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Summary of the European GEISER Project (Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs)

David Bruhn[1], Ernst Huenges[1], Kristjan Agustsson[2], Arno Zang[1], Xavier Rachez[3], Stefan Wiemer[4], Jan Diederik van Wees[5], Philippe Calcagno[3]

[1]GFZ Potsdam, 14473 Potsdam, Germany

[2]ÍSOR – Iceland Geosurvey, Reykjavík, Iceland

[3]BRGM – Bureau de Recherches Géologiques et Minières, Orléans, France

[4]ETH Zürich/Swiss Seismological Survey, Switzerland

[5]TNO Energy, Utrecht, Netherlands

dbruhn@gfz-potsdam.de

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ABSTRACT

The GEISER (Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs) project was funded by the European Commission from 2010 until 2013. The project addressed one of the major challenges the development of geothermal energy is facing: the mitigation of induced seismicity to an acceptable level. To address this objective, induced seismicity from representative geothermal reservoirs throughout Europe was analyzed (Soultz, Basel, Gross Schoenebeck, Iceland, Campi Flegrei). In addition, data from regions outside continental Europe were made available by companies and partners working in the respective caountries (Berlín, El Salvador; The Geysers, USA; Paralana and Cooper Basin, Australia). Induced earthquakes were analyzed with respect to their relationship with injection parameters, local stress fields, and geological settings. These analyses demonstrated that locating the hypocentres of the observed seismic events (seismic cloud) is dependent on the design of the installed network, the used velocity model and the applied location technique. Understanding the geomechanics and processes involved in creating induced seismicity. The influence of factors such as temperature, poro-elasticity, fluid injection rate, existing fault segments, and time dependent effects were investigated to better constrain the mechanisms involved during fluid injection. The project also addressed consequences of induced seismicity by providing an assessment of the seismic hazard presented by earthquakes triggered through human activity in comparison to hazards triggered by natural seismicity. Combining a statistics based approach – the classic probabilistic hazard assessment applied in seismology - with input from hydraulic and mechanical models about stress transfer and the rupture process, a dynamic forward-looking traffic light system is proposed to better mitigate large induced seismic events during geothermal operations. In addition, guidelines are proposed for licensing and site development for local authorities and industry. On the basis of these results and recommendations, strategies for soft injection have been proposed to mitigate large induced seismic events. Experience of past seismic events caused by the mining and the oil and gas industries have been included to address the proper handling of risk.

1. INTRODUCTION

Geothermal operations usually involve injection of fluid into one or several wells. For the development of enhanced geothermal systems, injection of large amounts of fluid at elevated pressures is the essential step of reservoir development, prior to exploitation. One of the key issues addressed by GEISER project is the seismicity, which is often induced by fluid injection (Majer et al. 2007). Earthquakes induced by human activities occur in most mining-related operations, depletion of oil and gas reservoirs, fluid injection in the subsurface and dam impoundment and they often reduce public acceptance of such ventures. Two promising geothermal projects jeopardized by this problem are at Landau/Germany and at Basel/Switzerland. In the latter case, the local population, felt repeated seismic events. These events, although not destructive, prompted the authorities to halt operations and eventually abandon the project. To avoid these problems, the GEISER project was designed to better understand and mitigate induced seismicity in the development of geothermal reservoirs.

In the reconnaissance phase of a field, the subsurface fault mapping, in situ stress and the seismic network are of primary interest in order to help assess the geothermal resource. The hypocentres of the observed seismic events (seismic cloud) are dependent on the design of the installed network, the used velocity model and the applied location technique. During the stimulation phase, the attention is turned to reservoir hydraulics (e.g., fluid pressure, injection volume) and its relation to larger magnitude seismic events, their source characteristics and occurrence in space and time. A change in isotropic components of the full waveform moment tensor is observed for events close to the injection well (tensile character) as compared to events further away from the injection well (shear character). Tensile events coincide with high Gutenberg-Richter b-values and low Brune stress drop values. The stress regime in the reservoir controls the direction of the fracture growth at depth, as indicated by the extent of the seismic cloud detected. Stress magnitudes are important in multiple stimulation of wells, where little or no seismicity is observed until the previous maximum stress level is exceeded (Kaiser Effect). Prior to drilling, obtaining a 3D P-wave (Vp) and S-wave velocity (Vs) models down to reservoir depth is recommended. In the stimulation phase, we recommend to monitor and to locate seismicity with high precision (decametre) in real-time and to perform local 4D tomography for velocity ratio (Vp/Vs). During exploitation, one should use observed and model induced seismicity to forward estimate seismic hazard so that field operators are in a position to adjust well hydraulics (rate and volume of the fluid injected) when induced events start to occur far away from the boundary of the seismic cloud

2. COMPILATION OF INDUCED SEISMICITY DATA FROM GEOTHERMAL SITES

The basis for all the scientific tasks to be performed needed to be laid by defining the precise datasets to be worked on as well as format and accessibility of the data. The datasets and an up-to-date list of the relevant literature both on induced seismicity and on the geology of the sites provided the prerequisites for the GEISER consortium to learn from experiences about induced seismicity, including experiences from oil and gas and other mining industries, to compile an inventory of key geothermal sites where fluid injection took place with/without induced seismicity, to subject all the data to an initial screening and to provide a standardized description of the data (metadata), listing all the relevant information for each dataset. This includes information about: type of data, which geothermal site it comes from, periods when data is available, quality parameters, ownership and confidentiality of data.

Datasets analysed were

- Latera (Italy), made available by Enel Green Power
- Berlín (El Salvador), made available by Shell
- Krafla, Hengill and Reykjanes (Iceland)
- Basel (Switzerland)
- Rosemanowes (UK)
- Groß Schönebeck (Germany)
- The Geysers (California, USA), made available by the USGS and Calpine, the site operator
- Paralana (Australia), made available by Petratherm

Additional datasets became available in the course of the project, as Geodynamics Ltd. (Australia) provided comprehensive information about their hydraulic stimulation tests in the Cooper Basin and continuous recording using a specifically installed network of broadband seismometers around The Geysers in California, sponsored by Statoil, and complemented the information available at the beginning of the project. In addition, information from the Campi Flegrei project in Italy became available during the project. The datasets were analyzed in terms of the spatiotemporal characteristics of the fluid-injected microseismicity and its relationship with injection and production parameters, the local stress field and the geological setting.

3. ANALYSIS OF INDUCED SEISMICITY IN GEOTHERMAL RESERVOIRS

As fluid injection and EGS operations normally produce a large number of microearthquakes, automatic processing is usually required. However, there is an uncertainty of automatic picks, if for example the data are noisy or if several events occur at the same time. A careful check of the picks, based for example on location error and residual values, is always a first step for improving the database. Another step to refine phase picks is to perform waveform cross-correlations for pairs of earthquakes recorded at the same station (Rowe et al., 2002). A refined approach was tested by Albaric et al. (2014) for data generated at Paralana. They first processed the data automatically with MIMO (Oye and Roth, 2003), to assess the quality of the automatic picks using a reference subset of events picked manually, and to crosscheck the database manually (for events with magnitude larger than one and for the large residuals). Finally, they improved the travel-time differences with waveform cross-correlation (Fig. 1) and relocated the events using the double-difference algorithm (Waldhauser and Ellsworth, 2000).

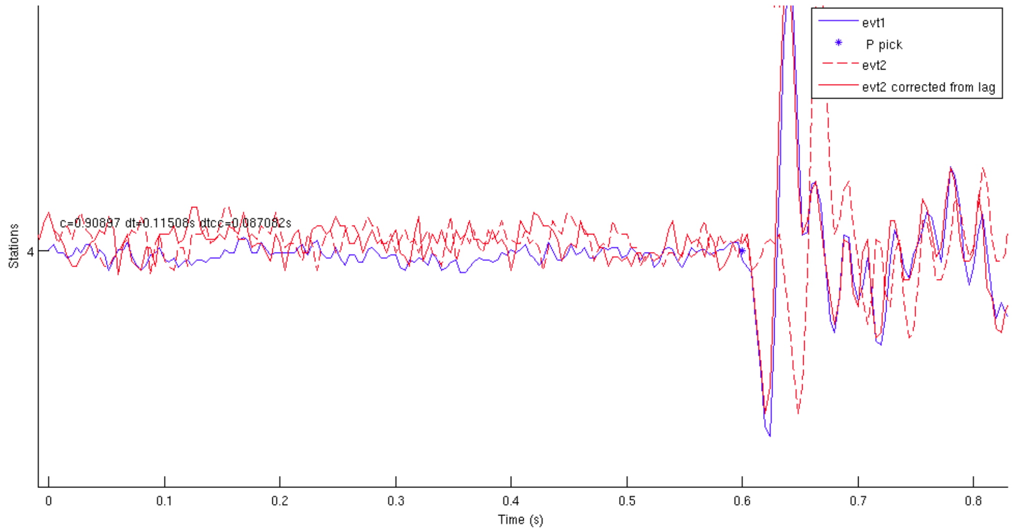

Figure 1: Seismograms of two events (1 and 2, blue and red, respectively) recorded at a surface station. Waveforms are aligned according to the automatic P-picks (blue star): wrong P-picks for event 2 is then highlighted by the gap between the waveforms (blue line and red dashed line). After waveform cross-correlation, the waveform of event 2 is correctly aligned (red line) with event 1 and the travel-time difference can be corrected

Seismicity data from three Icelandic geothermal fields, namely Krafla, Hengill and the Reykjanes peninsula, have been analysed. Data from Krafla that were obtained during the drilling of the IDDP well in 2009 have been analysed in some detail. The well was cased with a steel casing down to 1950 m and with a slotted liner around an aquifer at 1950-2080 depth at a top of a molten or partially molten magmatic intrusion. Low pressure stimulation with cold water during completion of the drilling and subsequent tests induced seismicity of magnitudes up to 1 in local magnitude. The epicentres initially followed the top of the magmatic layer horizontally away from the wellbore until it met an inclined fracture, most likely a pre-existing one. The epicentres then followed this fracture upwards showing the connection between the heat-mining zone at the top of the magmatic layer and the active fault systems (Fig. 2).

The data from Hengill contain seismic and pressure recordings obtained during drilling of an injection well in February 2011 for the 303 MWe Hellisheidi power plant in the Western part of the Hengill geothermal area. The injection well was drilled into a complex system of normal NE trending faults belonging to the axial rift zone of the Mid Atlantic Ridge in Iceland and N-S trending right lateral strike slip faults with character of the South Iceland transform zone. During the drilling, the well entered an open fracture at 1320m and total loss of circulation (40 L/s) was observed. A swarm of earthquakes was immediately initiated with magnitudes up to ML 2.2 (Fig. 3). The earthquakes were clearly felt in the neighborhood. These data were analyzed and used to investigate the interaction between injection and pre-existing fractures.

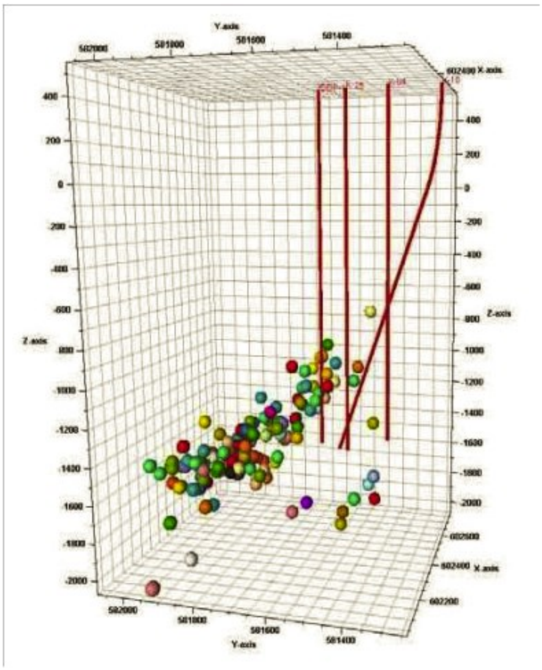

Figure 2: Location of induced events around the IDDP well at Krafla during low pressure stimulation with cold water

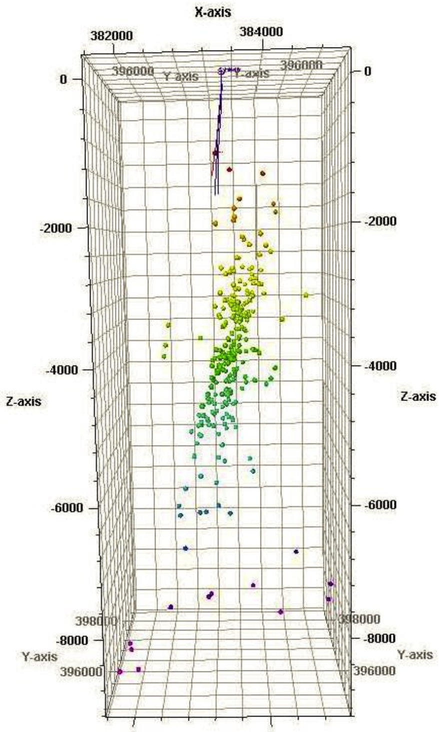

Figure 3: Induced seismicity during circulation loss of cold water while drilling an injection well

The Basel EGS project induced about 3500 seismic events in 2006. These occurred during the injection phase and the following months and were locatable by the six-station borehole network (Häring et al., 2008). Close to 200 of the strongest events were also recorded by various surface networks (e.g., Deichmann and Giardini, 2009). Preliminary hypocenter locations and magnitudes were obtained from manually picked arrival-times and amplitudes. This information was sufficient to map the overall orientation and dimension of the stimulated rock volume in near real time. Analyses on the vast data set acquired during the stimulation and high-precision relative location procedures of the stronger seismic events ($0.7 \leq ML \leq 3.4$), based on cross-correlations of signals recorded by a six-sensor borehole network and numerous surface stations in the immediate epicentral area, show that clustering of hypocenters on different spatial scales is a dominant feature of the microseismicity induced by the stimulation of enhanced geothermal reservoir in Basel (Deichmann et al., 2014). The detailed analysis of the sequences associated with the larger magnitude events (Mw >2) induced during the stimulation of the Basel EGS showed that the activated faults have dimensions on the order of several 100 m and are often oriented obliquely to the overall orientation of the microseismic cloud (Deichmann et al., 2014). These results reveal a complex internal structure of the flow paths in the rock volume stimulated by the water injection and imply that geo-mechanical models consisting of a single throughgoing structure are too simplistic.

Specific focus of the investigation of the multiple datasets of injection induced seismicity at Soultz-sous-Forêts was on the temporal variations of the elastic parameters through 4D seismic tomography, which is very useful for the understanding of the mechanical behaviour of the geothermal reservoirs, (e.g., Calò et al., 2013). Results of these studies show that injection tests performed in regions initially poorly connected to large faults are characterized by a low anomaly of the P-wave velocity mainly located around the zone where microseismic activity develops. In some specific periods (i.e. when the injected flow rate was suddenly increased) the velocity anomaly disappears suggesting that the velocity variations within the reservoir (and consequently the related variations of effective stress) are not associated with simple water diffusion from the injection well, but rather reflect the occurrence of large-scale aseismic events in the reservoir. In regions where pre-existing faults are well documented, the accumulation of effective stresses close to the well is avoided probably because the structures represent the main paths of the injected water. This results in a lack of large low Vp anomalies during the stimulation and in the occurrence of the induced seismicity located along the major structures.

The studies on analysis of seismic data from Berlín Geothermal Field, El Salvador performed at these sites were related to the high resolution reservoir characterization using induced seismicity data and state of the art waveform processing techniques. Three state-of-the-art algorithms, namely the Double-Difference (hypoDD) re-location technique, the Spectral Ratio (SR) technique and the Stress Inversion (SI) method were used to analyze induced seismicity generated by fluid injection and steam production. hypoDD significantly improves the precision of hypocenters allowing imaging of the fluid path and propagation in response to multiple injections with unprecedented detail (Kwiatek et al., 2014). In addition, the application of the SR technique provides refined source parameters that can later be used to interpret the subtle interactions between pressure perturbations, fluid flow and fracture (re-) activation within the reservoir.

The techniques described above to characterize induced seismicity and geomechanical processes at the two geothermal reservoirs represent selected case studies. These methods, however, can be applied to any data set of IS with a reasonably good quality of the recorded waveforms obtained from a sufficient monitoring network.

4. UNDERSTANDING THE GEOMECHANICAL CAUSES AND PROCESSES OF INDUCED SEISMICITY

The seismic events studied within GEISER were induced by injection either during regular operations such as in Iceland, where reinjection of cooled thermal waters caused microseismicity, or after hydraulic fracturing. The aim of the development of a geothermal site by hydraulic and/or chemical stimulation is to irreversibly increase the injectivity/productivity of a well by a local increase of the transmissivity of the fractures and/or faults intersecting the well and an improvement of the connectivity of the well to fracture and/or fault network. The generation of microseismicity is inherent to these methods of development of wells. However, if a large number of microearthquakes is inevitable, major events (magnitude larger than 2) must be studied carefully.

In GEISER, three major parameters were investigated to evaluate their relative importance and contribution to induced seismicity in geothermal systems:

1. Role of pore pressure changes
2. Role of faults and fractures
3. Role of temperature changes

Stress changes due to fluid injection or fluid withdrawal from geothermal wells were investigated by several approaches. A thermo-fluid dynamical approach in porous media to understand time dependent Coulomb stress changes involved the coupling of the two codes TOUGH2 and COMSOL. The approach consists of a two-step procedure: in the first step, injection or withdrawal of water is simulated by TOUGH2, by computing pressure and temperature changes in the volume; in a second step, the incremental stress tensor is computed by COMSOL. According to the models, stress changes can attain considerable values, able to significantly re-orient the mechanisms of most stressed fractures, with respect to the orientation due to the regional stress field alone. Also, the results highlighted that the main causes of induced seismicity during stimulation are due to the Coulomb stress changes generated by water injection, rather than by the effect of the temperature of the injected fluid.

Other analyses showed that for creating an EGS in compartmentalized sedimentary reservoirs, both the effects of pressure changes in the rock matrix and the impact of large scale heterogeneities should be taken into account. For simple systems dominated by few large fractures, poro-elasticity processes were most likely to control the overall thermo-mechanical process, by increasing the shear strength resistance of the fracture and balancing local traction and fracture opening effects, thus preventing large shear failure to develop.

A specific coupled continuous approach with FLAC3D was developed in order to study the role of pore pressure changes causing fault zone reactivation and inducing seismicity during the EGS operations. The results of this approach were compared to the results of the Block-Spring models as proposed by Baisch et al. (2010). A sensitivity analysis on key parameters such as the in-situ stress regime, the fracture or fault strength and fault frictional behavior after the onset of failure was performed for this purpose (Wassing et al., 2014). The models were also applied on the GPK3 stimulation case that was performed in Soultz-sous-Forêts in 2003. The basic features of the observed seismicity were reproduced. The 3D physical approach and the Block-Spring model showed their specific advantages: the Block-Spring model, if calibrated, establishes a fast modeling tool for sensitivity analyses; the FLAC3D implementation allows better understanding as it is based on actual physics. The most important output of the modeling is the frequency-magnitude relationship of the induced seismicity. It was demonstrated that it is well possible to arrive at relationships in line with what was observed in the field.

Fracture heterogeneities can also have a strong effect on the mechanical properties affecting the magnitude of an induced seismic event. This was shown by comparing a 3D multi fracture system and a single fault segment with heterogeneous properties under a given stress regime. Model results suggest that the development of shear is controlled by pressure diffusion, and therefore in both cases hydraulic properties, contrasts in properties of the various structures and boundary conditions are governing the mechanical process. The critical conditions with regard to the occurrence of large induced seismic events are obtained in the situation of some large fracture with unknown hydraulic properties at an intermediate distance to the well, and when the 'bulk' hydraulic diffusivity of the rock mass is limited. In the case this structure is also of poor natural hydraulic diffusivity, or locked by other fault segments, the risk of inducing a significant event is higher because it can be pressurized over a large region. Therefore tracking by geophysical methods any of these structural surfaces of potential failure at distances up to some hundreds of meters from a well is crucial.

Thermal effects and their impact during long term circulation tests were investigated by applying a Fractured Network approach based on a forward thermo-hydro-mechanical model of the in-situ observations made at Rosemanowes (UK). When injection pressure is maintained at constant level over time, shear can be re-activated at places where a previous rupture occurred, as soon as thermal tractions accumulated with time reach a magnitude similar to the stress drops generated during reservoir stimulation. The delay of a new event to occur is controlled by heat diffusion in the rock blocks adjacent to the fracture. Calculated seismic moments due to the long term cooling of the rock are one order of magnitude lower, but a small increase in injection pressure can trigger new seismic activity as soon as some thermal stress has accumulated. This result suggests that processes during initial reservoir development, the pre-stimulation phase, have a significant impact on the potential seismicity during or after stimulation. This is result is of major interest for the development of mitigation strategies.

5. SEISMIC HAZARD ASSESSMENT

The objectives of the GEISER project included the (i) development of a comprehensive framework to assess the earthquake hazard associated with natural seismicity and to the seismicity induced during and after EGS operations, (ii) development of statistical methodologies to assess the stability or increase in seismic hazard associated with EGS operations and (iii) testing of modelling tools of incremental accuracy to assess shaking and where possible damage which could be produced by EGS induced seismicity.

Part of the analysis was to compare natural seismicity with seismicity induced by geothermal operations. In particular, induced seismicity differs from natural seismicity in the fact that the rate of occurrence is correlated to the volume of injected fluids (e.g. Majer et al., 2007; Shapiro et al., 2010). Another characteristic of induced seismicity, compared to tectonic events, is the range of magnitudes considered. Induced seismicity can cause nuisance for magnitudes as low as m = 2 while standard hazard and risk modelling is defined for m =5+ (damaging events). It means that extrapolation of hazard and risk results from m = 5+ to $2 \leq m \leq 4$ inevitably leads to biases. This has been corrected at the hazard level with the definition of ground motion prediction equations (GMPEs) for induced seismicity data sets (Douglas et al., 2013; Edwards and Douglas; 2013).

After a systematic evaluation of the occurrence of induced seismic events at sites of geothermal projects in comparison to natural tectonic earthquakes and other types of induced or triggered seismicity in Central Europe (i.e., in Germany and adjacent areas), Grünthal (2014) concludes that observed induced seismicity at geothermal sites is minor in comparison to other sources of seismicity. Other types of induced events are those in areas of mining or exploitation of coal, salt and potash, hydrocarbon and ores. The analysis of induced seismicity used a data set of moment magnitudes $M_w \geq 2.0$, while the distinct larger natural seismicity includes events with $M_w \geq 2.5$.

The maximum observed magnitude of induced seismicity at geothermal sites is the smallest of the eight types of induced/triggered seismicity with $M_w = 3.2$ (Basel 2006) which is by far smaller than natural tectonic earthquakes ($M_w = 6.6$). The induced seismicity at geothermal project sites generates a well constrained cumulative frequency-magnitude relation. Its relation of the occurrence of the number of small to larger magnitudes, described as the *b*-value of 1.94, is among the highest of all types of induced seismic events and natural tectonic earthquakes (Fig. 4). The latter generate a *b* of about 1.16, which is characteristic for shallow crustal tectonic earthquakes. The high *b*-value of induced seismicity at geothermal sites means that, in comparison to other types of seismicity, a relatively large number of small events have to occur to enable the generation of larger ones. The rate of observed occurrence of relevant magnitudes M_w (e.g. in the range of $2.75 \geq M_w \geq 3.25$) at geothermal sites is the lowest of all types of induced events; i.e. one to two orders lower than for tectonic earthquakes and, e.g., two to three orders lower than for induced seismic events in the copper mining area of Legnica/Głogow (Poland). The maximum observed macroseismic intensities at geothermal sites were moderate only, with a few cases of weakest non-structural damage and without structural damage.

A key requirement for the accurate assessment of seismic hazard (and risk) is a ground-motion prediction equation (GMPE) that predicts the level of earthquake shaking (in terms of, for example, peak ground acceleration) of an earthquake of a certain magnitude at a particular distance. Few such models currently exist in regard to geothermal-related seismicity, and consequently the evaluation of seismic hazard in the vicinity of geothermal power plants is associated with high uncertainty. Various ground-motion datasets of induced (from Basel, Geysers, Hengill, Soultz and the Roswinkel gas field/Netherlands) and natural seismicity (Voerendaal/Netherlands) were compiled and processed, and moment magnitudes for all events were recomputed homogeneously. These data are used to show that ground motions from induced and natural earthquakes cannot be statistically distinguished.

Empirical GMPEs are derived from these data; and, although they have similar characteristics to recent GMPEs for natural and mining related seismicity, the standard deviations are higher. Douglas et al., (2013) developed stochastic models and subsequently GMPEs to estimate earthquake shaking in terms of peak ground acceleration and peak ground velocity that are valid from M_w 1 to 5. As an example, the potential use of these models using data from Campi Flegrei was shown within GEISER.

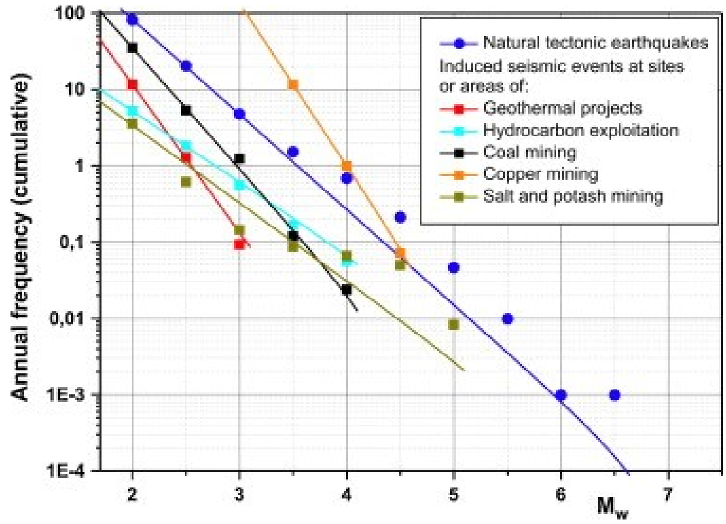

Figure 4: Frequency-magnitude distributions of all studied sources of observed seismicity normalized to their annual occurrence. Data for natural tectonic earthquakes are given according to observations from the last millennium. A maximum expected magnitude of M_{max} = 7.0 is applied to the maximum-likelihood fit of natural tectonic earthquakes . (from Grünthal, 2014)

5.1 Hazard models for specific test areas

A key challenge for the development of Enhanced Geothermal Systems (EGS) is to forecast the probability of occurrence of seismic events that have the potential to damage man-made structures. Therefore, a series of hazard models, based on different forecast models and hazard metrics were tested on various EGS induced seismicity sequences. Sequences include: Basel (Switzerland), Rosemanowes (United Kingdom), Soultz-sous-Forêts (France) and The Geysers (USA). The two types of proposed forecast models, statistical and physical, are complementary. At the present time, statistical models appear as a reasonable choice to forecast induced seismicity in a prospective way for decision support (e.g., traffic light systems). It has been shown that they fit the data well and that observed variations between the best models have a low impact on the overall uncertainty (Mignan et al., 2015). Physical models can also well reproduce observed induced seismicity sequences (e.g., Gischig and Wiemer, 2013). While statistical models may outperform physical models due to a lower number of parameters and a faster computation, physical models are crucial for a better understanding of the evolution of induced seismicity over longer time horizons, of b-value changes, or of Mmax (to only cite a few). However at the present time, there is no consensus on which physical model best describes induced seismicity.

To estimate the rate of occurrence of a seismic event of a given magnitude *M*, the maximum expected (or possible) magnitude (*M*max) needs to be defined as it is typically used in probabilistic seismic hazard assessment. While we usually know only the magnitudes of induced seismic events during development and operation of a geothermal reservoir (exploration, stimulation, circulation), *M*max stands for the very rare seismic event happening only every thousand or ten thousand years, and is difficult to be estimated based on observed data. This is because the observation periods in geothermal reservoirs are much too short to sample *M*max. Therefore, using the observed magnitudes instead of *M*max to assess the seismic hazard of a given site will result in an underestimation (lower limit value only).

Many efforts have been made to anticipate the size and rate of occurrence of earthquakes. In the structural geological approach, the maximum magnitude is inferred from the largest potentially active fault in the geothermal reservoir (e.g., Majer et al., 2007). Although typical reservoir faults may not be detectable by 3D seismic reflection they might be able to generate seismicity with local magnitudes between 3 and 4, depending on the stress drop (Evans et al., 2012). Apart from this structural geological approach, there are other methods to estimate the maximum magnitude: (1) The deterministic approach, (2) the probabilistic approach, and (3) the empirical approach (Zang et al., 2014). In the deterministic approach, the generation and propagation of fluid-filled fractures must take into account geometry, rock properties and in situ stresses for the simulation of a geothermal reservoir. In the empirical approach, the size of the activated geothermal reservoir is determined by the extent of the hypocentre distribution of the induced events stimulated rock mass – the so-called seismic cloud (e.g., Fehler et al., 2001).

To accomplish a classical Probabilistic Seismic Hazard Assessment (PSHA) a catalogue of induced seismicity is required. In addition, PSHA does not return any practical recommendation for how to treat the reservoir geomechanically in order to lower the probability of occurrence of induced seismicity. Thus, Hakimhashemi et al. (2014) propose to link the simulated stress changes from forward geomechanical numerical reservoir models with the statistical rate-and-state approach of Dieterich (1994). Using this link they translate the modelled time-dependent stress changes into time-dependent changes of seismicity rates. This approach is general and independent of the incorporated geomechanical numerical model used. The hybrid model approach is demonstrated using a geomechanical model that describes the stimulation of the well GPK4 at the EGS site in Soultz-sous-Forêts (France) including the shut-in phase. By changing the injection rate in the geomechanical model various synthetic injection scenarios were generated. With these scenarios the effect on the seismicity rate can be studied and recommendations can be provided for which injection rates will result in the least increase of seismicity rate. The results indicate an explicit coupling between the time-depending stress changes and the induced seismicity rate for each scenario. Even though the hybrid model cannot be used in general to derive absolute values of the rate of induced seismicity a priori (this is only possible if the geomechanical model can be calibrated against observed induced events), it serves as a tool to test the effect of stress changes on the induced seismicity rate. The approach developed here is a prototype model where the geomechanical model can be replaced by any other type of reservoir description.

Gischig and Wiemer (2013) used a 2D flow model with non-linear pore pressure diffusion in combination with a stochastic seed model. The transient pressure field was used to trigger seismicity at randomly distributed seed points. A differential stress normal distribution was assigned at each seed point, which is a potential seismic hypocentre. As in previous models, Mohr-Coulomb failure was assumed as well as an inverse relationship between stress drop and *b*-value (Scholz 1968). Random seismic magnitudes were assigned from *b*-values corresponding to stress drop values at seed points. These are the main assumptions of Gischig and Wiemer (2013), who generated synthetic seismic catalogue to reproduce the Basel induced seismicity data.

5.2 Advanced Traffic Light Systems

The most widely used tool so far for hazard and risk management and mitigation are so called traffic light systems first proposed by Bommer et al. (2006) for the Berlín geothermal project in El Salvador. This approach was also adopted for the EGS project in Basel, Switzerland (Häring et al., 2008). To monitor earthquake activity and for hazard mitigation actions, the traffic light system was adapted based on three components: 1) Public response, 2) observed local magnitude and 3) peak ground velocity. In a four-stage action plan, the injection of fluids would either be continued as planned (green), continued but not increased (yellow), stopped (orange) or stopped and a “bleed-off” initiated (red), where fluids would be actively released from borehole again.

The traffic-light system is defined ad-hoc and mainly based on expert judgment. The pressure reduction and eventual bleed-off of the system in Basel was consistent with the actions stipulated in the traffic-light systems. Adherence to this protocol, however, did not prevent the induced seismic events that eventually led to the loss of public acceptance and ultimately to the termination of the project. This outcome demonstrates that the traffic-light system a used up to this point is not a sufficient monitoring and alerting approach.

The way the initial traffic-light system is designed, actions are initiated in response to observations of the monitoring system. An advanced traffic-light system should ideally include a forward-looking component to have predictive qualities. Such an ‘Advanced Traffic Light’ (ATL) System has been developed within GEISER, forming the seismicity related safety components of a future control system for hydraulic stimulation. A schematic view of such a system is shown in Figure 5. Such ATL systems are a vital but currently non-existing ingredient of so-called protocols for induced seismicity management (e.g., Majer et al., 2007, 2012). Key distinguishing ingredients of such ATL systems are:

- **Forward looking:** Rather than being reactive schemes (i.e., a certain observed magnitude/intensity triggers a certain action), ATL systems are centered on robust, physics-based, forward-looking models that forecast the likely future seismicity evolution based on a range of key parameters (seismicity, pressures, permeability, static coulomb stress changes, etc.). Such forward-looking systems anticipate, for example, that the probability inducing the largest events in the hours after shut-in is substantial (e.g., Bachmann et al., 2012). The most advanced systems will not only limit the hazard and risk to acceptable levels, but concurrently optimize seismicity and reservoir creation.

- **Probabilistic:** Forecasts are made within a fully probabilistic framework that considers (1) the uncertainties related to our limited understanding of the physical processes acting during the stimulation and (2) the aleatory variabilities of the processes themselves. Such a probabilistic framework integrates also the view of the broader informed community. Induced seismicity hazard and risk assessment is thus elevated to the quantitative analysis level common for most critical infrastructures. By integrating the forecasted rates of events for all magnitudes, it also allows considering very unlikely, extreme events, without their becoming show stoppers in communication with the public.

- **Dynamic:** The forecasted seismicity is updated on the fly as new information becomes available (e.g., seismicity evolution, reservoir pressures etc.). All data are integrated combining prior knowledge with newly acquired data depending on the degree of certainty in the data and on past performance in forecasting. The updating strategy in terms of parameters to be estimated, time window and magnitude ranges to fit them to, is quite critical and an intrinsic component of each model. Mena et al. (2013) show that such an optimally on the fly combined model performs better than individual models, it is also smoother in its forecast earthquakes rates and subsequent hazard estimates.

At the heart of each ATL system is a set of models that forecast seismicity. From the GEISER perspective, there are three different classes of forecasting models that can be part of ATL systems (Figure 5): fully THM-coupled 3D numerical models including fractures on one side (e.g., Kohl and Megel, 2007; Rutqvist, 2011; McClure and Horne, 2011), purely statistical models on the other side (e.g., Mena et al., 2013; Shapiro et al., 2010) and hybrid models combining statistical and physical considerations (e.g., Bachmann et al., 2012; Goertz-Allmann and Wiemer, 2012; Langenbruch and Shapiro, 2010). The first class of models, fully coupled fracture models, is not yet ready for use in the probabilistic framework needed, where it is necessary to compute a large number (1000-10’000) of stochastic realizations of such catalogues to capture the uncertainty and extreme events, but can be used for deterministic (scenario based) analysis. While the Shapiro model performs best for the 2006 Basel induced seismicity and could be used as sole forecast model for hazard assessment, we suggest that development and testing of other models (e.g., geomechanical) should be encouraged to better understand the processes at the origin of induced seismicity in an EGS context.

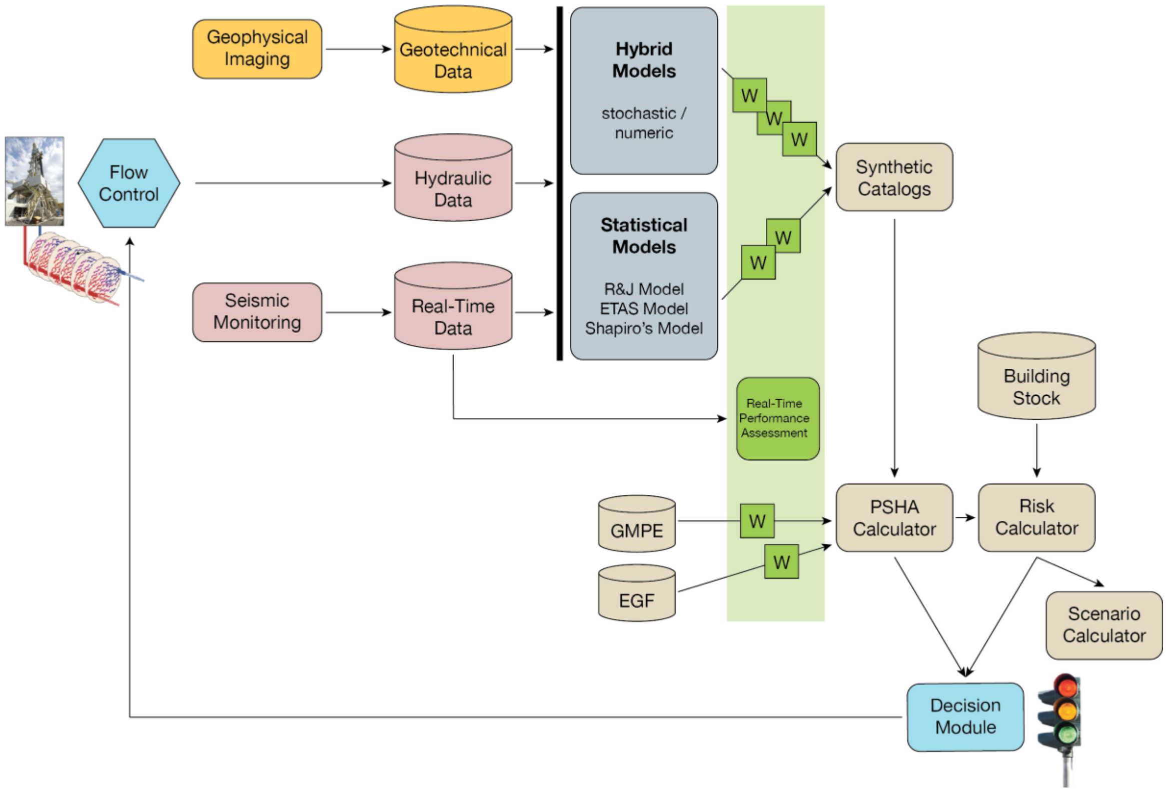

Figure 5: Advanced Traffic Light System: Schematic overview of the foreseen software framework. Legend: W = weighting; GMPE = ground motion prediction equation; EGF = empirical green's function; PSHA = probabilistic seismic hazard assessment

6. STRATEGIES FOR EGS OPERATIONS WITH INDUCED SEISMICITY

6.1 Guidelines for techniques/methodologies for seismological investigations to be applied in future EGS operations, developed on the basis of successful analyses of past sequences

Enhanced Geothermal System (EGS) operations are usually related to engineering of hot, low permeability rock. Similar operations are common, and will be applied in the future to a large extent in conventional fracture dominated geothermal systems. The reason for this is that geothermal energy can only be extracted from a small volume of hot rock surrounding the fracture systems. Permeability enhancement in boreholes and creation of artificial fracture for production, therefore, are considered crucial for future development of the reservoirs. The same applies to the re-injection wells in fracture-dominated reservoirs. The fluid injected must go either into open fractures that are a part of a tectonic fault system, or into new fractures that must be created. In general, the basic knowledge on design and safe operation of fluid injection is based on a geologic map with fault/fracture distribution, tectonic movements, stress field, and natural seismicity with estimates of the moment magnitude of the largest seismic event to be expected in the area of interest.

6.1.1 Seismological investigations

Our recommendation, in particular, is based on the analysis of induced seismicity in past sequences from geothermal areas located in different tectonic settings. The geothermal sites investigated include Basel (Switzerland), Berlin (El Salvador), Campi Flegrei (Italy), Krafla, Hengill and Reykjanes peninsula (Iceland), Paralana (Australia), Soultz-sous-Forets (France), and The Geysers, CA (USA). As a general note we strongly recommend to do a quality assessment of the recorded waveforms, and thereafter to apply four different techniques/methodologies for seismological investigations. We recommend to apply (1) a relocation method to reveal small-scale patterns in the induced event location clouds, (2) a spectral ratio technique to improve induced event source parameters, (3) a stress-inversion techniques to relate reservoir hydraulics to the stress field in situ, and (4) a passive continuous ambient seismic noise analysis for imaging changes in mechanical reservoir parameters during and after shut-in. These methods will provide the basis for the secondary well to be drilled. The costs for a thorough analysis of the waveform data practically is negligible when comparing to the costs of a borehole, which should be placed optimally.

6.1.2 Numbers suggested

Magnitude threshold (M= -1 to M= 0) as compared to the magnitude of completeness (Mc= 1, e.g. The Geysers); location accuracy (decameters); source parameters for event magnitudes down to (M= -1 to M= 0); magnitude of completeness should be two orders of magnitudes lower than the maximum acceptable/expected magnitude in the area. If tomography is planned for seismicity located at depth shallower than 5 km, a seismic network >16 stations in 6 x 6 km2 area with test injection is recommended. Source parameters like location, orientation, length, displacement, moment, rupture velocity, stress drop (apparent, dynamic, static) and seismic efficiency are the very foundation to (1) constrain mechanisms of M= 0 fluid-induced seismicity, (2) monitor near-well changes in reservoir stress, and (3) lead to more efficient reservoir management.

In terms of instrumentation, pre-site investigation should gather information on the velocity structure. This should include near-surface attenuation and noise studies for surface network design, and ray modeling for testing event location performance. After drilling a first well, Vp/Vs logging and in situ stress needs to be determined. This is important for interpretation of located seismicity and related source parameters. Data from borehole and surface stations allow to detect Vp/Vs-variations. For larger source-receiver distances (>3 km), a 3D velocity model is required. For this, seismic reflection lines and well-logs are needed.

6.1.3 Technical

Implement borehole and surface real time 4D systems (3D tomography at repeated times) for detection of shallow depth fluid migration paths based on (1) active mini-vibroseis trucks, and (2) continuous, ambient seismic noise analysis. For the passive seismic monitoring we recommend to use sensors adjusted to expected magnitude and frequency range. Field operator is advised to provide raw seismic data with no downscaling, high sampling rate and broad frequency band. This is a pre-requisite for applying the methods mentioned above (relocation, spectral ratio, stress inversion, ambient seismic noise). Distinguish between location accuracy of hypocenters relative to the injection borehole (absolute locations), and relative to each other (relative locations). A calibration shot is necessary prior to the start of the first stimulation. Based on the findings that more than half of the events occurred as sequences of events with almost identical waveforms, high-precision relative locations can help identifying orientation and length of faults activated during stimulation. This requires signal cross-correlation, master event and double-difference techniques. Combined with focal mechanisms, this information is essential to determine the stress state in the reservoir. Stress inversion from induced events, however, needs to be validated against stress analysis from wellbore measurements (borehole breakouts, hydraulic fracturing, extended leak-off tests).

6.1.4 Site specific issues

Distinguish between the injection into fractured, fault-free reservoir, and injection into fractured reservoirs with fault zone. In the first case, low anomaly of P-waves are expected in the zone of seismicity during injection. A cloud of induced events during injection is expected, and designated structures in the post-shut-in phase. The sudden release in flow rate will result in disappearance of velocity anomalies. The reasons for this are not pressure diffusion but large aseismic events. In the second scenario (reservoir with faults), no compact extended cloud of events will be expected, but seismicity will align along pre-existing faults. Monitoring by seismic noise tomography is recommended if no wells are available, VSP when first well is available.

6.1.5 Recommendations

Use hypoDD relative relocation to be performed for the located induced seismic events. This improves precision of hypocenters to allow for sharp images of fluid path ways and stress directions in response to multiple injections. Use spectral ratio technique to improve source parameters of the original seismic catalogue at geothermal sites. Refined source parameters are useful for interpretation of subtle interaction between pore pressure perturbations, fluid flow and fracture reactivation. Stress inversion from fluid-induced seismic events can help to relate stress field changes to hydraulic response of the reservoirs, and mechanical processes in the subsurface, in general.

6.2 Guidelines for Hazard Assessment

(1) Use a deterministic risk approach prior to injection to estimate roughly the expected losses (some hazard metrics could also be used) in function of induced event expected magnitude
(2) Use a probabilistic risk approach during injection by combining deterministic results to time dependent induced seismicity forecasts
(3) Distinct output metrics to communicate the risk to different interest groups (public authorities/regulators, operators, public, insurances)
(4) Include epistemic uncertainty using a logic-tree approach as well as realistic aleatory uncertainty (e.g., the seismic hazard "sigma") for an objective estimation of hazard and risk associated to EGS activities
(5) Define a clear traffic-light system following well-established methodologies and regulatory standards.

6.3 Mitigation of induced seismicity and its side effects

6.3.1 Injection regimes

A combination of different numerical tools has been employed to define the response of the reservoir to different injection parameters (temperature, pressure, fluid volume variation in time and space). In a numerical study using a hydro-mechanical coupled discrete particles joints model, Yoon et al. (2014) tested various injection scenarios which involve continuous and cyclic styles of pressure controlled and flow rate controlled injections. Results are compared which include: spatial and temporal evolution of induced seismic events in relation with fluid pressure distribution, moment magnitudes of the induced events, occurrence of post-shut-in large magnitude events, etc. Several field observations on induced seismicity phenomena are simulated which include creation of new fractures, re-activation of the pre-existing joints, post-shut-in seismicity and large magnitude event with non-double-couple source, Kaiser effect, moment magnitude vs. frequency distribution of the induced events following the Gutenberg-Richter law, etc. Cyclic injection results in larger volume of injected fluid but less number of total events and larger magnitude events; hence less seismic energy radiated by the induced events, slower relaxation of the fluid pressure after shut-in, longer and thinner propagated fractures with larger fluid saturated area. The major conclusions of this study are that the presented modeling is capable of simulating induced seismicity phenomena in Enhanced Geothermal System and fluid injection in fractured reservoirs in cyclic way has potential in mitigating the effects of larger magnitude induced events.

6.3.2 Seismic Monitoring

The guidelines defined are aimed at both regulators and operators and address two import aspects of seismic monitoring: (1) *monitoring requirements*, defined in terms of data quality, temporal/spatial coverage, resolution, etc., and (2) *monitoring network design and optimization*, which is presented in a number of case studies. For *the monitoring requirements* (1) we choose to follow the recent recommendations by the FKPE in Germany (Forschungskollegium Physik des Erdkörpers) working group on "Induced seismicity" for seismic monitoring in the general context of geotechnical facilities. The FKPE recommendation is intended for reliable observation of earthquakes one magnitude unit below the human perception threshold.

We adopt the FKPE recommendations for what we refer to as (a) *basic seismic monitoring*. However, the FKPE explicitly notes that their recommendation is not sufficient when the monitoring goal is to gain insight into the seismogenic processes. In the context of EGS and mitigation of induced seismicity the understanding of the seismogenic processes is of critical importance. We therefore extend the FKPE recommendations down towards lower magnitudes for what we refer to as (b) *reservoir seismic monitoring*. In our requirements we identify three main themes that are developed for both *basic* (a) and *reservoir* (b) seismic monitoring: (i) data quality, defined in terms of signal-to-noise ratios, frequency content and time-stamping accuracy; (ii) spatio-temporal coverage, defining both spatial and temporal intervals for the monitoring efforts; and (iii) data policy, where a general recommendation is to be as open and transparent as possible.

For the *monitoring network design and optimization* (2), we note that monitoring at least requires a network of continuously operating, time-synchronized seismic sensors. The network should be designed in such a way that it satisfies the monitoring requirements discussed above. In a surface network the sensitivity of a usually goes down to magnitudes around M=1 (at typical EGS reservoir depths), which is roughly one to two magnitude units below the perception threshold (i.e., the level that can be felt by humans at the surface). To extend the sensitivity of the network further down the magnitude scale it is usually necessary to install sensors in (deep) boreholes. To optimize the network design various approaches are possible and have been tested and included in GEISER. These studies can be provided as illustrations of proposed techniques for the design and optimization of seismic networks.

6.3.3 Guidelines

The following recommendations for European regulatory guidelines are proposed to prevent unsolicited effects of induced seismicity:

1) Set a maximum level of acceptable magnitude (Mtol), and associated threshold probability (Ptol) for earthquakes caused by stimulation and production. The project should be halted if the expected probability of Mtol is higher than Ptol and no operational adjustment can lower this probability.
2) Request the project developer for an assessment of expected probability of Mtol prior to stimulation and to set-up an advanced traffic light system to safeguard that the expected probability remains lower than Ptol, based on a physics based approach
3) Request the project developer to set-up a seismic monitoring network which follows recommendations above (6.3.2)
4) Provide incentives for project strategies promoting public acceptance. One such incentive can be a differentiation in exploration licensing, allowing for a desk study phase, prior to the drilling and stimulation license. The desk study phase allows to build an outreach program.

6.3.4 Public acceptance

A strategy for creating public acceptance for EGS-projects was formulated on the basis of experiences gathered by GEISER "Laying the Groundwork for Public Acceptance of Enhanced Geothermal Systems", which also includes recommendations for creating public acceptance of future EGS-projects. The proposed strategy entails the following steps:

- Preparation and context analysis: To identify different interests and (perceived) risks regarding a specific EGS project. This entails a cost-benefit balance for the stakeholders throughout the entire exploration and production workflow. This balance requires to take into account both technical-spatial and social-economic aspects in order to define the project strategies for creating public acceptance of EGS at a specific location
- Process design: The different interests and (perceived) risks allows to characterize the policy challenge. The policy challenge needs to be proper addressed through the project strategy, including a communication strategy and process definition of involvement of actors and associated actions
- the execution of the preparation, context analysis and process design are recommended to overlap with the common planning phase of EGS projects
- Implementation and evaluation: The next phases of developing an EGS project (drilling, logging and testing; stimulation; operation; post-operation) should correlate to the implementation phase of the project strategy. During the implementation of the project strategy (cq. stages of development of the EGS-project) the progress of the process will be constantly monitored and evaluated. If needed, the project strategy will be changed and adopted to the process dynamics.

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