TUNNEL & UNDERGROUND SPACE

TUNNEL & UNDERGROUND SPACE Vol. 23, No. 6, 2013, pp. 581-592
http://dx.doi.org/10.7474/TUS.2013.23.6.581

ISSN: 1225-1275(Print)
ISSN: 2287-1748(Online)

지열에너지와 관련한 유럽에서의 연구프로젝트 소개와 유도지진에 관한 GEISER프로젝트의 주요연구결과에 대한 사례연구

윤정석*, 다빗 부룬, 아노 짱

Overview of Geothermal Energy Projects in Europe and the GEISER Project on Induced Seismicity

Jeoung Seok Yoon*, David Bruhn, Arno Zang

Abstract This article provides an overview on the geothermal energy research in Europe and one of the EU funded projects 'GEISER (Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs)' in which the authors were involved. More details are given for description of GEISER, in particular, about aims and discussions and how the project was managed. Emphasis is given to one of the work packages 'Induced Seismicity and Large Magnitude Events (LME)' and results of this work package are summarized. This article intends to summarize the lessons learned in the GEISER project and give recommendations to future geothermal projects by creating Enhanced Geothermal Systems hydraulic stimulation where induced seismicity issues are expected to be a major issue and obstacle.

Key words Geothermal energy, European projects, GEISER, Induced seismicity, Large magnitude events (LME)

초 록 본 사례연구논문에서는 유럽에서의 지열에너지개발과 관련된 연구프로젝트의 현황에 대한 개괄적인 내용과, 저자가 참여했던 GEISER프로젝트(Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs)와 핵심세부과제인 유도지진(Induced Seismicity)에 관한 연구결과를 요약 정리하였다. 본 사례연구논문에서 다룬 GEISER프로젝트의 연구결과와 교훈을 통해 수리자극에 의한 지열저류층 개발과 그에 수반되는 유도지진에 따른 문제가 예상되는 향후 지열에너지개발 프로젝트에 도움이 될 수 있기를 기대한다.

핵심어 지열에너지, 유럽프로젝트, GEISER, 유도지진, Large magnitude events (LME)

1. INTRODUCTION

Geothermal energy is the energy stored in the form of heat below the Earth's surface. Today geothermal water is used in many applications such as district heating, as well as for heating and cooling of individual buildings by using geothermal heat pumps. For almost 100 years geothermal energy has been used for electricity generation. Today, so called Enhanced Geothermal Systems (EGS), enable the exploitation of the Earth's heat for producing electricity even if the natural productivity from water resources is not sufficient (Breede et al. 2013). To extract energy from hot, poorly permeable rock, water is injected from the surface into boreholes with high pressure in order to create fractures and open them in the hot rock. The fracture surfaces serve as heat exchangers, heating the water and, when it returns to the surface, it can be used to provide heat and to generate electricity.

EGS technologies have the potential to produce large amounts of electricity almost anywhere in the world.

Received: Nov. 13, 2013
Revised: Nov. 22, 2013
Accepted: Dec. 11, 2013

***Corresponding Author:** Jeoung Seok Yoon
Tel) +493312881716, Fax) +493312881127
E-Mail) jsyoon@gfz-potsdam.de
Helmholtz-Zentrum Potsdam, Deutsches GeoForschungs Zentrum GFZ, Telegrafenberg 14473, Potsdam, Germany

According to the European Commission's forecast, the capacity of the geothermal power sector by EGS only is expected to reach 1 GW in 2020 and 1.3 GW in 2030 (European Commission 2013a). The estimated maximum potential for geothermal power in the EU-27 is up to 6 GW by 2020 and 8 GW by 2030. This represents about 1% and 1.3% of projected EU gross electricity consumption by 2020 and 2030, respectively. In the heating sector, the estimated maximum potential for geothermal is up to 40 GW by 2020 and 70 GW by 2030 (direct and indirect use combined).

Geothermal resources have been used successfully and economically in some locations in Europe where geological conditions are exceptionally favorable, e.g. Italy and Iceland, but they can play a much more important role at the European scale if they can be made accessible at other places. Many other countries have started to make use of this source of energy by applying new approaches, e.g. EGS by hydraulic stimulation. However, the need for community support is essential to overcome initial barriers.

One of the key barriers is the need to re-inject the cooled thermal water, which can induce seismicity. Two promising geothermal projects affected by this are at Soultz-sous-Forêts France and the best known, at Basel Switzerland. In the latter case, repeated seismic events, although not destructive, were felt by the local population and prompted the authorities to halt operations. To avoid these problems, action had to be taken in order to better understand and mitigate induced seismicity in the development of geothermal reservoirs.

In this context, this article is intended to give a brief overview of how geothermal energy research is supported and performed in Europe, and in particular, on one of the EU funded projects, 'GEISER' in which the authors were involved. GEISER aimed at investigating, in particular, induced seismicity associated with water injection and mitigation measures. A large portion of this article is a summary of several documents submitted to the project as deliverables.

2. GEOTHERMAL ENERGY RESEARCH PROJECTS IN EUROPE

Research and development on technology plays a key role, particularly in the development of EGS,

Table 1. Geothermal energy projects funded by EU within FP6 and FP7 (modified from European Commission 2013b)

Project name	Total budget and EU contribution (portion %) and objectives
GEISER (Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs)	Total: €7,115,977 and EU contribution: €5,308,869 (75%) Improve the concept of EGS by investigating the role of induced seismicity, Development of stimulation method that can mitigate the effect of induced seismicity
ENGINE (Enhanced geothermal innovative network for Europe)	Total: €2,302,289 and EU contribution: €2,302,289 (100%) Co-ordination of the research and development initiatives for unconventional geothermal resources and EGS To provide an updated framework of activities concerning geothermal energy in Europe including scientific, technical know-how and practices, evaluation of socio-economic and environmental impacts; To define an innovative concepts for investigation and use of unconventional geothermal resource and EGS
I-GET (Integrated geophysical exploration technologies for deep fractured geothermal systems)	Total: €3,828,286 and EU contribution: €2,699,993 (71%) Development of an innovative geothermal exploration approach based on advanced geophysical method To improve the detection, prior to drilling, of fluid bearing zones in naturally fractured geothermal reservoirs
EGS PILOT PLANT (European geothermal project for the construction of a scientific pilot plant based on an Enhanced Geothermal System)	Total: €26,033,300 and EU contribution: €5,000,000 (20%) To install and operate a 1.5 MWe power plant making use of the deep reservoir/heat exchanger created during the period 2001-2003 at Soultz-sous-Forêts; To test the in-site performance of the selected equipment for establishing preferences for technical and economical gains for future larger industrial EGS installations; To use the pilot plant as a training facility to other European EGS teams for research

which allows the exploitation of the Earth's heat for producing electricity without having enough natural water resources.

Since 2002 (in the 6th Framework Programme, FP6), the European Union (EU) funded around 10 projects with a total budget of more than €M20. In particular, the flagship project EGS Pilot Plant for Soultz-sous-Forêts, which culminated in the construction of a scientific pilot plant based on an EGS, was awarded €M5. Under the current 7th Framework Programme (2007-2013) research is funded for advancing knowledge in *understanding* and *mitigating of induced seismicity* associated with geothermal field development.

Table 1 lists some of the EU funded projects (full or partial contributions) related to geothermal energy research and development within the 6th and 7th Framework Programmes.

3. GEISER (GEOTHERMAL ENGINEERING INTEGRATING MITIGATION OF INDUCED SEISMICITY IN RESERVOIRS)

The project GEISER started at the beginning of the year 2010 after successful contract negotiations with the European Commission. EU funding of €M5.3 was granted for 3.5 years. The project addressed several of the major challenges the development of geothermal energy is facing, including the *mitigation of induced seismicity* to an acceptable level. For this purpose, the project set the following goals:

(1) To understand why seismicity is induced in some cases but not in others;
(2) To determine the potential hazards depending on geological setting and geographical location;
(3) To work out licensing and monitoring guidelines for local authorities, which should include a definition of what level of ground motion is acceptable;
(4) To develop strategies to fulfill the task of the stimulation and improve the hydraulic properties of the geothermal reservoir without producing large magnitude induced seismicity that poses a threat to buildings and disturbs the public.

And four main topics were identified:

(1) 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; Bouillante, French Antilles). Induced seismic activity was analyzed in space and time and its relationship with injection parameters, the local stress field and the geological setting was investigated. These data sets were compared with other project data, where injection did not cause significant seismicity.
(2) Understanding the geomechanics and processes involved in induced seismicity. The influence of factors such as temperature, poro-elasticity, fluid injection rate, existing fault segments, and time dependent effects were investigated to constrain the possible mechanisms involved during fluid injection using various modeling approaches as well as laboratory experiments.
(3) Consequences of induced seismicity were 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) were used to quantify the probability of triggering larger seismic events and to define the potential damage caused by ground shaking. This activity resulted in guidelines for licensing and site development for local authorities and industry.
(4) Strategies for the mitigation of induced seismicity. On the basis of the recommendations formulated in (3) and of the results of (1) and (2), strategy for 'soft injection' was proposed. The optimization of a monitoring network and a real-time monitoring system were presented to help authorities and operators minimize the seismic hazard and manage the risks during operations and production. Experiences of past seismic events caused by mining and in the oil and gas industry were included to address the proper handling of public awareness and acceptance.

The overall strategy for the GEISER project was to start with a collection of representative data for comparison and analysis. On the basis of the analysis and detailed investigations into the mechanisms and processes involved in induced seismicity in geothermal developments, seismic hazard was assessed and ground shaking scenarios were calculated. At the end, guidelines for licensing of geothermal projects were prepared and strategies for the mitigation of induced seismicity during geothermal development and operation were proposed.

3.1 How it was managed

Participants and project structure

To reach these goals and to investigate the topics identified, the project was broken down into seven work packages (WP) which are inter-dependent (Fig. 1 and described below) and each led by one of the GEISER partners (Table 2).

WP1: Project Management (WP leader: GFZ)

WP2: Compilation of induced seismicity data from geothermal sites (WP leader: ISOR): In this work package, data on induced seismicity from representative sites in Europe were collected, to provide an overview of lessons learned from previous experience. This WP was designed for the smooth exchange of data between partners and to guarantee sufficient, comparable of these data from the various sources. For this purpose, data were checked and homogenized for comparison and further use in other WPs.

WP3: Analysis of induced seismicity (WP leader: GFZ): Different seismological approaches were applied and further developed to analyze data sets of induced micro-seismicity from geothermal areas. Based on the evolution of induced seismic activity in space and time, the inter-relation between the specific local geological settings, injection parameters and the

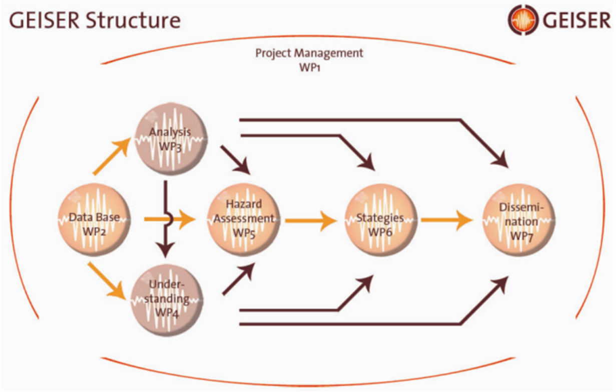

Fig. 1. GEISER structure, work packages and their interdependency

Table 2. GEISER partners

Partners	Country	Full name or Website
GFZ	Germany	German Research Centre for Geosciences
BRGM	France	The French Geological Survey
ÍSOR	Iceland	Iceland GeoSurvey
TNO	The Netherlands	The Central Geoscience Institute in the Netherlands
ETHZ	Switzerland	The Swiss Seismological Service
STATOIL		www.statoil.com
GEOWATT	Switzerland	www.geowatt.com
NORSAR	Norway	Applied Geophysics and Seismology Research Foundation
ARMINES	France	A joint research with schools of engineers
EOST	France	Engineering School and Research Institute in Geosciences
KNMI	The Netherlands	The Royal Netherlands Meteorological Institute
AMRA	Spain	Centre of Competence for Analysis and Monitoring of Environmental Risk
INGV	Italy	The Italian Institute for Research in Geophysics and Volcanology

occurrence of fluid-injection induced seismic events was addressed.

WP4: Understanding the geomechanical causes and processes of induced Seismicity (WP leader: BRGM): Different modeling approaches and laboratory experiments were performed to investigate some of the key factors influencing induced seismicity. The goal was to come to a better understanding of the basic physical mechanisms that induce micro-seismicity and to deliver management and production scenarios with relative estimates of the stress-state changes for different geothermal settings.

WP5: Seismic hazard assessment (WP leader: ETHZ): On the basis of the results from WP3 and WP4 and considering natural seismicity, this WP assembled all the components of hazard assessment to be conducted before the selection and start of operations at an EGS site, to result in guidelines for best practice. This included the analysis of the natural background seismicity, an estimate of the ground shaking produced by the micro-seismicity induced during the initial stimulation phase and the probability of triggering larger magnitude events ($M > 4$) ahead of its natural time of occurrence, either during the stimulation phase or during the long-term EGS operation.

WP6: Strategies for EGS operations with respect to induced seismicity and mitigation (WP leader: TNO): The objective of this WP was to provide strategies to operators and regulatory bodies to stimulate reservoirs and at the same to mitigate the effect of LME. These strategies were targeted as guidelines for regulatory bodies for the selection, licensing and long-term operation of EGS sites in different geological settings, at developing the concept of ‘soft stimulation’, at proper monitoring of induced seismicity, and at a minimization of the risk.

WP7: Dissemination (WP leader: BRGM): The achieved understanding and the recommendations for standardized procedures were disseminated among stakeholders/industry and public authorities as well as the scientific community.

Inter-dependencies of the work packages

Following the concept of the project to bring together expertise in geothermal utilization, seismic hazards, and public awareness, all WPs were strongly inter-connected. The database generated in the WP2 provided the basis for the applied work of all the other WPs. In addition, a State-of-the-Art of induced seismicity in geothermal field development is defined, based on literature review. The investigation of spatio-temporal characteristics of fluid-injection induced seismicity and the analysis of background and induced seismicity performed in WP3 provided essential input parameters for the modeling part in WP4. Understanding the role of LME in controlled reservoir stimulations as investigated in WP3 was important for the modeling. Results from both WP3 and WP4 were used for seismic hazard assessment in WP5 as well as for the mitigation concepts to be developed in WP6: a) Design and optimization of seismic network and earthquake monitoring procedures with input from WP3; b) The model of elastic interactions in porous, heterogeneous and fractured media, role of existing faults segments and temperature from WP4. The theoretical work in WP4 also provided the basis for a ‘soft stimulation’ strategy (targeted at mitigation of induced seismicity) to be proposed in WP6. The guidelines resulting from WP5 had a direct impact on the strategies in WP6. Finally, all activities contributed to the dissemination in the WP7.

GEISER portal and final conference

A website (www.geiser-fp7.fr) was created as a management tool of the project. The website provided a platform to the participants for exchange of data and documents, announcement of the meetings, etc. The website was the main information and dissemination portal for the project. Project and partners presentations, and newsletter and related websites and events were announced through the website. Besides the website, in total, five newsletters were created, which served well as summaries of the project activities not only to the participants but also for public.

GEISER final conference was held in Neapel, Italy. The final conference was intended to share the results not only with the project partners, but also with the rest of the world. Contributions from non-GEISER participants were presented, including U.S. Geological Survey, Lawrence Berkeley National Laboratory, Temple

University, ARRAY Information Technology Inc. (USA), Geodynamics (Australia), National Institute of Advanced Industrial Science and Technology (Japan), LaGeo (El Salvador), GNS Science (New Zealand), GEIE Soultz-sous-Forêts (France), University of Bonn and Free University Berlin (Germany). Programme of the conference and the abstracts and presentation materials can be found in the conference website (http://meetings.geiser-fp7.eu/conferenceDisplay.py?confId=15).

3.2 Characterization of Large Magnitude Events (LME) and their occurrence in space and time

One major topic addressed by a number of papers evolved from the project is the characterization of Large Magnitude Events (LME), coupled with the investigation of strategies to describe, and ideally mitigate the seismic risk of stimulation operations. This section gives a summary of the results from WP3 'Analysis of Induced Seismicity'.

Micro-earthquakes are induced during high-pressure stimulation and they enhance the reservoir permeability. At the same time, it is crucial not to induce or trigger LME, which may not only cause damage at the surface, e.g. Basel EGS (Häring et al. 2008), but also lower the efficiency of the geothermal system by the creation of 'hyper-permeable' pathways. If a LME occurs, it may create a master pathway for fluids that can shortcut the reservoir, preventing heat exchange from being efficient. A better physical understanding of the seismicity generation process is needed in order to develop techniques to reduce the probability of LME.

It was first proposed by McGarr (1976) that the total moment of an induced seismicity cloud is proportional to the volume of injected fluid. However, the actual amount of seismicity can vary drastically between different locations. Using a completely different approach of pressure diffusion theory, Shapiro et al. (2007, 2010) arrived at a similar result in which the total number of induced events is proportional to the injected fluid volume. In addition, they described the proportionality factor, called the 'seismogenic index', as a function of measurable seismological quantities and rock properties. Combining these considerations with the assumption that seismicity always follows a Gutenberg-Richter magnitude distribution leads to a probabilistic description of the maximum expectable magnitude.

Seismic hazard potential generally increases with injected volume, even though there are significant regional differences. Grünthal (2013) investigated the occurrence of induced seismicity at geothermal project sites and compared with all other types of induced/triggered seismicity including coal mining, hydrocarbon exploitation, salt and potash mining, ore mining, heavy rainfall in karst geology and artificial water reservoirs, as well as with natural tectonic earthquakes in the Central, Northern and North-Western Europe. The maximum observed magnitude of induced seismicity at geothermal sites is the smallest of the eight types of induced/triggered seismicity with M_w = 3.2 which is by far smaller than natural tectonic earthquakes (M_w = 6.6).

The above considerations and results provided the background for the results presented in the special issue 'Induced Seismicity' in the Elsevier Journal Geothermics. Most of the work was conducted as a part of the GEISER project. The compilation of papers ranges from the description of larger magnitude seismicity in past geothermal operations to numerical forward-modeling of seismicity clouds, all with the aim to obtain some general conclusions about the creation of LME in geothermal operations. The paper of this Special Issue will be available online at the beginning of 2014.

Evans et al. (2012) summarized the results from over 40 European case histories, describing the seismogenic response of crystalline and sedimentary rocks to fluid injection. The data suggest that injection into sedimentary rocks tends to be less seismogenic than in crystalline rocks. Large or damaging earthquakes tend to occur on developed or active fault systems. In other words, large earthquakes are unlikely to occur where there is not a fault large enough to release sufficient energy. Therefore, the risk of producing LME is increased if faults are present near the well. The authors compared the maximum magnitude of each project with the long term probability of exceeding a threshold level of peak ground acceleration (PGA), and speculated that fluid injection in areas with lower natural seismicity may have a lower risk of producing LME. However, a causal relationship between the two properties remains unclear and requires a more detailed geomechanical examination.

Table 3 lists the cases with the largest LME in order of decreasing magnitude. Some of these case studies including Basel (Switzerland), Soultz-sous-Forêts (France), Berlín (El Salvador), Cooper Basin (Australia), and The Geysers (USA, acquired with the support from Statoil during the project) were studied in detail. Apart from accurate magnitudes (moment magnitudes wherever available), Table 3 also lists the time and location of recorded LME at these sites. It has been frequently observed that LME occur after shut-in and at larger distances to the injection point, i.e. at the edges of the seismic cloud.

Kwiatek et al. (2013) conducted a case study on the geothermal project in Berlín, El Salvador, where a M_w = 3.7 LME occurred two weeks after shut-in of the injection. They found that the event is located on some part of an active fault that did not rupture before. They also found a dependence of Brune's stress drop to distance from the injection point, similar to what

Table 3. Key results from investigation on several selected geothermal sites

Sites	LME* year	LME, time and location	Geology, rock type, stress	Pmax (MPa)	Reservoir depth (km), fracture mechanism
The Geysers, California USA	4.6, 1982	On the edge of seismic cloud	Metagraywacke	7	3 km, cooling-induced shear slippage
Berlin, El Salvador	4.4, 2003	2 weeks after shut-in, on part of fault that did not rupture before	Young volcanic weak rock	13	2 km, opening and closing of flowing fracture
Cooper Basin, Australia	3.7, 2003		Granite with 3.6 km sediment cover, TF	68	4.1 to 4.4 km, slip on pre-existing sub-horizontal fractures
Alkmaar, The Netherlands	3.5, 2001		Sandstones, 2.6 to 3.1 km depth	18	2 km, reactivation Roer Valley Rift faults, gas production
Basel, Switzerland	3.4, 2006	Few hours after shut-in but before bleed-off, at the edge of the seismic cloud	Granite, Sh= 0.7SV, SH(N144°E±14°)	30	4.4 to 4.8 km, preexisting, en-echelon-type shear zone
Soultz-sous-Forets, France	2.9, 2003	In 2000, 2003, 2004 after shut-in	Granite, NF+SS, SH(N170°E)	16	4.5 to 5.0 km (GPK3), single large tectonic fracture zone
Landau, Germany (non-GEISER)	2.7, 2009	At the end of second stimulation, at the base of seismic cloud	Crystalline/Sedimentary rock, Sh<SV, SH(NS)	5	2.8 km, dilatants shear fractures
Paralana, Australia	2.5#, 2011		Sedimentary basin with basement below 4km, TF	62	4 km, reverse fault events
Rosmanowes, Cornwall, UK	2.0, 1987		Carnmenellis granite batholite	16	2 km, system of natural fractures
KTB, Germany	1.2, 1994		Gneiss, metagabbro, SS(1-8 km), SH(N160°E)	53	9.1 km, scientific wells, dilatant shear cracks
Groß-Schönebeck, Germany	-1.0#, 2007		Rotliegend sandstone, volcanic rock, NF, SH(N18°E)	60	4.1 km, only a total of 80 seismic events detected

Seismic: * Local magnitude, # Moment magnitude
Hydraulic: Pmax Maximum well head pressure
Stress: SH (maximum-), Sh (minimum horizontal), SV (vertical), SH orientation (N°E)
Faulting type: NF (normal faulting), TF (thrust faulting), SS (strike-slip faulting)

was found by Goertz-Allmann et al. (2011) for the Basel data set. However, their limited data set did not allow a spatial mapping of stress drop nor a correlation to the LME.

One of the most intensively studied EGS stimulation that triggered several LME causing damage at the surface is the project in Basel, Switzerland. In Basel the largest magnitude event (M_L = 3.4) occurred a few hours after shut-in and three additional events with $M_L > 3$ occurred one to two months later. These events occurred despite the implementation of a traffic light system (Bommer et al. 2006) that reduced the wellhead pressure after the first occurrence of a M_L 2.5 event. The largest earthquake occurred at the edge of the seismicity cloud. Comparison of the results of high precision relative locations of hypocenters pertaining to clusters of similar earthquakes and fault plane solutions with the strike of the strongly aligned seismicity cloud suggested that the strike or dip of the identified faults deviated substantially from this overall orientation. The concept of a single fault zone with a more or less constant orientation was obviously too simplistic. This had important consequences for models of fluid migration during stimulation and thus of the process of permeability enhancement as well as for seismic hazard assessments.

Spatial variations of source parameters such as stress drop and *b*-value of the Basel induced seismicity have been estimated by Goertz-Allmann et al. (2011) and Bachmann et al. (2012), respectively. It has been observed that stress drops are greatly reduced and *b*-values increases in the vicinity of the injection point where pore pressures are highest. LME in Basel were located in areas of higher stress drop and lower *b*-value. A comparison with estimated pore pressure variations due to fluid injections suggested that both stress drop and *b*-value are mainly driven by pore pressure variations. This had important implications on the distribution of seismic hazard.

Catalli et al. (2012) analyzed the role of Coulomb failure stress variations (ΔCFS) of the Basel seismicity and find that 70% of event locations were consistent with positive ΔCFS. They found that three out of the four LMEs in Basel were located in areas of positive ΔCFS. While pore pressure changes are certainly a first-order factor driving the seismicity at close distances to the injection, their results suggested that ΔCFS due to the already induced seismic events increases at later times and at larger distances from the injection point where the pore pressure change was strongly reduced. They concluded that event interaction is a key parameter in assessing seismic hazard of induced seismicity.

Apart from observational papers, some modeling papers provided more insight into the physical mechanisms driving induced seismicity and creation of LME. Goertz-Allmann and Wiemer (2012) developed a simple stochastic model to simulate induced seismicity in the Basel reservoir using linear pressure diffusion and seismicity triggering based on Coulomb friction. They linked Gutenberg-Richter *b*-value to differential stress in an inverse linear relationship. By randomly assigning magnitudes based on varying frequency-magnitude distributions, they were able to estimate the spatio-temporal variation of the occurrence probability of an event of a certain magnitude. Goertz-Allmann and Wiemer (2012) found a substantial increase of the mean probability for the time period after shut-in and also at further distances from the injection point, compared to a constant *b*-value model. Their results not only explained the observations at Basel (Goertz-Allmann et al. 2011, Bachmann et al. 2012), but were also consistent with observations at other geothermal projects (Kwiatek et al. 2013, Charlety et al. 2007, Evans et al. 2012). The presented modeling and magnitude probability estimation technique could be used in a refined traffic light system, where the future induced seismicity magnitude probability is estimated based on the previously recorded seismicity of an on-going operation.

Investigating the influence of some modeling parameters on the resulting seismicity suggested that the probability of LME is reduced if either the well is drilled less deep, or drilled into softer formations such as sediments instead of granite. This thought was taken further by Gischig et al. (2012) who investigated the influence of the injection parameters on the probability of occurrence of LME. However, their modeling results also suggested that the injection rate has a strong influence on the magnitude distribution.

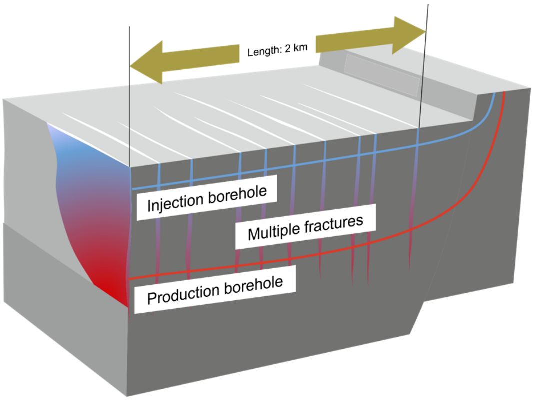

Fig. 2. Schematic view of multi-stage hydraulic fracturing in horizontal wellbores

According to their model, while maintaining the same volume, reducing the wellhead pressure and increasing the injection time reduces the probability of inducing a LME. This was also verified by particle based discrete element fracture network modeling by Zang et al. (2013).

In summary, the following insights were gained into the creation of LME at geothermal stimulations.

- The total seismic moment, and therefore also the probability of a LME is mainly driven by the injected fluid volume. Injecting less fluid typically leads to less seismicity, but also to smaller permeability changes in the reservoir. The latter can be achieved for example by sub-dividing the stimulated rock volume into several segments along a horizontal well, for example as shown in Fig. 2, as is typically done in hydraulic fracturing of Shale gas reservoirs.
- The LME probability is also reduced for shallower injections, and for injections into sediments instead of granite.
- The magnitude distribution of the seismicity and hence the LME probability can be driven by the injection parameters, most notably the injection pressure. At the same injected volume, lower injection pressure with longer duration of injection leads to lower LME probability.

Many LMEs have occurred on reactivated pre-existing fault planes. It is therefore necessary to identify pre-existing, seismogenic faults beforehand in order to better assess the seismic risk of a stimulation operation. The spatial distribution of faults and fractures can have an impact on the assumed frequency-magnitude distribution. Different frequency-magnitude distributions have a significant impact on assessments of the occurrence probability of an LME.

3.3 Overall summary of project results

Data sharing

A database of all relevant literature was established to serve as a reference for the work performed in the project. The literature was reviewed, including reports from non-government agencies such as the IEA, and the most useful literature has been defined. The database can be updated constantly and is accessible via a website. In addition, the datasets on induced seismicity to be worked were defined, and a meta-database has been established with link to owners or actual data. The data sets were assessed and data formats were defined for comparison of results. A master data set was defined from the various data sets available from Soultz-sous-Forêts.

Analysis of the fluid-injected micro-seismicity

Project partners worked on the various data sets to assess waveform data, improve technical procedures, and to image subsurface structures. First results suggested a significant improvement in the event locations using double difference relocation techniques. In addition, focal mechanisms from first motion polarities were defined at some of the geothermal test sites. An interesting observation was the aseismic motion identified at Soultz from 4D seismic P-wave tomography.

Larger magnitude events ($M > 2$) were investigated from the Basel and the Berlìn (El Salvador) data sets. Preliminary results suggested that the orientation of the fault segments identified by such events deviate significantly from the overall orientation of the seismic cloud at Basel. This was a significant constraint to be considered in realistic mechanical models developed in this project.

Understanding of geomechanics and processes of induced seismicity

Rock mechanics laboratory experiments and thermo-hydro-mechanical (THM) modeling, including dynamic rupture, have been performed. Laboratory experiments and hydro-mechanical modeling addressed the role of pore pressure in the rupture process. In addition, a heating system has been installed to the pressure vessel for the laboratory experiments to allow the investigation of temperature effects. Thermal impact was also studied in the data available from Soultz, and specific THM coupled models have been under development. Work has also started about the role of pre-existing fractures and the role of fluid circulation during fracturing.

Seismic hazard assessment

Seismic hazard assessment was performed to investigate and constrain consequences of induced seismicity. Results from the seismic analysis and the mechanical analyses were integrated in the assessment of the seismic hazard from induced seismicity. As a first step, the hazard associated to natural seismicity in the areas investigated in this project was determined. The seismic potential of a region served as a background seismic hazard for the studies performed in GEISER.

Seismic data of former EGS and on-going operations were collected for the development of strategies for the mitigation of induced seismicity. These data served as a basis for the investigation of correlation between seismic events and impact on human perception. Strategies for stimulation procedures minimizing seismic side effects were investigation (for example ‘soft stimulation’ modeling in Zang et al. 2013). Similarly, optimization of seismic networks for monitoring purposes and the development of real-time tools to monitor the evolution of induced micro-seismicity are subjects of on-going work.

3.4 Expected results and impact

The main impact expected from the project was the establishment of a procedure to realize the goals of enhancing geothermal systems with a reliable concept for the mitigation of induced seismicity. This concept ensured that geothermal energy can reach its full efficiency and profitability thresholds at the European scale. This goal required a mobilization of basic researchers in direct contact with project developers.

The results generated in this project are expected to help reduce unwanted hazards, and increase public acceptance, which is crucial for the installation and operation of geothermal plants. In addition, results of this project are expected to help increase EGS market introduction by providing licensing guidelines which will improve planning security. By developing a sound scientifically based concept for the mitigation of induced seismicity the GEISER project has the potential to help accelerate market introduction of EGS in many parts of Europe. The know-how for this concept will be developed in Europe, and its applicability is expected to be worldwide.

Regulatory guidelines handling operational hazards

With the provision of regulatory guidelines handling operational hazards due to underground exploitation, authorities will have better defined regulations and legal guidelines to cope with both political and physical damage of induced seismicity. This will provide planning security for developers and communities and is likely to unleash activity in the geothermal energy market.

Optimal monitoring infrastructures of underground exploitations

So far optimal monitoring of underground exploitations, balanced with operational, research and societal interests, is very seldom considered. In this project, it was aimed to optimize the monitoring impact by exchanging data, experiences, practice and new developments. It should be noted that, although the monitoring methods are specifically designed for the development of EGS, they can also be of great interest in hydrocarbon exploration, in the search for deep aquifers, in the planning of waste disposals and in other applications.

The success of the GEISER should have a kick-off effect on the development of geothermal resources in Europe but also it shall enhance the capability of European industry to compete on the world market of geothermal business. The project will represent a technological milestone in the development of a renewable, cost competitive geothermal energy.

4. CONCLUSIONS

Deep geothermal resources supply safe, reliable and environmental friendly energy. Through the development of advanced technologies such as Enhanced Geothermal Systems, geothermal energy could contribute substantially to the global energy production by accessing a larger part of the thermal energy stored in the Earth’s crust in regions where the natural permeability of the subsurface is not sufficient enough to extract hot water economically.

In this article, one of the EU funded geothermal energy projects, GEISER and summary of the results are presented. GEISER was aimed at an improved understanding and mitigation of induced seismicity hazards, and provided a State-of-the-Art risk management protocols.

As results, best practice guidelines are provided for safe and reliable EGS operations, centered on a probabilistic framework for the assessment of the risk posed by induced seismicity during all phases of an EGS project. The corner-stone of this framework is a well tested, forward-looking traffic light system, to be implemented in real-time in future EGS applications. This dynamic forecasting framework predicts the expected seismicity in the next hours and days. It is based initially on prior information, such as the proximity to faults, the subsurface stress conditions etc., but then is updated on the fly with real-time measurements of the observed induced seismicity and down hole pressure conditions.

GEISER also proposes a strategy to enhance public support for EGS projects, based on lessons learned from past projects. Nuisance and trivial damage should be addressed with care and considered as a significant project risk. For non-structural damage, a pre-agreed procedure is needed to evaluate and compensate the costs. The GEISER research efforts and best practice guidelines are important steps to enable the efficient and safe use of deep geothermal energy resources throughout Europe.

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Yoon, Jeoung Seok

2000 Handong Global University, Korea, B.Sc.in Construction, Urban and Environmental Engineering
(2002년 한동대학교 건설도시환경공학부 공학사)
2002 Seoul National University, Korea, M.Sc. in Civil, Urban and Geosystem Engineering
(2002년 서울대학교 지구환경시스템공학부 공학석사)
2007 Seoul National University, Korea, Ph.D. in Civil, Urban and Geosystem Engineering
(2007년 서울대학교 지구환경시스템공학부 공학박사)
Tel: +49-331-288-1716
E-mail: jsyoon@gfz-potsdam.de
Current affiliation: Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Section 2.6 Seismic Hazard and Stress Field

Zang, Arno

1987 Johann Wolfgang Goethe-University Frankfurt/Main, Germany, Diploma Geophysics
1991 Johann Wolfgang Goethe-University Frankfurt/Main, German, Ph.D. Geophysics
1998 University of Potsdam, Germany, Habilitation Geophysics
Tel: +49-331-288-1325
E-mail: arno.zang@gfz-potsdam.de
Current affiliation: Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Section 2.6 Seismic Hazard and Stress Field

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Bruhn, David

1991 Technical University of Clausthal, Germany, Diploma in Geology
1996 Swiss Federal Institute of Technology Zurich (ETH Zürich), Switzerland, Ph.D.

Tel: +49-331-288-1374
E-mail: david.bruhn@gfz-potsdam.de
Current affiliation: Helmholtz Center Potsdam, GFZ German Research Centre for Geosciences, Section 4.1 Reservoir Technologies and International Centre for Geothermal Research (ICGR)