey of the Coso geothermal area that was acquired before exploration in the area began; the HYS_catalog_2013 that contains 58,000 double-difference relocated events and covers the years 1981 to 2013; and a catalog of 57,000 events with absolute locations from the local network recorded between 2002 and 2007. Using this method we identify 10 clusters with more than 20 events in the pre-production survey and more than 100 distinct seismicity clusters that contain at least 50 and up to more than 1000 earthquakes in the more extensive catalogs. The cluster identification method used yields a hierarchy from the links of several generations of parent and offspring events. We analyze different topological parameters of this hierarchy to better differentiate natural swarms from induced clustered seismicity and also to identify aftershock sequences of notable mainshocks.

We find that the branching characteristic given by the average number of child-event per parent event is significantly different for natural swarms than for induced earthquake clusters.



Local catalog of the 2002-2007 seismicity with identified clusters drawn in distinct colors. The figure is centered on the geothermal reservoir with wells drawn in red (production) and blue (injection).

Shear-tensile/implosion source model vs. moment tensor: benefit in single-azimuth monitoring. Case study of Cotton Valley hydrofracture treatment

Jan Sileny, Inst. of Geophysics, Academy of Sciences, Prague

Moment tensor (MT) has become a standard for description of seismic sources, both in earthquake seismology and for various types of induced seismicity. It is a general dipole source, but for practice it may be too general, its generality causing troubles during its reconstruction from noisy data in the inverse process, which may be additionally ill-conditioned due to inexact hypocenter location and/or availability of a rough velocity/attenuation model only. Then, the retrieved source may be biased. It seems reasonable to assume a simpler source model directly describing the physical phenomena anticipated in the particular focus. A simple combination of a shear slip with a tensile crack or 1D implosion (STC) may be a good model both for natural earthquakes and induced events. The model simplification introduced is crucial in cases of depleted sensor configuration when the moment tensor fails, in single-azimuth monitoring in particular. This is just the case of application in oil and gas industry, where the monitoring of seismicity induced by hydrofracturing is typically performed from a single monitoring borehole. Then, MT is able to provide constrained solutions only (e.g. deviatoric), but STC detects also non-shear component correctly, providing important information on increase of permeability of the reservoir. The success in the reconstruction however depends of the type of the mechanism: from the model cases of a vertical strike-slip and 45^0 dip-slip the resolution of the former is limited taking into account an inexact modeling of velocities in the test site, while the latter is determined well anyway.

By re-processing of the strong events induced by the gel hytrofracturing of the treatment well within the Cotton Valley 2-monitoring-well experiment we tested the two-well vs. hypothetical single-well inversions. In most cases the resolution of the mechanism in terms of confidence regions was better from two-well inversion as anticipated, the opposite case probably indicates inconsistence of observations from well 1 and 2. Gross features as for both the orientation and the off-plane slip component were however mostly the same, which demonstrates that the STC model is well applicable even in single-well inversions where the traditional MT model fails by definition.

Optimizing Multi-Station Template Matching to Characterize Induced Seismicity

Robert J. Skoumal, Michael R. Brudzinski, & Brian S. Currie, Miami University

Due to the large scope of wastewater injection and hydraulic fracturing, it is important to quickly classify induced seismicity from naturally occurring events that occurred in proximity to industry activities. Multi-station waveform cross-correlation is an excellent tool for identifying similar/repeating seismic events, but its application has been limited due to the large computational cost of the routine and that many seismic sequences have inherent variability. By creating a highly optimized routine, we were able to identify the optimal parameters (template length, filter frequencies, station configurations, etc.) involved in the procedure. Applying our routine to the wastewater induced sequence in Youngstown, Ohio yielded 566 events, while other template matching studies have found ~100-200 events. We also identified 77 events caused by hydraulic fracturing near Lowellville, Ohio which included a M 3 event, the largest hydraulically fractured induced event to occur in the United States. In addition to identifying induced events, we have also been able to characterize naturally occurring seismicity in Ohio that occurred near wastewater injection wells. Due to the efficient nature of the routine, the technique has been applied to monitor induced seismicity in the midcontinent of the United States. Our routine uses pre-existing seismic networks and is therefore a cost-efficient method of monitoring induced seismic events.

Preliminary Analysis of the Aquistore, Boundary Dam Carbon Capture and Storage Project Passive Seismic Data

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1. School of Earth Sciences, University of Bristol, Bristol, U.K. 2. Geological Survey of Canada, Ottawa, Canada

The Bounday Dam project, Saskatchewan, Canada, is the world's first commercial power plant carbon capture and storage (CCS) project. CO_2 capture began at the plant in October 2014 and the start-up of CO_2 injection is planned for January 2015. The passive seismic monitoring set-up at the CCS site is unrivalled in this sector with baseline data available since July 2012 from an array of 51 vertical component geophones buried 20m deep. In addition, three three-component Guralp 40T broadband stations provide data since November 2013. The instruments cover a ~1.5km x ~1.5km area, approximately centred around the injection well.

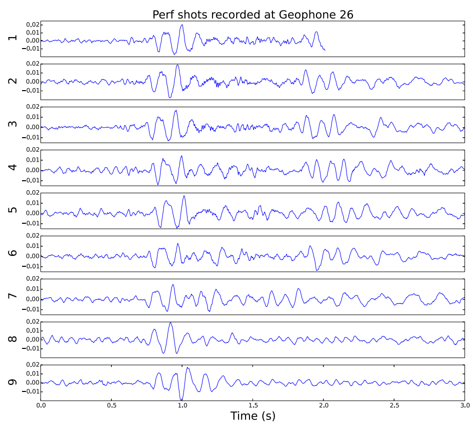
Our preliminary analysis of the baseline data identifies several sources of noise associated with industrial activity at the power plant, around the wells and traffic on nearby roads. Through the inspection of data throughout 2012 and 2013 we make the following observations:

- There are noise sources at or near the injector well with dominant frequencies 10–15 Hz.
- There are other noise signals with frequencies around 5–6 Hz. These have been observed at a variety of receivers in the array but are not normally seen on recordings of more than 5 instruments at once and it is not thought they originate from seismic activity.
- Noise with frequencies 10–20 Hz that lasts between a few seconds and 100s seconds.
- Signals thought to be associated with traffic on a road running approximately N-S close to the west end of the array (~150m west) have amplitudes approximately 10 times larger than background noise.
- Broadband station recordings exhibit noise amplitudes up to 5 times higher during the day than at night.

This characterisation will enable noise removal and allow any seismic events to be more easily identified once injection begins.

This baseline analysis has also allowed us to calibrate our event detection, location and magnitude estimation procedures using perforation shots in the injection well and reported regional events. We use a standard STA/LTA picking algorithm to detect nine out of 13 perforation shots (see figure below). The shots were made 14–16 September 2012 at depths 3173m – 3366m below the surface. Unfortunately only three shots were fired when 10 or more geophones were recording. The first six shots have the same sized source and the associated signals are very similar. We calibrate our 1D local and near-regional velocity models, developed from well log and seismic refraction results, respectively, using perforation shots and magnitude > 2.0 regional events. The detection limit of the array is $M_w \sim -1$ for events at injection depths but the completeness magnitude is likely to be higher.

With near real-time analysis of the passive seismic data we will report and characterise any induced seismicity associated with CO_2 injection to improve understanding of the geomechanical response of the site to injection and inform injection activities.



Understanding the role of fractures in hydraulic stimulation from anisotropic attenuation measurements of microseismic waveforms.

P. J. Usher, University of Bristol

J-M. Kendall, University of Bristol

Microseismic monitoring is increasingly used in the monitoring of hydraulic fracture stimulations, reservoir depletion, enhanced geothermal systems, mining operations, and carbon capture and storage projects. These industries require monitoring to understand complex processes that happen in the subsurface. An example is microseismicity caused by the interaction of rocks, pore fluids, injected fluids and fractures, both natural and anthropogenic. If we can understand these complex systems better, we make these energy industries more efficient and reduce their environmental impact.

Standard microseismic monitoring techniques focus on locating microseismic events or investigating the focal mechanisms of the microearthquakes (Rutledge et al., 2004). Shear wave splitting analysis goes a step further and investigates the anisotropic velocity of the medium, which may be enhanced by the development of aligned fracture sets (Wuestefeld et al., 2011). Attenuation measurements provide further insights into fluid and fracture properties. As an example, Kelly et al. (2013) used clusters of earthquakes to measure changes in attenuation with time. They showed how a large earthquake can affect fluids within the natural fractures around the fault system. Modelling of squirt flow within partially filled fractures provides a mechanism to explain this (Chapman, 2002). Hence attenuation and velocity anisotropy can be explained by the interaction of the fluids and fractures.

We consider a dataset from Cotton Valley, East Texas. We use the log spectral ratio method to look at temporal changes in attenuation, in both the fast and slow S-wave. The log spectral ratio method measures Δt^*, a relative measurement of attenuation with respect to the path length between two waveforms.

Our results show Δt^* increases for the slow S-wave (Fig. 1) for a sequence of events that also show an increase in shear wave splitting delay time. In contrast the fast shear wave for the same events shows no increase. This measurement is consistent for different reference events, and the increase is significantly larger than that caused by differences in path length.

We concluded that the attenuation measurements show an increase in fracture density for the Cotton Valley hydraulic fracture experiment. The results also show that attenuation is anisotropic because it is different for different S wave phases. Attenuation measurements could be used to understand the roles of fluids and fractures in a number of reservoir settings.

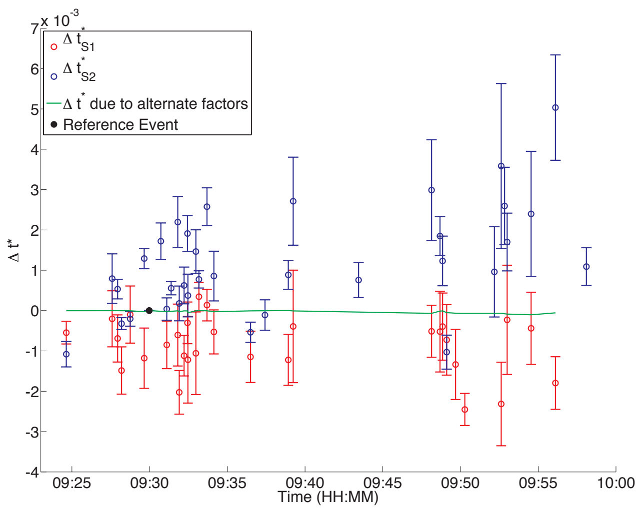


Fig. 1: The change in attenuation with time for the fast S-wave (S1) and slow S-wave (S2). The S2 increases with time whereas S1 does not.

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Time reversal stacking of P and S waves to determine location and focal mechanism of microseismic events recorded during hydraulic stimulation

Josef Vlcek, Tomas Fischer, Jan Vilhelm. Faculty of science, Charles University in Prague

We present an automatic method of processing microseismic monitoring data acquired at the surface by a very dense star-shaped array using the back projection approach that allows simultaneous determination of hypocenter position of events and of their focal mechanisms. We employ the availability of both – denser deployed vertical component geophone groups to use P-waves and sparsely deployed three-component accelerometers to use both P and S-waves. Hypocenter coordinates are searched in a grid by time-reversal stacking of the short-time-average to long-time-average ratio of absolute amplitudes at vertical components and polarization norm derived from horizontal components of P and S-wave, respectively. To make the location process more efficient we start with coarse grid and zoom to the optimum hypocenter using an oct-tree algorithm. The focal mechanism is then determined by stacking the vertical component seismograms corrected for the theoretical P-wave polarity of the focal mechanism, which is searched in the space of strike, dip and rake angles. We test the method on 34 selected events of a dataset of hydraulic fracture monitoring of a shale gas play in Northern America. We find that by including S-waves the vertical uncertainty of locations improves by a factor of two and equals approximately the horizontal location error. A twofold enhancement of horizontal location accuracy is achieved if a denser array of geophone groups is used instead of the sparse array of 3C seismometers.

Monitoring Geothermal Systems on an Actively Deforming Volcano

Matthew Wilks, J-Michael Kendall, Andy Nowacki & James Wookey. University of Bristol.

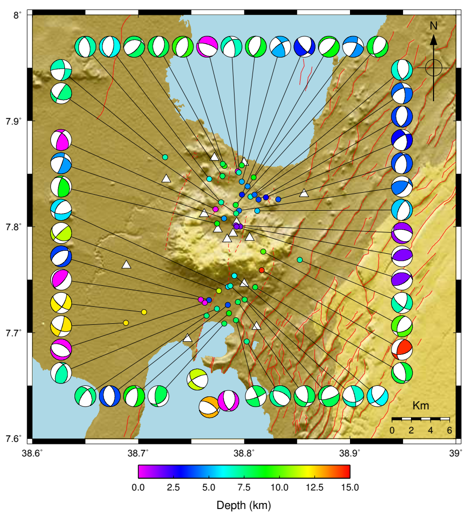
The volcanic centres of the Main Ethiopian Rift (MER) are known to play a central role in facilitating continental rifting during the ongoing extension of the crust. Recent InSAR studies have shown that a number of these axial volcanoes are deforming, but the region has remained relatively understudied south of 8°N despite this activity. Furthermore, many of the volcanoes have shown potential to generate geothermal power, where subsurface magma bodies are thought to heat the hydrological system and provide an abundant, renewable energy resource.

One such volcano is Aluto, where the first geothermal power plant in Ethiopia was built in the 1990s. Aluto is located in the Central MER towards the eastern rift escarpment and between Lakes Ziway to the north and Langano to the south. Despite the known capability of geothermal and hydrothermal systems to induce seismicity, Aluto has not received any previous seismic monitoring in spite of the large, proximal population to it. As a consequence a local network of 12 three-component seismometers was deployed at Aluto in January 2012 and recorded the seismic activity for a two-year period.

Over the duration of the project, 1361 events were detected within a 15 km radius from the centre of the caldera. Events are located using a 1D velocity model where the upper 2300 m of the model is derived from borehole data. A crustal tomographic velocity model of the MER is used at greater depths. A double difference relocation algorithm has been used to refine the locations and yields 574 well-located events in the region. Event depths range from the near surface to a maximum of 15 km. Most of the seismicity is clustered around the edge of the caldera, suggesting ring fault patterns, but a significant amount of seismicity also follows the NNE-SSW trending Wonji Fault Belt east of Aluto. Gaps in seismicity are observed at depths between ~2 km and ~6 km that we suggest could represent a region of enhanced ductility and correspond to the hydrothermal reservoir. Deeper events are most likely associated with magmatic processes.

A local scale developed for the MER has been used to assess event magnitudes. These range from M_L=-0.40 to M_L=2.98, with a b-value of 1.40, a value consistent with studies of other volcanoes around the world. Furthermore, we observe seasonality in the shallow seismicity and suggest the occurrence of a time lag of around 130 days between the periods of peak rainfall and the induced seismicity that follows.

Focal mechanisms for the 53 events are produced using P- and S-wave polarities and amplitude ratios. The majority of our obtained source solutions represent normal faulting, which agrees with the extensional setting of the rift. Many solutions however do not reflect the assumed subsurface structure and we also derive thrust and strike-slip events that further highlight the complex environment around this dynamic volcano. At present a link between periods of power generation and seismic activity is not supported by the data but future work will examine their relationships in greater detail.



Abstracts Posters

Session 7

Industry Projects and Future Initiatives

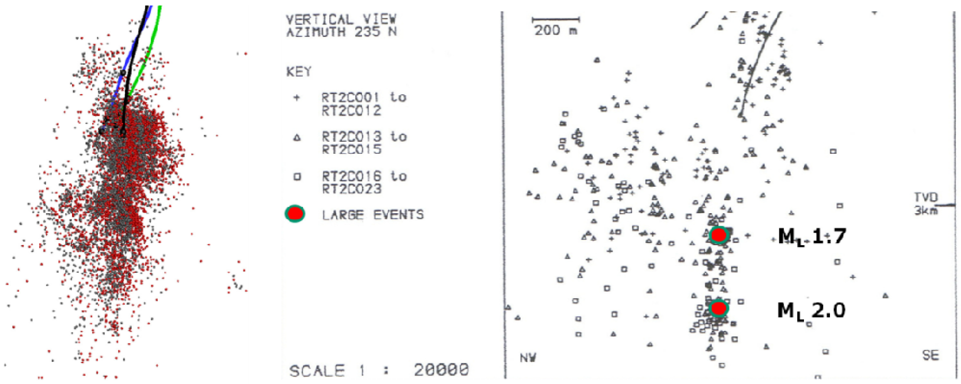
Title: The role of probability based models in EGS Hazard assessment

Andrew Jupe, altcom Limited, Penzance, Cornwall, UK (andy.jupe@altcom.co.uk)

The presentation will initially consider the current approaches to hazard assessment in EGS (Engineered Geothermal Systems) development. It will discuss some of the physical bases for these approaches and the practical implications for EGS operations. It will then focus on the potential for probability based seismicity models, both in terms of estimating the maximum event size and the longer-term possibility for implementation of real-time adaptive "traffic light" systems.

Probability based models are of practical interest to EGS developers because, unlike deterministic fault models, they do not require a detailed knowledge of fault parameters, hydro-mechanical interaction within the reservoir or the seismic rupture process. However probabilistic models not only require an *apriori* statistical sample, but also confidence that large events are not somehow "anomalies" or "special" events, but are part of a continuous statistical and scalable distribution. This latter assumption appears inconsistent with the current concept of "induced" and "triggered" seismicity. The implication being that "induced" events are part of some continuous statistical distribution, whereas "triggered" events are anomalies, related to some specific, and sometimes unknown, large-scale structure.

To illustrate this potential ambiguity the presentation will consider a specific example of apparently "anomalous" seismicity from the UK Hot Dry Rock EGS Project (Rosemanowes) in the 1980's. The largest event was M_L 2 and was felt locally. This was one of a small number of "large events" that appeared distinct in terms of both magnitude and focal mechanism compared to the 5000+ other "induced" events. Consequently there was an ongoing debate as to whether the large events were in fact anomalies or a statistically "predictable" result of the long-term EGS injection operations.



A present-day implication is whether it is justifiable to adopt a probability based hazard assessment approach for planned EGS development within the region, or whether a purely deterministic approach is necessary that takes into account a detailed knowledge of local geological and tectonic conditions, with its high associated exploration demands.

Recent re-analysis of the Rosemanowes data suggests that the large events were in fact consistent with the same statistical relationship between seismic energy release and injected fluid volume as the bulk of the microseismicity, and also with the range of focal mechanisms expected from the interaction of injected fluid, stress regime and fracture distribution. It can therefore be demonstrated that the large events observed at Rosemanowes should not be considered anomalies, but as a statistical and geomechanical consequence of the overall net fluid loss within the subsurface.

This example is significant because it illustrates the care that needs to be taken when distinguishing between "induced" and "triggered" seismicity. It also strengthens the justification for the use of probability based models and the potential for real-time adaptive "traffic light" systems.

Empirical Ground Motion Prediction Equation for Induced Seismicity related to Hydraulic Fracture Stimulation

Adam Baig, Ted Urbancic

Public perception of induced seismicity related to different injection processes is becoming more of an issue in recent years due to a number of well-documented case studies, mostly associated with waste-water injections but with some reports of association directly with hydraulic fracture stimulations. While in most cases of injections, particularly where instrumentation is deployed to characterize the seismicity, the size of these type of events is small enough not to be felt on the ground, there are reports of higher magnitude events which have been sensed by the local population and in extreme cases are strong enough to lead to damage to vulnerable structures. Seismic hazard evaluation requires empirical ground motion prediction equations (EGMPE) which relate event parameters like magnitude and location to site characteristics such as peak ground acceleration (PGA) or peak ground velocity (PGV). The local hazard assessment could estimate more precisely by developing and using local EGMPEs.

In this paper a new EGMPE is developed by using induced seismicity data. The dataset is related to recording hydraulic fracture stimulations utilizing eight surface stations over two years period for a reservoir at approximately 2.5 km depth in the Horn River basin. Each station is equipped with both force-balanced accelerometers (FBA) and 4.5Hz geophones deployed near surface. This dataset contains ~12000 records from 817 events with moment magnitude ranges from 0.2 to 2.9 and hypocentre distance from 2550 to 10000 m (figure 1). This magnitude-distance range is poorly covered by existing ground motion equations and present ones are associated with mining or enhanced geothermal systems. The rich database with homogenous moment magnitude from just hydraulic fracturing stimulation procedure is the base of the new model.

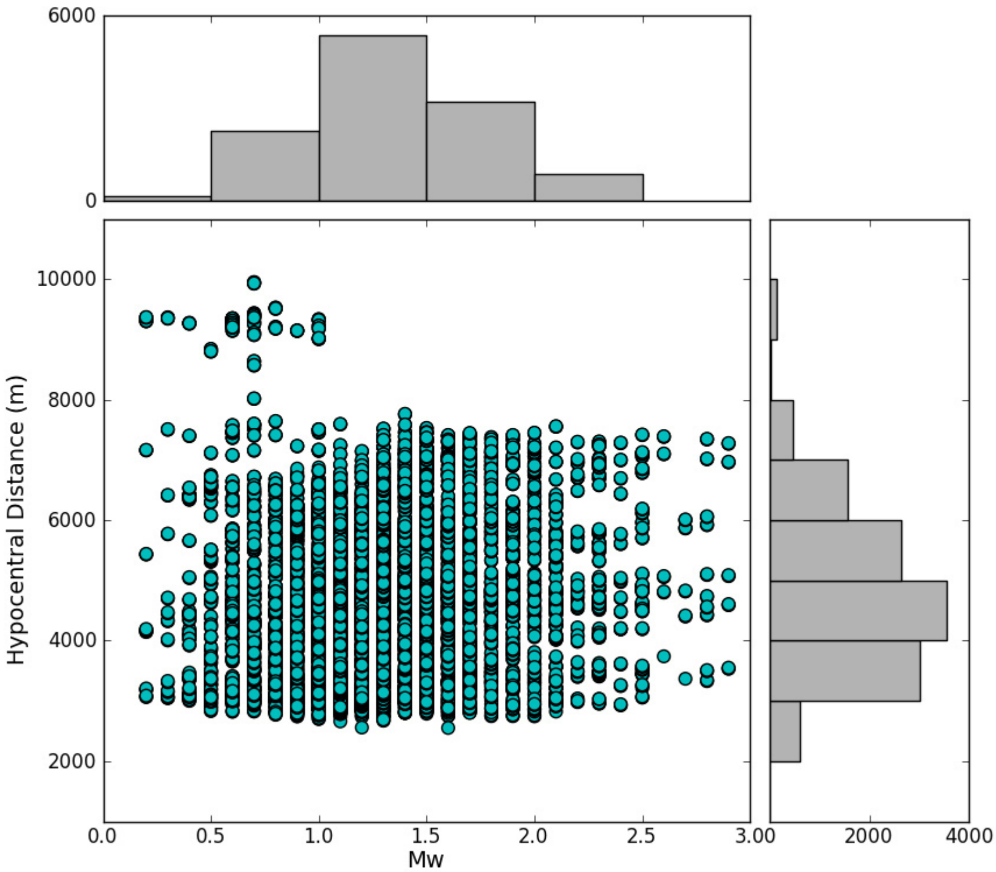


Figure 1. Moment magnitude and hypocentral distance for all records used in this study.

Seismic Risk Analysis for the EGS Pilot-Project in the Community of Haute-Sorne, Switzerland

Falko Bethmann, Olivier Zingg, Peter Meier, all Geo-Energie Suisse AG

In the framework of an environmental impact assessment study for a geothermal pilot project in the community of Haute-Sorne in Switzerland, Geo-Energie Suisse AG has conducted deterministic and probabilistic seismic hazard studies. Here we present how complex and manifold measures of hazard and risk are transferred into a simple risk framework for authorities to judge the risk posed by induced seismicity of a geothermal power plant.

We use deterministic approaches to illustrate a range of damage scenarios. Based on the results we determine a conservative magnitude scenario where damage to properties can no longer be excluded and adjust thresholds for a traffic light system accordingly. In addition we use probabilistic approaches to quantify residual risk and give failure probabilities for the proposed traffic light system.

Based on a logic tree method described in Mignan et al., 2015 we then combine results of the deterministic and probabilistic studies. Uncertainties at the hazard and risk level are considered in a systematic way.
To illustrate risk, we present exceedance probabilities for intensities as well as financial losses and casualties. We discuss how risk can then be evaluated within frameworks that are known to authorities, e.g. structure norms, regulatory frameworks for hydro dams or the Swiss ordinance on the prevention of major accidents.

On decision-criteria for the identification of microseismic events using migration-based methods

Volker Oye, NORSAR; Kamran Iranpour, NORSAR

Automatic event detection methods generally use a given threshold of the signal-to-noise ratios derived from certain functions of the waveform data. Phase identifications on different sensors of the network are then assigned to one event and are used to locate the event. In the case of large surface networks, as often used for hydraulic fracturing monitoring, the signal-to-noise ratio on the single traces is often below 1 for most of the occurring microseismic events. Nevertheless, the large number of seismic traces allows applying migration-based location methods, taking advantage of constructive stacking power of certain attributes of the waveform data (see e.g. Oye et al., 2014).

In some cases, the microseismic events are identifiable by visual inspection on selected traces of the network, in other cases, however, no significant energy can be traced back to the individual traces. To still identify whether a microseismic event occurred or not, a threshold of the stacked energy that is above some factor of the stacked energy variance is often taken as a decision criterion. Other obvious criteria are again threshold values of the maximum stacked amplitude, or, again, a signal-to-noise threshold of the stacked amplitudes. In case of ocean-bottom cable networks above hydrocarbon reservoirs, marine seismic shooting is a common feature in the noise field as well as shipping traffic, drilling operations and other noise from construction. To study the impact of such noise on the identification of events recorded below the noise level, we conducted synthetic tests using interference of random and coherent noise originating from various places inside and outside of the network and buried the waveforms of a real microseismic event in the synthetic waveforms.

The most important criteria to decide whether an accumulation of stacked energy at a certain point in the subsurface belongs to a real microseismic event or not are a combination of the stacked amplitude above a given threshold (maximum beam strength), the temporal change and focus of the beam strength, and the size of the volume that exceeds the background amplitude. An additional parameter is the shape of the volume of enhanced stacking energy. This shape should reflect the geometry of the seismic network and the velocity model for a given event location, and phases used in the location method (e.g. Gharti et al. 2010). For example should an event, located in the center of a surface array, using P-wave phases only for stacking, have a larger elongation of enhanced stacking energy along the vertical axis as in the horizontal direction. This can be used to discriminate random accumulation of noise from real events.

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CAN INDUCED GROUND MOTION BE APPLIED AS A VIABLE STRUCTURAL LOAD IN SEISMIC ENGINEERING?

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The induced seismic events with their m_L magnitudes reaching 4 or even exceeding 5 (see e.g. McGarr et al. 1989, [1]) may generate substantial surface ground excitations. Shallow source, compare to natural earthquakes, together with small epicentral distances result in surface tremors [2], which may negatively influence environment, concern local communities and even lead to serious structural damages. For these reasons one may want to investigate what would be the level of these excitations danger for the safety of buildings and how to eventually mitigate these effects for existing buildings or for the planned buildings of the mine infrastructure in the vicinity of mines.

Mitigation of natural earthquakes has led to special seismic codes used by civil engineers in structural design (e.g. [3, 4]). Their application for the induced tremors is faced however with two important issues:

1) different spectral content and duration of the surface acceleration records of mine tremors compare to natural earthquake records,
2) different definition of seismic risk associated with induced seismic events compare to strong natural earthquakes expected with the return period of about 500 years at the place of the planned building site.

Particularly the second issue is difficult to tackle in a rational way. The philosophy of civil engineering seismic codes is directed towards extreme loads expected with 10% probability during 50 years of typical building exploitation. In terms of the seismic risk this means strong events with 475 years return period. In such cases the buildings should be designed including substantial non-elastic deformations and respective non-linear effects controlled by so called '*q*' factors expressing plastic behavior of the designed structures.

On the other hand the extreme mine tremors may occur with return period of a few years which would require their different treatment than natural earthquakes in structural design. Still, however, the application of linear approach in structural response computations results in too conservative approach taking into account the surface Peak Ground Accelerations (PGA) often exceeding 30% *g* as often recorded even during moderate rockbursts .

The lecture planned for the Davos Seminar will be devoted to present a practical approach to mitigate mine tremors in structural design using the European seismic code [3] and developed recently for the Copper Mine Basin LGOM in Poland [5].

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