# Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs — The European GEISER Project

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## ABSTRACT

The GEISER (**G**eothermal **E**ngineering Integrating Mitigation of **I**nduced **SE**ismicity in **R**eservoirs) project is co-funded by the European Commission to address the mitigation and understanding of induced seismicity (IS) in geothermal engineering. The aim of the project is to contribute to the improvement of the concept of EGS by investigating the role of IS, which is twofold:

1. as an instrument to image fluid pathways induced by hydraulic stimulation treatments, which has been done to some extent in previous projects; and
2. as an implication of such treatments to potential seismic hazards.

Work started in 2010 by addressing four major points:

– *Analysis of induced seismicity*
– *Understanding the geomechanics and*
– *Consequences of induced seismicity*
– *Strategies for the mitigation of induced seismicity*

Within the first year of the project, a number of reference sites were defined where data sets with seismic and downhole data are available for further processing and analysis. In addition, laboratory experiments and mechanical models as well as hazard assessment tools are developed on the basis of existing data. At the end of the project, guidelines for regulatory bodies will present the basis for future licensing procedures of geothermal projects.

## Introduction

The development of engineered or enhanced geothermal systems (EGS) requires injection of fluids at high pressures to improve productivity of a geothermal well (Enhanced Geothermal Systems, EGS), which leads to microseismicity (Majer et al. 2007). In exceptional cases, the seismicity can be felt or even become a nuisance for the population. A promising geothermal project at Basel/Switzerland was halted by authorities after repeated seismic events, although not destructive, were felt by the local population.

Microseismicity is not only an unwanted side-effect of injection it is also of importance as a source of information to the extent of the reservoir and about conditions within the rock mass. To obtain this information downhole seismic monitoring systems are essential to record high frequency seismic data that contain key information about the failure location and process. Microseismic monitoring has been recognized as a key technology ever since the first EGS was developed at Fenton Hill. Since then, the EGS community has been the core of innovation regarding high-resolution mapping of microseismic structures (Fehler et al., 2001). The high resolution methods applied to microseismicity arising from the stimulation of EGS have revealed that the events occur on discrete fractures/faults, and thus serve to essentially illuminate the key hydrogeological pathways within stimulated reservoirs (Evans et al., 2005; Baisch et al., 2006).

The objective of GEISER is to mitigate the unwanted side-effects of IS without preventing the desired effect of reservoir enhancement during stimulation. For a better understanding of the process and for the development of suitable mitigation strategies, the project goals are:

– understand why seismicity is induced in some cases but not in others
– determine the potential hazards depending on geological setting and geographical location
– work out licensing and monitoring guidelines for local authorities, which should include a definition of what level of ground motion is acceptable
– develop strategies for successful stimulation and improvement of the hydraulic properties of the geothermal reservoir

without producing seismic events that pose a threat to buildings and disturb the public.

The GEISER portal is located at http://www.geiser.eu where a presentation of the project and the partners, newsletters and more information are available. The Website also offers a meetings section and an area with restricted access for exchange among the partners.

## Work Performed in the Project

Four main topics are identified:

***Analysis of induced seismicity*** from representative reservoirs throughout Europe, with input from experts and data from regions outside Europe (Berlín, El Salvador; The Geysers, USA). IS activity is analyzed in space and time and its relationship with injection and production parameters, the local stress field and the geological setting is investigated. These datasets will be compared with other project data, where injection did not cause significant seismicity.

***Understanding the geomechanics and processes*** involved in IS. The influence of factors such as temperature, poroelasticity, fluid injection rate, existing fault segments, local stress regime and time dependent effects are investigated to constrain the possible mechanisms involved during fluid injection using various modeling approaches as well as laboratory experiments.

***Consequences of induced seismicity*** are addressed by providing an assessment of the seismic hazard presented by events triggered through human activity in comparison to natural seismicity. Results from (1) and (2) will be used to quantify the probability of triggering larger seismic events and to define the potential damage caused by ground shaking. This activity will result in guidelines for licensing and site development for local authorities and industry.

***Strategies for the mitigation of induced seismicity***. On the basis of the recommendations formulated in (3) and of the results of (1) and (2) strategies for "soft injection" will be proposed. The optimization of a monitoring network and a real-time monitoring system will be presented to help authorities and operators minimize the seismic hazard and manage the risks during operations and production. Experience of past seismic events caused by mining and in the oil and gas industry will be included to address the proper handling of public awareness and acceptance.

## First Results

The sites with data used for the project include the European test site at Soultz-sous-forets in the Upper Rhinegraben (North-Eastern France), several Icelandic sites such as Hengill, Reykjanes and Krafla, Latera/Italy, Gross Schönebeck and the deep research well KTB in Germany, Basel/Switzerland as well as data from the gas field in Groningen/Netherlands. In addition, non-European datasets include Berlìn/El Salvador and The Geysers/USA. For the ***analysis of induced seismicity***, spatio-temporal characteristics of fluid-injected microseismicity have been investigated at for all the test sites.

Data acquired during seismic monitoring at Hengill/Iceland to obtain an updated velocity model (Jousset et al., 2011) were used to perform ambient noise studies. From the analysis of the dispersion curve (Fig. 1), the velocity is obtained as a function of

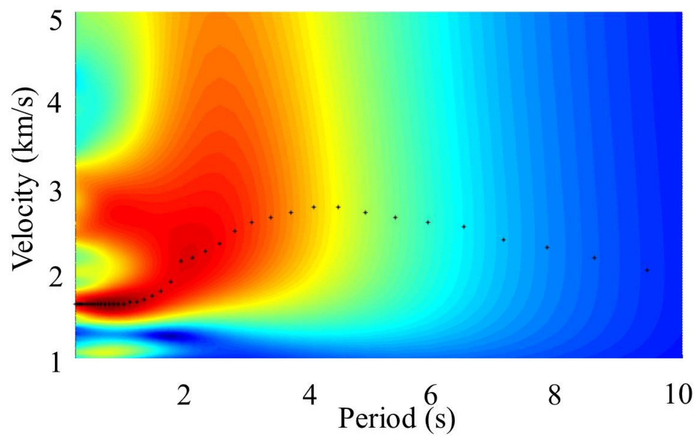


**Figure 1.** Example of a group velocity dispersion curve derived from frequency-time analysis of ambient noise data at Hengill volcano (Iceland).

frequency. Comparison with the results calculated by Jousset et al. (2011) demonstrates the usefulness of noise data for the generation of a velocity model, which is required for seismic analysis.

At Soultz-sous-forêts, large scale aseismic motion was identified through 4D P wave tomography. To connect the well GPK2 to the reservoir created in the granite at 5 km depth, more than 23 000 $m^3$ of water were injected. The microseismicity induced by this hydraulic stimulation was monitored with a network of fourteen seismic stations deployed at ground surface. Some 7215 well located events have been used to conduct a 4D tomography of P-wave velocities. The method combines a double-difference tomography method (tomoDD) with an averaging process (WAM) that corrects for parameter dependence effects. The total set of 7 215 events has been divided into fourteen subsets that explore periods defined with respect to the injection scheme. Particular attention is given to changes in injected flow rates, periods of stationary injection conditions, and post injection periods. Fast changes in $V_P$ velocities are identified in large rock mass volumes precisely when the injection flow rate varies while little velocity variation is detected during stationary injection periods. The VP anomalies observed during stationary injection conditions are interpreted as being caused by effective stress variations linked to fuid diffusion, while the fast changes observed concomitantly to changes in flow rate are considered to be caused by non-seismic motions.

Analysis of seismic data from Krafla in North Iceland, where 60 $MW_e$ are generated, involved preparation of data, location of earthquakes and comparison with drilling and injection activity in the area. Two clear and interesting results are found. (1) For the analyzed time period the seismogeneic zone extends to 2.2 km depth (Fig. 2), which is indicative of high temperature (700 °C) and ductile deformation. (2) A clear temporal/spatial correlation between injection phases and seismicity at the IDDP-1 (International Deep Drilling Project) borehole is observed. The borehole bottoms at 2050 m where it encountered magma (Friðleifsson et al., 2010). During injections at bottom hole, seismic activity started at the bottom followed by upward migration to about 1 km along a line or plane from about 350 m NW of the bottom of the hole dipping approximately 20°.

The occurrence of larger magnitude events in geothermal reservoirs is of major concern and requires further study. For this purpose, the spatial and temporal evolution of seismic source parameters

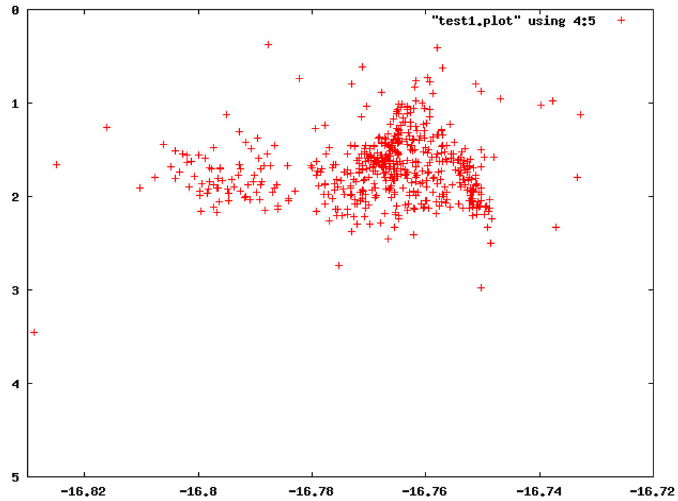


**Figure 2.** Depth section of earthquake hypocenters at Krafla, 2010. Vertical axis is depth in km and the horizontal axis is longitude.

including moment magnitude, source radius, radiated energy, static stress drop and apparent stress is analyzed for Berlín HFR site, El Salvador (Kwiatek and Bulut, 2011) and Gross Schönebeck (Kwiatek et al, 2010). In addition, the effect of pore pressure and crustal stress have been analyzed for the event at Basel (M= 3.4). Relative stress-drop values derived from a spectral stacking method applied to the entire data set of more than 3000 events reveal a systematic increase of stress drop with distance from the injection borehole with time. At least qualitatively, this result correlates well with the space-time evolution of pore pressure estimated from a linear diffusion model (Goertz-Allmann et al., 2011).

For the ***understanding the geomechanics and processes*** laboratory experiments were conducted, where significant acoustic emission activity was recorded during the fluid migration into dry sandstone samples. Complementary to the laboratory experiments hydro-mechanical numerical modeling is used to simulate the changes in Coulomb Failure Stress (ΔCFS) due to fluid injection and fluid depletion from a point source in a continuous porous rock volume using the TOUGH2 code. Figure 3 shows the ΔCFS values on optimally oriented faults and the associated faulting

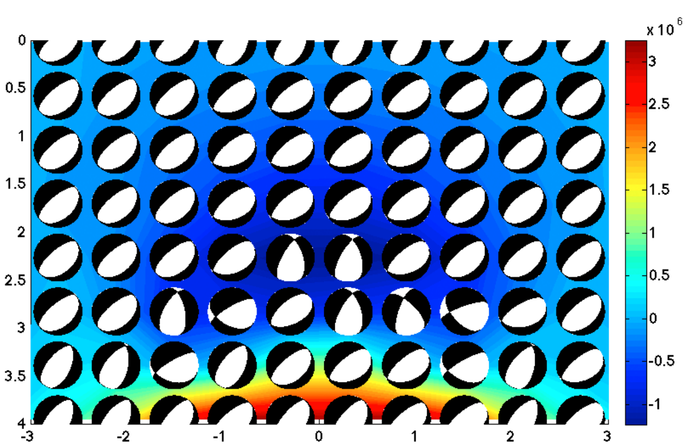


**Figure 3.** Change in Coulomb Failure Stress (ΔCFS) for optimal oriented faults in MPa and the associated faulting mechanisms in a hypothetical geothermal site, due to fluid depletion from a point source.

mechanisms. The ΔCFS shown here can attain considerable values (peaked at 3 MPa), capable of significantly re-orienting the mechanisms of most stressed fractures with respect to the regional stress field.

Hydro-mechanical modeling in fractured media included the study of stress change during/after injection or stimulation periods in a synthetic geometrical model, and the study of the fracture network morphology in the occurrence of swarms of events with the Discrete Fracture Network approach. Using focal mechanisms of the stimulation phase of well GPK2 in Soultz, in 2000, the stress change in the reservoir was computed at the end of this stimulation period, using the USGS software Coulomb (Lin et al., 2004; Toda et al., 2005). This work follows some previous computations made by Dorbath et al. (2008). The preliminary results show some very heterogeneous Coulomb stress change in the reservoir, with orders of magnitude peaked at 5 bar (see figure 4). Further work will focus on the temporal evolution of Coulomb failure stress and possible co-seismic triggering.

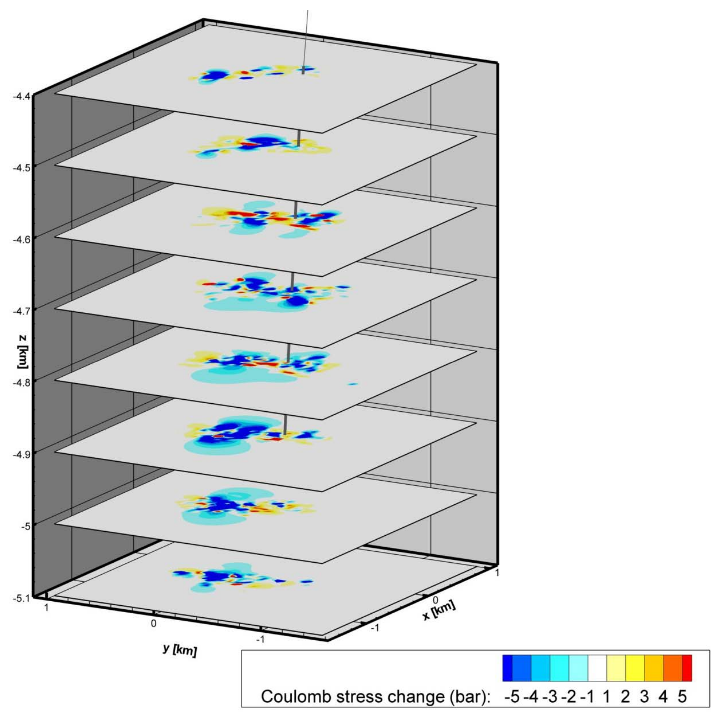


**Figure 4.** Coulomb stress change of optimally oriented faults for normal faulting at different depths for the stimulation of GPK2. 715 focal events mechanisms of magnitude higher than 1 are taken into account. Coefficient of friction: 0.8.

In parallel, the stress change equations (thermo-poroelastic model) are being implemented in the code FRACTure in order to investigate the influence of these processes on simple model geometries. In addition, changes of Coulomb failure stress will be implemented in this code to assess the contribution of stress redistribution through microseismic events on other induced events.

For the study of the ***consequences of induced seismicity,*** seismic hazard due to IS and to triggered seismic events is compared with natural seismic activity. A preliminary study on the influence of spatial and depth variations in tectonic fabric/rheology on spatial partioning of seismic hazard was conducted.

First results suggest that the probability inducing a larger event, and possibly of $M_{max}$, is depth dependent. In addition, meta-data collected from a wide range of passive and active deep geothermal systems were analyzed for the potential to trigger felt earthquakes. This work will serve to define proxies to estimate the seismic potential of a region. Ongoing research will address shaking and damage scenarios from EGS induced and triggered events and the development of guidelines for best practice in seismic hazard assessment for site selection and licensing.

For the development of ***Strategies for the mitigation of induced seismicity*** potentially "*s*oft stimulation" techniques are tested numerically. For that purpose, datasets for Gross Schönebeck, Berlìn and Latera (stimulation treatments) are reviewed. We are relying on numerical simulations to evaluate the fracture size, the productivity index increase and stress variations.

To understand microscale processes involved in fault reactivation, diffusive processes at pore level, evaluating thermoelastic effects and/or lubrication of water, direct input from the geomechanical modelling is used and integrated in the analysis. The incorporation of these results in a numerical simulation is a major challenge which will take another one or two years, but it should be feasible to provide an estimate of the expected seismicity, both for high pressure hydraulic fracturing and low pressure fracture opening, within a stimulation simulator. Understanding the mechanical processes will also provide better real-time tools both, for treatment effectiveness evaluation and seismicity.

Other steps will include the design and optimization of seismic network and earthquake monitoring procedures and the development of real-time tools to monitor the evolution of induced microseismicity and triggered events, including traffic light systems. Last not least, public awareness and sensitivity to ground shaking due to injection and/or during EGS operations will be addressed to gain acceptance for EGS projects in general and to develop effective communication strategies. At the end of the project, the goal is to be able to provide boundary conditions for regulatory guidelines leading to mitigation of induced seismic hazards.

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