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Deep Geothermal Energy
R&D Roadmap for Switzerland, 2014

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Introduction

The Deep Geothermal Energy roadmaps are intended to identify gaps in knowledge required for the development of deep geothermal energy in Switzerland.

They were developed through a series of workshops held in spring 2014 which were attended by academic and industrial stakeholders. The focus of the workshops and their dates were:

1. Exploration	17 March 2014
2. Reservoir Characterization	24 March 2014
3. Drilling and Well Completion	20 March 2014
4. Reservoir Creation	3 April 2014
5. Power Plants	16 April 2014
6. Economic modelling	16 April 2014
7. Risk Governance	11 April 2014

The roadmap documents were written by Keith Evans (Exploration, Reservoir characterization, Drilling and completion, Reservoir creation), Ueli Wieland (Economic modelling, Power plants) and Stefan Wiemer (Risk governance). The documents are based on the workshop discussions and protocols prepared by the workshop conveners, and input from the participants in the Roadmap Review meeting of 12 May 2014.

The roadmaps are a dynamic documents that will be updated on a yearly basis.

The summary of the roadmap presented below highlights the major challenges identified by the workgroups and outlines the principal initiatives to be taken in addressing them.

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Summary of the DGE Roadmap for Switzerland

Preamble: This condensed version of the Deep Geothermal Energy Roadmap summarizes research and development actions needed to exploit the deep geothermal resources of Switzerland for electricity generation at a commercially competitive price within the next 10 years.

Objectives: To enable the large-scale exploitation of deep geothermal energy for electricity generation in Switzerland, solutions must be found for two fundamental and coupled problems: (1) How do we **create an efficient heat exchanger** in the hot underground that can produce energy for decades while (2) at the same time keeping the nuisance and risk posed by **induced earthquakes** to acceptable levels? There is general agreement that only by enhancing the permeability of the underground in a controlled way, can these goals potentially be met. We believe that in order to make progress in answering these questions as rapidly as possible without compromising safety, three overarching and complementary initiatives will be conducted that supplement the SCCER capacity build-up:

a. Advance the capability to quantitatively model the stimulation process and reservoir operation

Numerical simulation is an essential tool for understanding the complex, coupled interactions of mechanical, hydraulic, thermal, and chemical processes active during reservoir creation and operation. Moreover, it allows scenario testing (e.g., the effect of different injection schemes) that may aid in decision making. This initiative will adapt and expand the capabilities of existing cutting-edge simulation codes by developing tools specifically targeted towards deep geothermal energy development. The new tools will allow the simulation of diverse mechanisms of permeability creation within explicitly rendered, geometrically complex geologic structures. Aside from simulating the evolution of permeability during stimulation injections, the tools will provide a basis for physics-based forecasting of seismic hazard, and also include fluid-rock interactions that are important for simulating changes occurring during reservoir operation. Interfaces with industry-standard reservoir rendering tools such as Gocad/SKUA, FRACA, FRACMAN or GOFRAC will be provided to allow the import of site-specific reservoir models, thus integrating numerical simulation into industrial workflows that will emerge with pilot and demonstration projects.

b. Advance process understanding and validation in underground lab experiments

This activity aims to better understand the processes activated by relatively high-pressure fluid injection into crystalline rocks under realistic conditions, thereby advancing the technology from overall TRL 3-4 to 4-5 (for Technology Readiness Level (TRL) definitions see European Union TRL definitions). Since many of the relevant processes for EGS, such as microseismicity and geophysical imaging, are scale invariant, meaningful experiments can be conduced safely within a deep underground lab (DUG-Lab) at depth of ≤1 km. Experiments conducted in the DUG-Lab under controlled conditions will allow: (a) to test concepts of **reservoir creation and long term operation** where there are numerous knowledge gaps that concern the nature of the permeability creation mechanisms activated by high-rate stimulation injections in fractured crystalline rock, and the development of stimulation strategies for controlling the process so as to optimally balance permeability creation against seismic hazard; (b) to test and validate methods for seismic hazard assessment and **risk mitigation strategies,** such as adaptive traffic light systems; (c) test new approaches to **reservoir characterisation** for developing a 3-D structural discontinuity model of the reservoir from sparse data derived from borehole logging and geophysical imaging; and (d) test and refine **exploration and monitoring techniques,** such as full waveform tomography inversion and interferometry methods, for tracking fluid pressure propagation, and stress evolution. These insights will lead to the development of advanced numerical modelling tools, as well as petrophysics laboratory experiments, which can be used to extrapolate the results to the temperature and pressures at the P&D target depth of 4-5 km.

Within the DUG-Lab, it is planned to conduct **stimulation experiments** at scales of 10 - 100 m with a high degree of experimental control. The experiments will explore the effects of stress/discontinuity geometry and injection design on stimulation efficiency. Within smaller scale-experiments (length of 1-10m) the temperatures and, to a lesser extent, the pressures can be increased artificially. A dense network of seismic, pore pressure and strain/tilt sensors within and around the stimulation volumes, together with detailed characterization of the rock mass from mapping and geophysics, and the eventual exposure of at least part of the volume with mineback operations will provide a world-class dataset. The analysis of the data will be helped by the complementary, parallel effort to develop the robust reservoir simulation and seismic hazard forecasting tools of Initiative 1, which include the relevant physical processes of permeability creation and earthquake rupture mechanics. Such tools are key to upscaling the results of the 10-100 m scale DUG-Lab experiments to the higher-stress and temperature environment of the full-scale P&D projects. To constrain the seismic risk for loss calculations and **insurance applications**, laboratory experiments will be used to calibrate ground motion prediction codes as well as the damage propensity of Swiss buildings exposed low intensity shaking.

The DUG-Lab should be operated by the SCCER consortium, under the leadership of ETH Zurich. Experiments should start in early 2015, and continue for at least three years, so that they can provide guidance and method validation for upcoming pilot and demonstration projects. They will also provide an opportunity for the SCCER teams and industry scientist to engage in trans-disciplinary research under operational constraints and with realistic data. Access to the data should be opened up to the entire scientific community no more than one year after an experiment was conducted. The DUG-lab should also be proposed as an international experimental facility, part of the EPOS rock laboratory infrastructure and proposed to the EU Horizon 2020 programmatic call LCE-02-2015.

c. Execute a petrothermal P&D project, supported by a major scientific monitoring & analysis initiative.

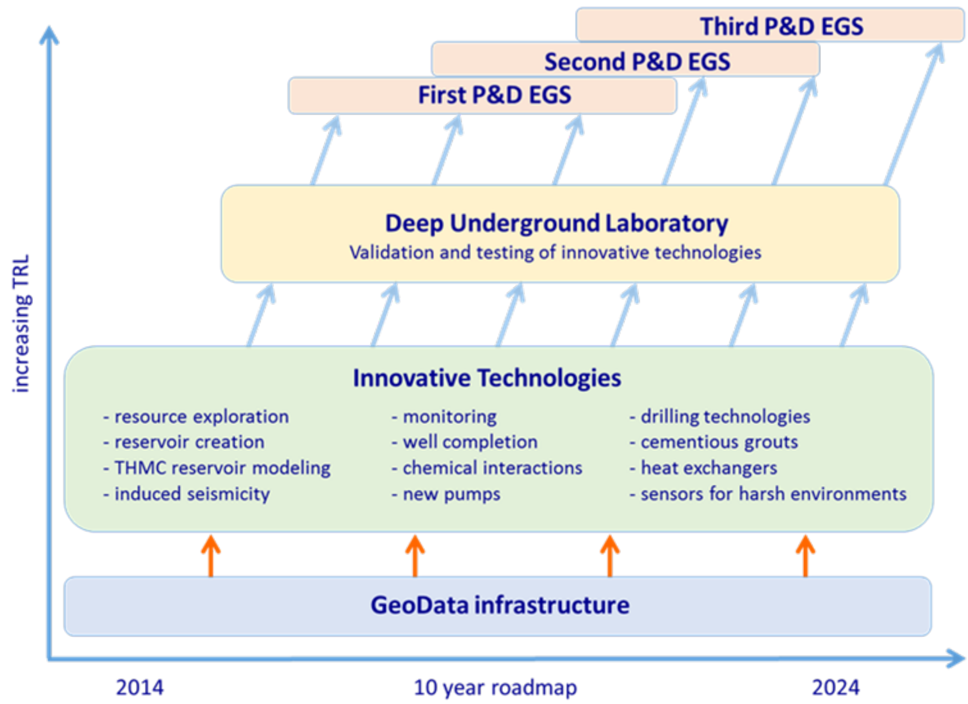
The next deep geothermal P&D project executed by industry will target the advance from overall TRL 4-5 to 6-7. It will focus on creating a petrothermal reservoir in crystalline rock at about 4-5 km depth using *multi-zone stimulation technology* deployed in inclined wells. We believe that for the assessment of the technology overall, this P&D should be designed and executed in such a way that not only the safety of operation is maximized, but also the knowledge gain with respect to process understanding and risk governance. Therefore, additional measurements and analyses are required that may not be needed, or cannot be funded, solely from an operator's point of view. This includes exploration and monitoring to refine the description of the geological context of the site, background seismicity, in-situ stress conditions pre-existing natural fracture zones, and risk relevant faults with length exceeding 1 km in the project area. A high-resolution 3D seismic survey and interpretation that extends at least 5 km from the drill site in all directions is highly desirable. These R&D efforts should include an independent 'social site characterisation' and continued monitoring of public perception and acceptance. Tools and methodologies for monitoring or estimating the reservoir porosity/permeability evolution, migration of induced seismicity, and fluid pressure propagation from surface and downhole measurements that have been optimised in DUG-Lab experiments will be applied in near-real time during the stimulation.

Reservoir characterisation will focus on imaging intermediate-scale structures (i.e. 0.1 - 1 km) within the reservoir, because these structures are likely to have a major influence one the response of the rock mass to stimulation. Such structures cannot be resolved from surface seismics, but borehole seismic methods such Vertical Seismic Profiling (VSP) adapted to image steep basement discontinuities, are promising in this regard. New approaches to constrain the size distribution of discontinuities (from fractures to faults) from variations in stress orientation along the borehole, and the size distribution of micro-earthquakes, are under investigation, as are constraints imposed by fracture interaction during genesis (TRL 1-2). Improved methods are also under development to extract stress magnitude information from wellbore failure observations (TRL 3-4). Reactive tracer tests between wells in hot reservoirs are likewise considered a gap. Such tests, when combined with non-reactive tracer tests, can provide an estimation of the surface area and volume of flow paths linking the wells, which are key parameters for estimating production longevity. Reactive tracers for cool environments are available, but those for hot reservoirs, such as will be encountered in the P&D projects, require further development. Instrumentation development needs include a robust down hole seismometer that can operate for long periods at elevated temperature (TRL 3-4).

To maximise the funding and research strength available, the next P&D project should be proposed also as a European initiative under the LC-03-2015 call and should be classified as an IPGT test site. Data from the site should likewise be made available through an open data policy.

Longer-term goals: The focus of **exploration and monitoring** will in the long-term address the nationwide mapping of parameters of interest, such as subsurface temperature distribution, location and orientation of faults and fractures, stress orientation and magnitudes, and the presence of mobilizable fluids. It will also include the long term monitoring of induced seismicity specifically with the goal of distinguishing with confidence between natural and observed earthquakes. The publically available heat flow map of Switzerland should be updated by including data collected since 1999, and a 3-D model of temperature down to 5 km depth should be developed. In the longer term, a systematic effort should be made to secure subsurface temperature and stress information when the opportunity arises, particularly in the Alps where data is sparse or, in many areas, non-existent. Consideration could also be given to the reprocessing of seismic lines in the Alpine Foreland to better-define lithologic structure, and the location of the Permo-Carboniferous troughs, perhaps aided by gravity surveys. Exploration research will be greatly assisted by the establishment of a national repository for borehole information under Swiss Topo.

Drilling and completion are the major cost components in any geothermal system. Innovative approaches to drilling technologies, such as spallation drilling, offer the long-term prospect of substantially reducing these costs and thus constitute potential game-changing research. Improved cements for geothermal wells are being developed that reduce the likelihood of premature hardening during cementation of casing. **Risk governance** will focus in the long term on standardised tools and best practise during all phases of future projects. The ability to forecast before drilling the reservoir properties and seismogenic response will be critical to maximise the success rate of future projects. Finally, **cost optimisation** of all components will become a dominant theme once EGS technology has been proven to be feasible and safe.



Terminology

Types of geothermal reservoir of interest

Classical EGS systems seek to extract heat from low-permeability rocks where there is relatively little water in-place by constructing a heat exchanger between two or more boreholes in the rock mass. The technology to achieve this was pioneered at the Fenton Hill site in New Mexico, USA by the nearby Los Alamos National Laboratory, who developed two reservoirs that operated from 1974 to 1992 in two separate phases. Such systems were referred to as Hot Dry Rock systems. Subsequently, other terms have been used to emphasize different aspects of specific reservoirs, such as Hot Dry Rock (HDR) and Hot Wet Rock systems. More recently, classical HDR systems have become known in German speaking countries as Petrothermal systems, to emphasize the distinction from hydrothermal (conventional geothermal) systems where there is a significant quantity of hot water in-place. Petrothermal systems are also known as EGS systems. However, there is no consensus as to whether 'EGS' denotes Enhanced or Engineered Geothermal Systems. A sensible distinction between the two is to identify Engineered Geothermal Systems as Petrothermal systems, to emphasize the fact that they involve the engineering of the heat exchanger. Enhanced Geothermal Systems are more logically identified with poorly-performing hydrothermal geothermal systems whose productivity has been *enhanced* by applying reservoir stimulation technology. Since the focus of this roadmap is the development of systems in deep rock masses that have relatively little water in-place, the term 'petrothermal' and 'EGS' are used, with the latter denoting engineered geothermal system.

Distinction of rock mass discontinuities at different scales

Shear discontinuity structures exhibit geometries that appear similar at different scales, but their mechanical and hydraulic properties change with scale. Thus, it is important to define a terminology for referring to structures at the scales of interest to reservoir development. In this document, single discrete discontinuities of dimensions up to tens of meters will be referred to as fractures, discontinuity structures of dimensions up to several hundred metres composed of organized clusters of smaller-scale fractures will be referred to as fracture zones, and structures larger than this will be referred to as faults. It is recognized that discontinuities exist at all scales, and the boundaries between the three discontinuity categories are not physically well-defined, although faults, having accommodated greater slip, are more likely to have developed a continuous gouge core. Fracture zones can equally be thought of as faults in the decametre to hectometre scale. The practical reasons for distinguishing the three scales are as follows:

- Faults are important for hydrothermal systems as high permeability/porosity targets, whilst for petrothermal systems large faults are potential sources of damaging earthquakes and are to be avoided.
- Brittle fracture zones up to scales of several hundred meters are key structures for the development of petrothermal systems inasmuch as experience shows their permeability can be enhanced by hydraulic stimulation if stress conditions are appropriate. However, their relatively small scale makes it less likely that earthquakes large enough to be felt will be induced by the injection operations.
- The role played by fractures that are not part of fracture zones in the stimulation of permeability of the rock mass is less obvious, and depends upon the attributes of the family in question such as density, connectivity and sealing. An important objective of the reservoir creation research program is to develop stimulation strategies that will promote connectivity and hence flow through these fractures.

1. Exploration roadmap

Workgroup Participants

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Additional contributions

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Scope

Exploration is considered to be all activities pursuant to the identification of promising sites for the drilling of a geothermal exploration well. The activities associated with the well drilling, exploration well or otherwise, are considered in the chapter on 'Reservoir characterization'.

This roadmap addresses both hydrothermal and petrothermal reservoirs, although the primary focus lies with petrothermal systems since these are considered to have greater potential for large-scale deployment. The exploration tasks differ in that hydrothermal reservoirs require prospection for subsurface fluids, whereas petrothermal reservoirs do not.

There are 6 principal aspects of the underground that need to be considered in identifying favourable sites for the drilling of an exploration borehole:

- Heat flow and temperature distribution
- Lithology
- Fracture/fault distribution
- Stress state
- Risk of producing felt earthquakes
- Presence of high connected-porosity/permeability (i.e. in-place fluids)

In the current “exploration roadmap”, the characterization of fracture/fault populations and of stress regime are considered independent aspects. The core processes underpinning reservoir creation for petrothermal systems are governed by the interaction of the stress field with discontinuities (i.e. natural fractures, fracture zones or faults), but in ways that are not yet well understood. For this reason, it is not yet possible to definitively identify configurations of stress and discontinuity population characteristics as being favourable or unsuitable for petrothermal reservoir development. Consequently, no attempt is made at this stage to combine stress and fracture information for evaluating site suitability.

Heat flow and temperature distribution

Importance and state of current knowledge

The temperature field in the Swiss underground is of paramount importance for geothermal development. Knowledge of heat-flow and temperature distribution in the underground is most complete in the Swiss Plateau, Jura and Pre-alps, and poor in the Alps with the exception of Ticino. The most recent publically-available heat flow map of Switzerland, produced by Medici and Rybach in 1995, shows surface heat flow estimates north of the Alps trending from ~70 mW/m^2 in the south to ~100 mW/m^2 in the north, with some localized zones in the north where values as high as 140 mW/m^2 are inferred. Thus, heat flow is generally higher than the average for continental crust of 65 mW/m^2. The large-scale trend of increasing heat flow towards the north in the Foreland reflects variations in basal heat flow (lower crust, mantle lithosphere, asthenosphere). The localized heat flow variations in the north probably reflect hydrothermal activity whose depth of extent is uncertain. More recent unpublished analyses of heat flow that include more data from boreholes drilled since 1995 confirm the overall pattern of heat flow suggested by Medici and Rybach, but add refinements that are important for temperature prospection. It is thus essential to update the publicly-available heat-flow map of Switzerland by incorporating all existing data.

Currently available temperature data from numerous boreholes in the region north of the Alps provide good constraints on the temperature distribution down to 2.5 km depth in many areas of interest[1]. However, there are very few holes deeper than 2.5 km in Switzerland. Thus, temperature at 5 km must be inferred from diffusion-based models of heat flow constrained by the shallower data. Temperature predictions at 5 km are impacted by uncertainties in thermal conductivity structure at depth and a possible advective component to heat transport from fluid flow, the latter being particularly important in the zones of high surface heat flow in the northern Foreland. Generally, greater uncertainty in temperature estimation at 5 km applies to localities remote from deep boreholes, or in regions with large lateral gradients in heat flow, which current maps suggest can reach 2 mW/m^2 per lateral kilometre near the localized zones of high heat flow in the north. A 5 mW/m^2 change in heat flow into the base of the crustal column at say 10 km will result in a change in temperature at 5 km depth of 9°C, assuming a mean thermal conductivity of 3 W/m/°C for the rock column.

In the Alps, the absence of a thermal blanket of sediments means that a temperature gradient of at least 35°C/km must prevail in the crystalline rock to reach 180°C at 5 km depth. This is a relatively high gradient for crystalline rock, and would require a high surface heat flow arising from high basal heat flow or highly radiogenic rock or both (for comparison, the temperature gradient in the granite at Basel is only 28°C/km, even though there is a high heat flow of 85-100 mW/m^2). However, uplift of the Alps, which in some areas is as high as 20 km in 20 Ma, would also serve to increase the temperature gradient. (It should be noted that the presence of thermal springs in the Alps reflects structurally-driven hydrothermal activity and does not necessarily indicate high temperatures at 5 km depth.) The few existing heat flow data in the Alps do not suggest high heat flow, but the data are too sparse to draw firm conclusions in this regard. There are also few measurements of the petrophysical properties of rocks relevant to evaluating thermal structure of Alpine regions. An advantage of geothermal exploitation in the Alps is posed by the opportunity to benefit from the severe topography by locating drill sites in valleys.

Knowledge gaps and research recommendations

Further work should address the following:

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[1] A new map showing the depth of the 70° isotherm in the foreland north of the Alps is included in the TA-Swiss report "Energie aus dem Innern der Erde: Tiefengeothermie als Energieträger der Zukunft" to be published in November 2014.

- Update the publicly-available heat-flow map for Switzerland by using all available temperature information to constrain models of the thermal structure of the Swiss underground. This requires access to information that is currently proprietary. The models should simulate steady-state conductive heat flow within a medium that has the appropriate regional lithological structure and petrophysical properties, and be constrained by measured temperature profiles from boreholes, corrected for paleo-temperature and advection affects.
- From the thermal modelling above, produce a 3D-representation of *estimated* temperature distribution in the Swiss underground, with 2-D maps showing the *estimated* temperature at 2 and 5 km depth.
- Improve knowledge of the thermal structure in the Alps by:
  - Consolidate and expand the number of heat flow measurements by processing existing data or seizing the opportunity to make measurements in future underground construction projects.
  - Expand the database of petrophysical property measurements for crystalline rock types found in the Alps.

Lithology

Importance and state of current knowledge

The lithology of the target heat reservoir determines: the physical properties that have a bearing on the temperature gradient and the response to geophysical exploration methods (e.g. electrical conductivity, MT, seismic attenuation); the chemical properties that influence pore fluid composition, the response to chemical stimulation, and the processes occurring during long-term reservoir operation (clogging or dissolution of porosity, corrosion); the structural properties such as the presence of anisotropies (schistosity, bedding); and the hydraulic properties such as the connected porosity of the rock matrix (exclusive of faults/fractures).

The 3D distribution of major lithologies in the sedimentary cover of the Swiss Plateau, Jura and northern Alpine margin are well known from existing regional geophysical atlases. However, if the target reservoir temperature is taken as 180°C, then the target rock volumes lie within the upper crustal crystalline basement and Permo-carboniferous troughs almost everywhere in Switzerland. The types of lithologies in the basement and Permo-Carboniferous troughs are quite well defined. However, knowledge of their 3D distribution is presently poor and should be improved. The thickness of the weathered zone at the top of the basement is also of interest.

Knowledge gaps and research recommendations

Further work should address the following:

- improve the definition of the 3-D lithology distribution of the basement underlying the sediments of the Alpine foreland
- map the thickness of the weathered zone at the top of the basement
- refine 3D maps of stratigraphic horizons from existing seismic surveys
- evaluate the sensitivity of exploration geophysical methods to detect different lithologic types
- identify and correlate lithologies observed in cuttings and core samples from available deep wells to construct geological models that allow for spatial extrapolation.

Fracture/fault distribution

Importance and state of current knowledge

The terminology used for distinguishing shear discontinuities at different scales is described in the section 'Terminology'. The attributes of the discontinuity population that are of primary relevance to deep geothermal reservoir development are the location and orientation of faults, particularly large ones. The orientation of fracture zones and fracture families, and the density of fracturing is also relevant, but resolving these smaller structures at reservoir depths is difficult. In the Alps, where structures in basement rocks are observable in outcrop, the degree to which the attributes of the near-surface discontinuity population can be extrapolated to depths of several kilometres is uncertain. Other attributes that are relevant to reservoir development such as connectivity and permeability, cannot be determined from surface observations.

In the sediments north of the Alps, the recently published seismic atlas of Switzerland provides a structural model down to a few kilometres depth. The approximate locations of faults that cut the 2-D seismic lines are indicated, although the coverage is limited. Knowledge of the 3-D network of faults in the sedimentary cover could be radically improved by including data from the large number of remaining lines that have not yet been reprocessed. However, old basement faults which have not been active since Mesozoic deposition began have no expression in the sedimentary cover and thus would not be imaged. Studies of crystalline rock masses underlying sediments in the basement of northern Switzerland by Nagra suggests that rock mass volumes that are unfractured on reservoir scales (< 1 km dimension) are rare or absent, at least in the uppermost 1500 m of the basement.

The Permo-Carboniferous troughs that underlie the Swiss Plateau and Jura are potential hosts of petrothermal systems, and the bounding faults are of interest to hydrothermal systems since they may be associated with a high degree of fracturing and porosity. The distribution of these troughs remains poorly known.

There are some localities where attributes of the discontinuity population in basement rocks have been relatively well determined for engineering or tectonic studies. Such cases are exceptional. Characterizing steep discontinuities in the hidden basement is a challenge, because they are difficult to detect by seismic surveys. In this regard, studies of basement discontinuities in quarries and hydropower tunnels in the southern Black Forest might yield useful 'analogue' information, since the rocks have been subject to a similar history.

Knowledge gaps and research recommendations

- Improved mapping of faults in the basement. Exposures in the Alps, and in quarries in the south Black Forest provide opportunities to study discontinuity distributions, but the situation is more challenging for the basement beneath the sedimentary cover north of the Alps. Reprocessing of existing seismic lines whose penetration depth extends to basement is unlikely to resolve high-angle basement structures unless they produce a vertical offset of the interface of the basement with the overlying Mesozoic sediments. So the absence of an offset does not imply the absence of a fault. Seismic reflection is not well suited to resolving high-angle basement faults. Nevertheless, 3-D seismic reflection surveys could be useful for identifying basement faults that have been active in dip-slip sense since Mesozoic. Natural seismic activity can also be used to obtain the approximate location of currently active faults, although the absence of natural seismicity does not imply the absence of active faults.
- Improve knowledge of the distribution of the Permo-Carboniferous troughs, particularly the location of their boundary faults. This could be addressed with seismic reflection surveys combined with gravity surveys.
- The characteristics of discontinuities with scales smaller than 1 km in deep basement is difficult to assess from surface measurements, particularly north of the Alps where there is sedimentary cover that contains an evaporite detachment horizon. Advanced methods of processing seismic reflection data (e.g. shear-wave splitting) can resolve velocity anisotropy, which can be reflective of preferred fracture orientation, stress orientation, or both.
- Testing the robustness of ‘analog approaches’ for characterizing fracturing at a locality where information is sparse (i.e. assessing the validity of using information from rock masses at other localities that are assumed to have experienced a similar fracturing history).

Stress state

Importance and state of current knowledge

Stress is a first-order parameter that, together with the discontinuity distribution, governs the response of the rock mass to fluid pressure change. It is also important for wellbore stability. The stress state in the reservoir can be described to first order by seven values describing the linear trends with depth of vertical stress magnitude, Sv, minimum and maximum horizontal stress magnitude, Shmin and SHmax respectively, together with the orientation of Shmin (usually taken as constant with depth to first order). Deviations from this simple, laterally-uniform model, referred to as stress heterogeneity, are invariably present, and may have a significant influence on the response of the rock mass to injection.

Vertical stress is almost entirely gravity-derived, and thus can be readily estimated from knowledge of the density of rocks.

The mean orientation of Shmin (and by implication, SHmax) at depths up to several kilometres has been estimated at deep borehole sites in Switzerland from wellbore failure observations. These estimates are usually consistent with indications from local earthquakes that reflect stress at significantly greater depths (8-15 km). Moreover, the variations in Shmin orientation define a reasonably coherent pattern that can be related to active tectonic processes, although some local deviations are evident. Nevertheless, the current stress map of Switzerland provides a useful indication of the likely orientation of Shmax in many regions. However, the same is not true of stress magnitudes due to the paucity of magnitude measurements in boreholes. Earthquake focal mechanisms solutions indicate regional difference in the relative magnitudes of the three principal stresses. The few reliable stress determinations that have been conducted in Switzerland provide no reason to doubt that the potential reservoir rock masses in Switzerland are critically-stressed inasmuch as they support high levels of shear stress and are close to failure.

Knowledge gaps and research recommendations

- Improve knowledge of stress magnitudes in the Swiss underground. This will require:
    - project developers conduct the type of hydraulic tests that will estimates of Shmin magnitude to be derived (i.e. hydrofracture, mini-frac, or extended leak-off tests).
    - the development of methods to extract useful estimates of SHmax magnitude (assuming Shmin is known) from wellbore failure observations, in particular, the geometry of breakouts. This in turn requires that project developers run the type of logs necessary to provide an adequate description of wellbore failure (i.e. acoustic televiewer).

Potential for producing damaging earthquakes

Importance and state of current knowledge

Large faults proximate to geothermal development sites are potential sources of triggered earthquakes large enough to produce damage or be felt by the local population. The strength of such faults can be bounded, but not precisely. Similarly, the stress distribution prevailing on such structures can be estimated if stress measurements are performed in proximity, but again not precisely. These two uncertainties prohibit the estimation of the proximity of conditions on a fault to large-scale failure. From a seismic hazard mitigation perspective, it is important to identify such faults, and determine whether they are active. As noted in the section 'Fracture/Fault Distribution' of this roadmap, 3-D seismic reflection surveys are not well-suited to resolving high-angle basement faults, unless they have been active in dip-slip sense since Mesozoic and so have offset the basement-sediment interface. Thus, 3-D seismic surveys are relevant to hazard assessment, even though the absence of an offset does not imply the absence of a fault. Scrutiny of the seismic record for local earthquakes, and the operation of seismic networks at prospective sites are necessary in this regard. However, the absence of seismicity on a fault does not necessarily imply it is not active.

Empirical studies of the seismic response of the underground to fluid injections associated with geothermal reservoir development and operation might allow combinations of factors that promote felt or damaging events to be identified. A particularly important parameter for the assessment of seismic hazard at a locality is Mmax, which is a measure of the largest earthquake that could occur at a location due to reservoir operations.

There is considerable on-going research into the mitigation of seismic hazard associated with EGS reservoir creation operations. However, the seismic response to long-term operation of an EGS has not received much attention. Two long-term effects of relevance arise from thermo-elastic stresses generated within and around the reservoir volume by cooling, and the cumulative effect of net injection in systems where the more fluid is injected than produced (i.e. unbalanced circulation). There is no experience with long-term operation of an EGS beyond the two years of continuous circulation of the system at Rosemanowes in Cornwall, UK, where reservoir temperature was only ~90° and so thermo-elastic stresses developed due to cooling would be significantly less than expected for a 180° reservoir. In the case of unbalanced circulation, there is evidence to suggest that seismic hazard increases with net cumulative volume injected, which would favour systems which are close to balanced. It is doubtful that systems which require a large amount of make-up water to achieve commercial production flow rates would be practical, the recommended maximum being 10% of production. In this regard, the hazard associated with EGS operation is substantially less than for long-term fluid injection in isolated wells.

Knowledge gaps and research recommendations

- Identification of observable physical and environmental parameters that indicate a greater propensity for injection to produce felt earthquakes on a fault.
- Evaluation of the long-term effects on seismic hazard of EGS reservoir operation.

Presence of high connected-porosity/permeability (i.e. in-place fluids that can be mobilized)

Importance and state of current knowledge

The identification of subsurface fluids in high connected-porosity sedimentary formations or around damage structures such as faults facilitates the development of hydrothermal systems. Prospection methods to this end seek to identify the higher electrical conductivity of the fluids. Magneto-telluric methods are most commonly employed by conventional geothermal reservoir prospection. Some uncertainty exists regarding the impact of surface installations such as pipelines, railways, and deep evaporite formations on the resolving power of MT-methods. This aspect requires investigation.

The presence of gas in the target formation or target fault structure can pose a safety issue in drilling and in reservoir operation. Gas in overlying formations can pose a safety issue during drilling prior to well completion.

Knowledge gaps and research recommendations

- Evaluate the practicality of applying MT-methods for the prospection of hydrothermal resources in various Swiss settings (e.g. Alps, Plateau).

Recommendations for short-term action for exploration

Update the publicly-available heat-flow map for Switzerland by using all available temperature information to constrain thermal conduction models of the thermal structure of the Swiss underground.

- Every effort should be made to include data that is currently proprietary.
- A determined effort should be made to improve our knowledge of the thermal structure of the upper crust of Alpine regions, particularly in the top 5 km.

A corollary of the modelling will be the production of a 3-D image of temperature distribution, from which 2-D maps of estimated temperature at 2 km and 5 km depth can be extracted.

Improve the 3-D mapping of faults, stress state and sub-surface electrical conductivity at the sites that have been earmarked by industrial partners as prospective geothermal plays. A long-term goal that would have benefits beyond geothermal prospection is to extend this mapping nationwide.

2. Reservoir Characterization roadmap

Workgroup Participants

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Scope

Reservoir Characterization covers activities performed once a site has been selected for drilling. It includes all activities pertaining to the characterization of the reservoir in the state it exists before and after stimulation. There is a separate roadmap dedicated to stimulation.

This roadmap addresses petrothermal reservoirs, since these are considered to have greater potential for large-scale deployment.

The description of reservoir characterization operations is broken into 6 principal topics:

- Temperature measurement considerations
- Characterization of lithology and petrophysical properties
- Development of a discontinuity model in the reservoir
- Characterization of stress and stress variations within the reservoir
- Characterization of hydraulic properties
- Characterization of seismogenic properties

Monitoring of drilling parameters such as rate of penetration, torque and mud logging for gas, is routine and will not be dealt with explicitly.

As a prelude to the discussion, the impact of well design (i.e. vertical versus inclined) on reservoir characterization operations and objectives, and the merits of drilling a slim exploration well are first addressed.

Impact of well design on reservoir characterization

The approach taken for reservoir characterization depends upon the well design. There are two aspects to this. Firstly, if the well is to be deviated from vertical so as to lie sub-horizontal in the reservoir, then stress- and perhaps discontinuity-orientation information must be collected at the base of the vertical section to help decide the optimum azimuth for the sub-horizontal section. Logging operations and deployment of downhole sensors are more complicated in sub-horizontal than vertical holes since the wireline tools do not sink to hole bottom under gravity. Secondly, if a multi-zone completion is to be used in the reservoir, then the intervals for isolation (and later stimulation) should ideally be selected on the basis of logging information acquired prior to completion.

An optional consideration is to explore conditions in the prospective reservoir by first drilling a smaller-diameter, vertical *exploration well*, ideally to penetrate the basement. The saving in drilling costs depends upon the depth of the basement surface, as well as the hole diameter and type of drilling approach used. Over much of the Swiss plateau and Jura, the hole would have to penetrate evaporite layers which may pose a difficulty for the continuous core drilling used in mining and geotechnical engineering. Small hole sizes pose little problem for wireline logs, since the oil and gas service companies offer a broad range of sondes that can be run in holes as small as 76 mm (ultra-slim tools). Stress characterization from wellbore failure and hydrotests, together with drilling experience would provide the information needed for designing subsequent deviated wells. The stimulation and seismic response of the rock mass could be assessed by conducting a high-rate injection, although this would impose a lower limit on the hole size due to friction losses. A dedicated exploration well could also permit a borehole seismometer, or better still, a string of seismometers to be placed close to the reservoir. The near-field sampling of the waveforms of events generated by the reservoir stimulation operations would allow improved definition of the structures activated by the reservoir creation process. A downhole tiltmeter could also be deployed to monitor the static deformation field. However, the requirement that the well allow the placement of downhole seismometers or tiltmeters would impose constraints on the minimum hole size. Further considerations of the practicality of drilling a slim exploration borehole prior to a full-size hole are presented in the section 'Exploration hole' in the Drilling and Completion roadmap.

Temperature measurement considerations

Importance and state of current knowledge

Circulation of mud during drilling results in strong cooling of the rock volume around the borehole that may take months to dissipate. Measurement of the reservoir temperature profile a few days after drilling and again a week or two later allows a useful estimate of the undisturbed reservoir temperature to be made. The estimate improves when later logs are included in the analysis.

Measurement of the temperature of the drilling mud prior to exiting the bit provides useful information for extracting stress magnitude information from drilling-induced tension fractures. Such downhole data can be acquired with measurement-while-drilling (MWD) systems.

Distributed temperature sensing with fibre optic cables offers the possibility of continuous monitoring of the profile of temperature along the well in the reservoir. This is of general interest, but it is particularly important for monitoring the temperature of fluid exiting the reservoir at the feed zones in production wells. Such data provides early warning of thermal breakthrough, which imposes strong constraints on the flow paths in the reservoir. Fibre-optic cables for distributed temperature measurement are now available for long-term monitoring of high-temperature wells in the oil and gas industry, and can be permanently embedded in the well completion or run into a hole after the well has been completed. Importantly, they can remain operational even when a downhole pump is used.

Knowledge gaps and research recommendations

- The temperature of drill mud prior to exiting the bit is a parameter of interest to the stress analysis and should be measured if possible.

Characterization of lithology and petrophysical properties

Importance and state of current knowledge

Determination of the lithologies penetrated by boreholes is routinely done by combining geophysical logs with cuttings analysis. Drilling parameters and mud-logging can also provide an alert to a lithology change or the intersection of a major discontinuity such as a fracture zone. Geophysical logs usually provide good resolution and depth control of lithological variations, but interpretation of their mineralogical nature is greatly enhanced if there is 'ground truth' from cuttings or core.

Mineralogical determination from cuttings suffers from mixing of cuttings, and variations in the rise times of different minerals, which limits the ability to resolve the detailed nature of mineralogical changes that occur over short section of hole, such as from dykes, or alteration in fracture zones. Cuttings also provide little or no information on the mineralogical fabric of the rock, which can only come from core samples.

The rock mass petrophysical properties of interest that can be determined with standard geophysical logs in crystalline rock are: p- and s-wave velocities, bulk density, dynamic elastic moduli (by combining velocity and density logs), uranium, thorium and potassium content, and radiogenic heat production (from a spectral gamma log). The standard logs also provide various measures of enhanced porosity that can occur at discontinuity structures (i.e. neutron, density, resistivity, sonic). The porosity of intact crystalline rock is generally not resolved from logs, and must be determined from tests on core samples, as must all related poro-elastic properties. Porosity is important for estimating the volume of injected fluid that enters storage in the intact rock during the stimulation. Measurements of thermal conductivity and thermal expansion coefficient, taking account of anisotropy when significant, are also best conducted on core, although it is possible to obtain useful but imprecise estimates from mineralogy, as is also the case with specific heat capacity.

The characterization of the strength of intact rock and fractures also requires core samples. Strength indices derived from logs (usually velocity) can be found in the literature but are not considered robust. Knowledge of intact rock strength is important for simulating permeability creation processes, and for extracting stress magnitude information from breakouts. Sliding experiments on rock samples can help define the evolution of frictional strength of fracture surfaces during sliding episodes which includes the effects of weakening and healing of the interface (i.e. rate-and-state friction laws). Such a characterization is important for physical models of the failure process, and for assessing the likelihood that slip on fractures can occur aseismically. The strength of larger-scale structures such as fracture zones is more difficult to estimate as it is influenced by the geometry of the structure and the presence of rock bridges and possibly alteration. Samples of fractures captured in core are valuable for revealing the presence and nature of alteration or filling, which is relevant for assessing their large-scale strength. Slickensides, which indicate the predominant direction of relative shear displacement suffered by the fracture, may also be evident. The upscaling of the small-scale roughness, aperture or hydraulic permeability of the cored fracture surface to the full scale of the discontinuity are challenging problems.

Core is very expensive to extract from deep wells, but nevertheless provides relevant information that cannot be obtained in any other way. If a short spot-core sample is taken, it is a matter of luck whether a fracture will be captured. Coring in a fracture zone runs the risk of core loss because of mobilization of the damaged material in the drilling mud, unless special precautions are taken. An alternative to conventional core recovery is to take sidewall cores. These can extracted from depths of interest selected on the basis of the geophysical logs. It is important that the samples are large enough to facilitate laboratory testing.

Knowledge gaps and research recommendations

- The question of whether the knowledge benefits that stem from the availability of core justify the expense of the coring operations needs further consideration. The absence of core would primarily impact research.

Development of a discontinuity model of the reservoir

Importance and state of current knowledge

The terminology used for distinguishing shear discontinuities at different scales is described in the section 'Terminology'. The discontinuity distribution within the reservoir rock mass is a key factor that, together with stress, determines the rock mass response to stimulation injections. Local outcrop of reservoir rocks are usually not available, and so the discontinuity information must be obtained from borehole or geophysical observations.

Discrete fracture network (DFN) models of reservoirs are usually generated by combining deterministic information of the fractures and fracture zones imaged along boreholes with stochastic realizations of the fracture network within the reservoir generated using distribution functions that describe the various attributes of the discontinuity population. The development of DFN models is an area of active research which attempts to compensate for the sparse sampling of the fracture network by incorporating constraints on the network geometry from the mechanical interaction of the fractures during the process of genesis.

The basic information for generating a DFN can be summarized as follows. Conventional fracture imaging logs define the location and orientation of individual fractures that cut the wellbore. This information constrains the statistical distributions of fracture orientation, which allows fracture families to be identified, and fracture spacing, including clustering characteristics. The logs provide no information about fracture length and connectivity, and so it is usual to assume some distribution function that is seen to be realistic for outcrop studies. However, it would be much better to constrain the distribution from observations of the reservoir in question. Two possibilities under investigation are to constrain the fracture length distribution from the magnitude-frequency distribution of micro-earthquakes triggered in the rock mass during stimulation, or to use the scaling characteristics of stress orientation variations determined from wellbore failure. Fracture length scaling constitutes a gap.

Clusters of fractures are often an expression of the internal structure of larger structures (e.g. fracture zones) that are believed to exert a large influence on the permeability of the rock mass and thus are targets for stimulation. These structures are best identified by combining fracture imaging logs with geophysical logs that are sensitive to the higher connected porosity associated with damage (e.g. velocity, density, neutron). Larger structures may also be identifiable from drilling parameters. The orientation of larger-scale structures is usually not well-defined, although some constraints are imposed by the observed orientations of their internal fractures. Their scale and extension from the borehole, a matter of considerable importance, cannot be quantitatively determined from standard geophysical logs, although structures that have greater width and damage are likely to be larger.

The imaging of larger structures within the reservoir represents a major technology gap. Vertical seismic profiles (VSP) with clamped and oriented borehole seismometers can, in principle, image larger structures within 100 m of the borehole. They can also resolve velocity anisotropy arising from a preferred orientation of fractures or a rock fabric. Field experiments in geothermal reservoirs to demonstrate the capabilities of VSP are planned. High-resolution imaging of the microseismicity accompanying stimulation injections is currently the richest source of information regarding reservoir structures remote from the wellbore. Once a second well is drilled, cross-hole seismic profiling becomes possible, although a strong source will be needed if the holes are 500 m or more apart.

Knowledge gaps and research recommendations

- Development of methods for estimating the length distribution of discontinuities in a reservoir.
- Development of constraints on DFN models that respect fracture genesis considerations.
- Development of borehole-based seismic methods such as VSP for imaging large discontinuity structures within the reservoir.

Characterization of stress and stress variations within the reservoir

Importance and state of current knowledge

The determination of the state of stress and its variability within the reservoir is essential for the understanding through quantitative simulation of the reservoir response to stimulation injection. Knowledge of the orientation of the principal horizontal stresses also enters into the selection of the optimal azimuth of sub-horizontal wells, thereby requiring a first campaign of measurement before the well is deviated from vertical.

The stress state in the reservoir can be described to first order by seven values describing the linear trends with depth of vertical stress magnitude, Sv, minimum and maximum horizontal stress magnitude, Shmin and SHmax respectively, together with the orientation of Shmin (usually taken as constant with depth to first order). A description of deviations from this simple, laterally-uniform model, referred to as stress heterogeneity, are also needed to adequately describe the initial conditions in the reservoir.

The vertical stress and its gradient can be obtained by integrating a bulk density (gamma-gamma) log.

The mean orientation of Shmin can be obtained from wellbore breakouts and/or drilling-induced tension fractures (DITFs) which can be readily imaged from available wireline logs. These features are almost always present in deep boreholes, and are often sufficiently continuous to allow the variability of Shmin-orientation to be quantitatively described, thereby providing a window into stress heterogeneity.

Minimum principal horizontal stress magnitude, Shmin, can be estimated from high-pressure, small-volume, cyclical injection tests performed on short-section of hole, ideally free of natural fractures. The procedure is identical to that used for hydrofracture stress measurements. However, most recent deep geothermal projects in Switzerland have dispensed with such measurements for practical reasons (e.g. time taken with the rig on standby, and the high risk of inflation packer failure in deep-hole situations), with adverse consequences for stress characterization. An economic opportunity to make such measurements arises following a casing cementation operation. It is common practice in the oil and gas industry to drill a short section of the hole below the casing shoe and pressure-test the section to determine the pressure at which leakage from the section begins to increase (a formation-integrity test (FIT) or a leak-off test (LOT)). A variant of this that features a cyclical pressurization and known as an extended leak-off test (X-LOT) provides an estimate of Shmin, although it is only an upper-bound since there is the possibility that it is opening a pre-existing fracture, rather than a new fracture normal to Shmin.

The estimation SHmax magnitude is the most difficult stress attribute to estimate. It is becoming increasingly common to estimate SHmax from the measured width of breakouts, although this method remains at the research stage. Improvements in the understanding of the conditions under which breakouts form (i.e. the failure criterion) is important. DITFs can also be used to constrain SHmax provided the temperature of the mud exiting the bit during drilling is measured, or can be reasonably estimated. It should be emphasized that SHmax estimates from wellbore failure observations are much better constrained if estimates of Shmin are available.

Focal mechanism solutions from earthquakes triggered in the reservoir during hydraulic stimulation also provide constraints on the average stress tensor within the volume that contains the microseismic sources.

Knowledge gaps and research recommendations

- Improve methods for estimating stress magnitude estimates from the geometry of breakouts. This requires a better knowledge of the conditions under which breakouts form.
- Improved understanding of stress heterogeneity. Identification of the factors underpinning observed stress variations might lead to scaling relations that would allow the statistical simulation of stress heterogeneity in reservoir rock masses. Such descriptions would improve the specification of initial conditions for reservoir simulators. Stress heterogeneities are also likely to be related fracture zones and faults and thus value could be gained by treating the problem of identifying fracture zones/faults and stress heterogeneities jointly.

Hydraulic characterization

Importance and state of current knowledge

Following drilling, an initial production test is preferred since it helps to clean-out drilling mud and cuttings from permeable zones and also provides an opportunity for sampling the formation fluid, which is desirable to permit geochemical and isotopic analyses. However, production tests require the capability to handle hot fluid at the surface and may not be practical. Downhole sampling of the fluid can reduce the volume of fluid that must be flowed-back to obtain a relatively uncontaminated sample, and is essential to capture dissolved gas content. Pre-stimulation injectivity/productivity of wells in petrothermal reservoirs is likely to be small, and hence flow rates are likely to be small. Tests at several different flow rates are required to evaluate whether the impedance to flow is pressure dependent. Transient data from such tests can provide useful information about the hydraulic characteristics of the reservoir, but require downhole pressure measurement.

Discontinuities along the well that are permeable are important because they are targets for hydraulic stimulation. Thus, their location must be identified before the well is completed with zonal isolation system. A spinner log run during a low-pressure injection test can indentify the location of fractures that take major flow, and allow their transmissivity to be determined. However, fractures which take minor flow during an injection test are also important since they have connected permeability. Such fractures can be identified as zones of enhanced cooling in temperature logs run after the injection, or from Stoneley wave reflection logs.

Once the well is completed, a more exacting, pre-stimulation hydraulic test program can be conducted on each interval, the details of which depend upon the type of completion. It is important that pressure is monitored downhole during testing to allow well-test analysis methods to be applied to the transient data.

The post-stimulation hydraulic characterization program also depends upon the constraints imposed by the completion. If the well is cased to bottom, with the reservoir feed points accessed through perforations, then double-packer systems could be used to selectively test the stimulated intervals. If all intervals are tested together, then spinner logs must be used to determine the flow taken by each interval (i.e. the flow profile of the well)

Long-term circulation of a built system will require occasional repeat measurement of the flow profile (e.g. repeat spinner logs). It would be advantageous to have permanent flow measurement at each interval, but there is currently no technology available that could serve this purpose.

Tracer tests conducted between two boreholes yield valuable information on swept volume of the flow paths linking the wells. Swept area can, in principle, be derived by using reactive and non-reactive tracers. However, there are relatively few documented examples where this has been successful in geothermal systems, and so it is still considered to be research. Single-well tracer tests have been proposed, but their practical utility is uncertain.

Knowledge gaps and research recommendations

- Hydraulic tests must have downhole pressure recording to facilitate analysis of transient phases and thus obtain a more complete hydraulic characterization of the reservoir than given by the steady-state parameters of injectivity/productivity.
- Velocity logs run in 'Stoneley mode' should have sufficient recording time to allow permeable fractures to be identified (Stoneley reflectivity processing).
- Permanent downhole flow measurement is a technology gap.
- The use of reactive/non-reactive tracers for estimating swept area requires further investigation.

Characterization of seismogenic properties

Importance and state of current knowledge

The seismogenic response of the reservoir to stimulation is important not only for the imaging of potential permeability enhancement, but also for seismic hazard. It is planned by GeoEnergy-Suisse that a seismic network able to locate events as small as magnitude Ml -1.0 that occur within the reservoir will be operational at least 6 months before drilling activity commences. It is considered desirable to evaluate the seismogenic response of the reservoir prior to the reservoir creation injections so that statistical parameters required for predictive modelling can be obtained.

At some stage in the development of a system, the opportunity to operate a seismometer at depth close to the reservoir will arise. This opportunity should always be taken, because the recording of waveforms closer to the reservoir allows finer details of the processes underpinning the seismic event to be resolved. There is currently no commercially-available, clamped 3-component seismometer that has a proven track record of operating in a hot borehole for long periods. This is recognized as a technology gap.

Knowledge gaps and research recommendations

- Development of a clamped 3-component seismometer that can operate in slim boreholes (i.e.< 160 mm) at temperatures of 150°C for long periods.

Recommendations for short-term action for reservoir characterization

Activity in reservoir characterization will accelerate once site activities at the Pilot and Demonstration project or the planned Underground EGS laboratory commence. For the immediate future there are several issues that should be addressed

- The development of the capability to produce Discrete Fracture Network (DFN) models of EGS reservoirs, and the underlying problem of constraining the probability distribution functions of the various discontinuity attributes, particularly the scaling of fracture length. Existing data from the Basel and perhaps other reservoirs can be used.
- Development of methods to extract stress magnitude information from breakout geometry.

3. Drilling & Completion roadmap

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Scope

This chapter of the roadmap addresses issues and research needs for drilling and well completion.

Well design considerations

Previous attempts to develop petrothermal reservoirs have featured vertical wells completed with long open-hole sections in the reservoir. Stimulation injections performed into such sections invariably resulted in flow enhancement at only a few of the fracture zones along the well. Commonly, the uppermost zone becomes dominant, most likely because the natural stress gradients in most reservoirs favour upward growth of stimulation for both shear and hydrofracturing/jacking. As a consequence, a large volume of rock around the lowermost part of the open hole will not be stimulated. It is planned to incorporate two design features in future wells to ameliorate this problem. Firstly, zonal isolation technology, which allows the targeted stimulation of several selected zones along the well, will be employed. Secondly, the well trajectory will be deviated from vertical to lie ~30° from horizontal in the reservoir section. This has the advantage of giving a long section in the reservoir along which stress conditions are more uniform. Furthermore, since target discontinuity structures in the regions of interest tend to be predominantly sub-vertical, more structures can be intersected by an appropriate choice of azimuth. The combination of sub-horizontal wells and zonal isolation for multi-zone stimulation (hydrofracturing) has proven decisive for opening up gas and oil shale reservoirs to commercial exploitation. This roadmap assumes that both measures will be implemented in developing petrothermal reservoirs.

Exploration wells

Importance and state of current knowledge

There are clear benefits to drilling a vertical exploration hole to explore conditions in the target reservoir before committing to a full-size, deviated hole. Such a hole would provide the reservoir characterization information needed to assess its suitability for development of a petrothermal heat exchanger within it, and also for choosing the optimum trajectory of the full-size deviated well. It could also allow the placement of downhole seismometers and tiltmeters near to the reservoir, which would be valuable for monitoring the stimulation. However, an evaluation of drilling costs for wells accessing basement in the Swiss Plateau suggests that there is little financial saving to be gained by reducing well size from ~8 inch to ~6 inch. The projected costs are similar. Continuous core-drilling systems that are used in mining typically produce micro-holes of 3-4 inch diameter and can drill to several kilometres depth. Such small hole sizes would allow logging, and might also allow the deployment of MEMS-type seismic monitoring sensors, but not conventional sensors. The practicality of drilling such small holes through the evaporite layers that are present under large areas of the Swiss Plateau is questionable. Nagra evaluated the benefits of drilling micro-holes for exploration and reservoir characterization and concluded that the risks outweighed the cost benefits.

Knowledge gaps and research recommendations

- Project developers currently do not plan to drill a slim exploration hole to the reservoir prior to the full-size well. The benefits of such an exploration well are primarily research-orientated. The discussion as to whether to drill an exploration well at the first P&D site, and how to finance it, should be continued.

Drilling considerations

Importance and state of current knowledge

The technology for drilling deviated wells is now standard and readily available. Rotary steering systems (RSS) that function up to 200°C are now available. However, there is relatively little experience worldwide in drilling deep, sub-horizontal wells (i.e. within 30° of horizontal) in crystalline rocks. Sub-horizontal wells have already been drilled in crystalline in the offshore fields of Vietnam where oil is found in faults within granitic rock (e.g. the White Tiger field), so it is clearly possible. Nevertheless, it is recognized that the greater abrasion of crystalline rock poses a risk to drill tubing integrity. This is an issue that should be addressed by the drilling companies.

There are several innovative drilling technologies that are currently being researched, such as spallation drilling which is being developed at ETHZ. These offer the prospect of radically reducing drilling costs, but are unlikely to be ready for commercial deployment with 10 years.

Knowledge gaps and research recommendations

- Continue fundamental research on innovative drilling technologies (long-term)

Completion: zonal isolation

Importance and state of current knowledge

Zonal isolation is generally recognised as a key technology that could radically improve the performance of petrothermal systems. There are three completion options for realising zonal isolation which can be summarized as follows.

The simplest and cheapest way that zonal isolation can be accomplished is through the use of diverters in an open hole completion. Diverters are additives to the stimulation injection fluid that accumulate in and block active feed-zones, thereby forcing the wellbore pressure to rise and new feed zones to become active. The diverter material can be removed after the injection. Thermally-degrading diverters were successfully used in the hydraulic stimulation of a well at the Newberry, Oregon EGS project. The disadvantage of diverters for zonal isolation is that they do not offer the ability to selectively control which zones are stimulated. This control can be secured by building the zonal isolation capability into the well completion. This is routinely done in gas-shale reservoirs, and is the preferred solution for GeoEnergy-Suisse in their planned wells.

There are two ways of achieving a zonal isolation capability with available completion systems. The first is to run a train of swellable packers on tubing into the open hole section of the reservoir, and hang the tubing from the bottom of the well casing. The packers are long (3-10 m) and expand on contact with the fluid in the hole to isolate the sections between the packers. The separation of the packers in the train is customized so that the intervals targeted for stimulation are isolated once the packers expand. Access to each isolated interval is secured either through sliding sleeves activated by wireline, or by including ball-on-seat orifices in the tubing whose size decreases with depth. The latter allows the individual intervals to be stimulated sequentially from bottom to top. Swellable packers that are stable up to 200°C are now available. Potential issues in employing this technology in geothermal holes in crystalline rocks are: (1) the inhibition of premature swelling during run-in due to removal of coating by abrasion, and (2) the possibility of large wellbore breakouts in crystalline rocks that may compromise sealing. Knowledge of the in-situ stress field allows the azimuth of the sub-horizontal wells to be chosen such as to minimise the development of breakouts. Both issues also apply to shale gas wells, but have not prevented their use.

The second option is to completely case and cement the well in the reservoir section. The fracture zones that are targets for stimulation would be accessed by perforating the casing/cement at the precise location of the target zones using standard perforating-gun technology. In principle, this approach is the simplest completion strategy, and was attempted in the early work at Fenton Hill in the 1980s, with mixed results. Potential problems are posed by: (1) the possibility of incomplete filling of the annulus by the cement, (2) the uncertainty in the performance of perforation-gun technology in crystalline rocks, and (3) the likelihood that the cementing operation will squeeze cement into permeable zones that are the prime target for stimulation. The latter problem might be solved by performing a high-rate hydraulic stimulation through the perforations to try to re-establish hydraulic communication between the wellbore and the target structure beyond the cement invasion zone. Experiments to investigate this important aspect, and evaluate perforation gun performance in crystalline rock could be conducted under controlled conditions in an Underground Research Laboratory.

Knowledge gaps and research recommendations

Zonal isolation issues that could be addressed by experiments conducted under controlled conditions in an Underground Research Laboratory are:

- Evaluation of the performance of perforation-gun technology in crystalline rock.
- Investigate the problem of re-establishing access to a permeable zone that has taken cement in the near-wellbore region.

Completion: flow management

Importance and state of current knowledge

Under operational conditions, there is great benefit to being able to control production/injection at each of the intervals. Management of the flow profile along the reservoir would help ensure that as many flow paths linking the wells as possible are active. The positive feed-back effects of cooling will tend to promote the dominance of one or two inlets in the injection well, and this should be prevented. Another scenario where flow management is important is to allow remedial action when one feed-zone in a production well begins to produce cooler fluid. Management of the flow profile can be realised by sliding valves actuated by wireline. These could be built into the expandable packers/tubing system. For the cemented-casing completion case, an internal tubing string with packer isolation would be required. Alternatively, cementation of problem zones may be the most practical flow-management solution.

Knowledge gaps and research recommendations

- Adjustable control of flow at feed zones will be required for proper reservoir management. It is not clear to what degree existing technology meets this need.
- At the very least, remedial measures will be needed to block flow from production zones that have suffered thermal breakthrough. The effectiveness of cement injection to seal a feed zone should be investigated.

Distributed measurements along the wellbore using fibre-optic systems

Importance and state of current knowledge

Distributed measurement of temperature along optical fibres is now an established technology. Optical fibres can now be packaged to allow them to be run into geothermal wells or be permanently integrated into the well completion to provide continuous profiles of temperature along geothermal wells. Continuous measurement of the temperature profile of a production well can provide an early warning of the onset of thermal breakthrough at a feed-zone, and is thus of importance for the operational management of the well. Recent advances have extended the capability of distributed-measurement fibre-optic systems to resolve pressure and acoustic emission signals.

Knowledge gaps and research recommendations

- The technology is important for the P&D projects and will also be useful for experiments in the deep underground laboratory. A research group within Switzerland should take responsibility for gaining expertise in the deployment and measurements of fibre-optic systems in deep wells.

Recommendations for short-term action for drilling and completion

- Plan and execute experiments in crystalline rock under the controlled conditions of an underground Research Laboratory to address the uncertainties of regaining hydraulic communication with a target fracture zone after cementing a casing using perforation gun technology.
- Task a research group to monitor and gain experience with technologies for the fibre-optic based distributed measurement of temperature and other parameters in deep borehole situations.
- Continue the development of spallation-drilling technology

4. Reservoir Creation and Stimulation modelling roadmap

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Scope

This chapter of the roadmap is concerned with the reservoir creation in petrothermal systems, which current knowledge suggests have greater potential for large-scale deployment in Switzerland than hydrothermal systems. However, aspects of the roadmap are also relevant to the hydraulic stimulation of hydrothermal systems.

The target rock mass is assumed to be crystalline rock at depths of 4-5 km. Petrothermal reservoirs could also, in principle, be developed in sedimentary rock, using similar procedures. However, differences in the dominant mechanism of permeability creation in response to the stimulation injections might be anticipated (i.e. hydrofracture rather than hydroshear). In addition, chemical stimulation methods are more relevant for permeability enhancement in sedimentary rock.

Reservoir Creation covers activities performed to develop the requisite hydraulic linkage between two or more boreholes to serve as a heat exchanger. Numerical simulation is a key tool to gain insight into the processes activated, and thus is included in this roadmap as a primary element of the research program. The characterization of the reservoir in the state it exists before and after stimulation is addressed in the 'Reservoir characterization' roadmap.

Importance of well design for reservoir creation strategy

Previous attempts to develop petrothermal reservoirs have featured long open-hole sections, and have resulted in the stimulation of relatively few feed zones along the well. Future experiments will almost certainly use zonal isolation technology that allows the stimulation of several selected zones along the well. Thus, this roadmap assumes that this technology is realized in the P&D projects. The technology options for accomplishing zonal isolation are summarized in the 'Drilling and Completion' roadmap. A second possibility arising from current plans is that the wells will be deviated from vertical in a direction that favours the extension of permeability creation in the vertical plane normal to the well trajectories, so as maximize the chances of linking the well satisfactorily from each of the stimulation zones along the well. This geometry will also be assumed in this roadmap.

Aspects of reservoir creation for consideration

The workshop team concluded that basic research into the fundamental hydro-mechanical mechanisms of permeability creation, and the geological factors that promote each mechanism was key to understanding the 'stimulatability' of a potential reservoir. Therefore, two principal tasks for the reservoir creation research roadmap were identified as:

- An improved quantitative understanding of mechanisms of permeability enhancement.

- Development of improved numerical simulation tools for quantitative modelling of the stimulation process

Additional important objectives that the workshop identified are:

- Improve the ability to relate geophysical measurements to reservoir properties
- Development of integrated workflows that connect exploration, reservoir creation and characterization by linking reservoir geology and geometry modelling tools with numerical process simulation
- Knowledge of the lessons learned from previous pilot sites should be better known and analyzed in the Swiss geothermal community.
- Reservoir creation and stimulation must be closely coupled to risk governance and mitigation strategies for induced seismicity.

Quantitative understanding of stimulation mechanisms

Importance and state of current knowledge

A number of petrothermal pilot and demonstration projects have been built and tested since the late 1970s (e.g. Fenton Hill, USA; Rosemanowes, UK; Hijiori, Japan; Soultz, France; Cooper basin, Australia). These have demonstrated that, with a few exceptions in gneissic rock, hydraulic stimulation is effective in radically and permanently increasing the *injectivity or productivity* of wells in crystalline rock. This implies that substantial enhancement of the permeability of feed zones can be accomplished, in at least the near field of the wells. However, questions remain as to the degree of permeability enhancement that can be accomplished deeper into the reservoir. In the case of the Basel reservoir, stimulation was progressing as planned but induced seismicity was too vigorous to continue the stimulation. Indeed, only in the case of the Soultz 3.5 km system have stimulations created a hydraulic linkage between wells that had sufficiently low reservoir impedance to permit commercial flow rates. (Reservoir impedance is the pressure difference between injection and production wells at reservoir depth required to produce unit production flow rate, and the maximum value for commercial systems is usually considered to be 0.2 MPa/l/s.) The following lessons can be drawn from the field projects:

- Permeability enhancement appears to occur primarily on existing fractures and fracture zones activated in jacking or shearing or both. It appears difficult to drive mode-1 hydrofractures over significant distances in naturally-fractured crystalline rock masses. The hydromechanical interaction between the propagating hydrofracture and the natural fracture system is believed to be an important factor in limiting this distance.
- Almost all stimulation injections were conducted on large open hole sections and resulted in activation of only a few fracture zones, one of which usually dominated. Often, although not always, the dominant inlet/outlet to the reservoir is seen to lie near the top of the open hole section, probably reflecting stress control.
- In most reservoirs, the vertical gradients of the principal stress magnitudes favour upward growth of stimulation. An exception is the Rosemanowes reservoir where the stress gradient favoured downward growth.
- Mechanical effects also appear to influence optimal reservoir operation. Downhole pumps have been successfully used to increase production in some reservoirs (e.g. Soultz 5 km system). However, in others (e.g. Rosemanowes, Fenton Hill) the best circulation characteristics were obtained by operating the production well with a back-pressure (up to 9 MPa at Fenton Hill). This reflects the stress-dependence of fracture aperture, whereby the backpressure lowers the effective stress on feed-zone fractures, resulting in wider apertures and lower resistance to flow.
- Thermal breakthrough was observed at relatively early times (weeks to months) during circulation of several systems that had well spacing of 90-150 m. These observations suggest

that the distances between injection and production wells substantially greater than several hundred metres are required to avoid premature thermal breakthrough. A separation of 500-600 m has been adopted in recent Petrothermal projects. This separation defines the distance to which significant permeability enhancement must be achieved in the hydraulic stimulations.

Knowledge gaps and research recommendations

The knowledge and experience gained from previous projects will certainly be helpful in developing petrothermal reservoirs in the upcoming pilot and demonstration projects. However, they also highlight our limited understanding of the basic mechanisms underpinning the accomplished permeability enhancement. An improved understanding of these mechanisms is key to designing stimulation strategies that are optimal from both the permeability creation and also the seismic hazard perspective. The following points are recognised as knowledge gaps:

- *Increasing the reservoir volume and the area swept by flow between wells.* Experience from previous pilot projects indicates that stimulation mostly reactivated existing fractures and that a few larger structures will dominate the flow systems. Creating additional connected fracture permeability through which flow moves between wells is a primary goal for future stimulation technology. The isolation and targeted stimulation of multiple zones within the reservoir using zonal isolation technology should allow a larger volume of the reservoir to be stimulated. However, a complementary research objective is to identify stimulation techniques that will maximize the connected permeability away from the dominant structures, either through the creation of new fractures, or the shear-activated stimulation of minor fractures. Stimulation experiments conducted at scales of ~100 m under controlled conditions in underground laboratories could yield a better understanding of hydrofracture propagation and hydroshear in fractured crystalline rocks, and would be a step forward.
- *The role of pre-existing conditions in determining stimulation efficiency.* The pre-existing stress and geologic conditions prevailing within the reservoir might be expected to have a large influence on the response of the rock mass to the stimulation injections. The relationship of the stress field orientation to the discontinuity network geometry (i.e. orientation of fracture families and larger structures) is clearly of major importance for determining whether jacking or shearing will occur. Shearing can initiate rock-bridge failure, and give rise to permeability enhancement through a number of mechanisms, such as shear-dilation, wing-cracks, pull-apart aperture at fault jogs or block rotation. Thus, the permeability response to shearing is much more complicated than merely shear-induced dilation, as commonly implemented in numerical models. Which of the mechanisms are activated depends upon details of the discontinuity population such as fracture connectivity, size scaling, density, and the presence of filling or alteration. A better understanding of the influence of these factors on the permeability-creation mechanisms is needed to accurately simulate the process.
- *Understanding the fluid pressure evolution and distribution during stimulation.* The overpressure distribution prevailing in crystalline reservoirs under stimulation conditions exerts a large influence on the types of stimulation mechanism that can be activated (e.g. hydrofracture or hydroshear) and the degree of stimulation accomplished, but is subject to considerable uncertainty. Direct measurement is difficult because of the large pressure gradients of the fracture-constrained flow. Modelling is challenging because of the divergent flow field, and the evolving permeability and pore-volume changes within the potentially tortuous channels of the heterogeneous fracture network. It is planned to address this issue in hydraulic stimulation experiments to be performed at scales of 100 m in an Underground Research Laboratory where a high degree of experimental control is possible.
- *Aseismic slip during stimulation and non-stimulation phases.* Aseismic slip may be a major process in reservoirs during the stimulation and operational phases of a reservoir, but its identification is difficult. Monitoring of tilt in a deep observation borehole near a reservoir undergoing stimulation would be useful in this regard, but unfortunately deep observation

boreholes are rarely available until a second well is drilled into the reservoir. Nevertheless, a better understanding of the conditions that promote aseismic slip could potentially permit the design of “softer” stimulation approaches.

- *Understanding of fluid flow channelling.* Fluid flow channelling due to the irregular aperture distribution in rough fractures and at fracture intersections is considered a major hydrodynamic effect in fracture reservoirs. Its effect on the distribution and propagation of fluid pressure during stimulation and on the swept (i.e. heat-transfer) area during reservoir operation are poorly understood. Experiments conducted under controlled conditions in the Underground Rock Laboratory could address this issue.
- *Understanding the controls that govern reservoir 'stimulatability'.* An important long-term goal is to be able to identify conditions that have a large influence on whether a rock mass can be stimulated to the degree required to support commercial operational with an acceptably low risk of producing damaging seismicity. Progress in addressing the preceding points of this list will be essential in answering the questions if, why, and how connected permeability can more easily be stimulated at some sites than others. As noted earlier, the geologic pre-conditioning and current stress-field, and their relationship to each other, are likely to be essential elements. Understanding their role may aid future exploration strategies to identify the most “stimulatable” rock masses. One practical goal of the improved understanding of stimulation mechanics as given above is to allow a quantitative prediction of the evolution of the stimulated volume at a given site by integrating data from stimulation monitoring and reservoir characterization in near real time.
- Limiting induced seismicity to acceptable levels. Shear on pre-existing fractures zones is needed for reservoir stimulation; however, the nuisance and potential seismic risk posed by these earthquakes must be limited to acceptable levels. Specifically needed are validated predictive tools to model with the evolution of induced seismicity before and during stimulation, strategies for soft stimulation, as well as validated mitigation strategies that limit the expected maximum event size of induced earthquakes.

Improved numerical simulation tools for quantitative modelling of the stimulation process

Importance and state of current knowledge

Numerical simulation is the only method to fully quantify the complex interaction of mechanical, hydraulic, thermal, and chemical processes during reservoir creation and operation with full control of all parameters in order to improve our understanding of the stimulation processes. Moreover, it allows scenario testing (e.g., the effect of different injection schemes) that may aid in decision making. Numerical simulation is, therefore, a key tool for research on reservoir creation.

Unfortunately, there is currently no numerical simulation tool that integrates and resolves the dynamic interaction of all relevant physical processes associated with hydraulic stimulation. These processes include: mechanical effects, such as elastic and thermal strains, poro-elasticity, fracture mechanics, fracture compliance, and slip-driven dilation and related effects (wing-cracks and pull-apart aperture-creating features); forced fluid flow effects such as non-Darcian flow in complex fracture networks of variable hydraulic properties, and thermal effects such as viscosity and density variations.

Existing tools are able to simulate individual aspects or combined subsets of processes. However, such partial simulations or models are typically done separately. For example, it is currently impossible to run a hydromechanical simulation on the same geometric discrete fracture and matrix geometric model (e.g., in the form of a finite element mesh) as a thermo-hydraulic fluid flow simulation. This seriously hampers the integration into future industrial workflows from exploration through site characterization and stimulation to production.

Some current tools that are an “industry standard” are continuum approaches (such as TOUGH-FLAC), thereby seriously limiting the possibility to gain insight into processes in complex, heterogeneously fractured reservoirs. Nevertheless, it is good practice not to rely on a single code, and so existing models will find application in validating aspects of the new code.

Knowledge gaps and research recommendations

Planned improvements of simulation tools shall focus on:

- allowing the simulation in geometrically and geologically realistic, discrete fracture-matrix representations of reservoirs that can be adapted to site-specific geologic models (link to characterization roadmap)
- implementing the capability to invoke as complete set of physical processes as possible within the environment of a single tool, or at least allowing simulations of different processes on the same discrete fracture-matrix representation to be performed.
- designing interfaces to industry standard geology & geometry modelling tools such as Gocad/SKUA, FRACA, FRACMAN or GOFRAC in order to be able to perform simulations for site-specific reservoir models and integrate numerical simulation into industrial workflows that will emerge with pilot and demonstration projects.
- Considering uncertainties in a systematic fashion in order to support safety relevant decisions.

Realizing these points will provide simulation tools that will

- significantly aid achieving the above formulated goals towards a comprehensive understanding of stimulation mechanisms by providing a numerical “test bed”
- integrate into workflows from reservoir exploration through reservoir characterization and stimulation to production to provide physics-based input to decision making
- allow linking physical modelling of reservoir characteristics and performance to ‘economic’ modelling and process optimization modelling

Improve the ability to relate geophysical measurements to reservoir properties

Importance and state of current knowledge

Monitoring the evolution of permeability creation and, in particular, obtaining information on connected permeability, fracture density, and net created porosity during stimulation would provide insights in the processes occurring within the reservoir, and would be valuable for data-based decision making. Seismic tomography has been successfully applied to imaging velocity and attenuation changes within reservoirs undergoing stimulation, using microearthquakes occurring within the reservoir as sources. Electrical resistivity and MT surveys have also been used to study changes occurring within the reservoir, although the resolution from these surface-based methods is poor. Microseismicity provides the best real-time information on the extent of reservoir development. It can also allow the details of the activated structures to be resolved, usually after a lengthy analysis process, although a reduction in this turn-around time is anticipated. A drawback with all these methods is that they measure properties that are only indirectly relate to the properties of interest for reservoir creation.

Knowledge gaps and research recommendations

The development of accurate, rapid interpretation techniques that allow the characterization of the evolving fracture network during stimulation would be highly beneficial for successful heat exchanger design. Linking this to advanced numerical simulation procedures may aid control of the stimulation operation, help assess seismic risk and predict the optimal placement of production wells.

Methods and workflows to derive information about the properties of interest need to be improved:

- Refine and accelerate the interpretation of microseismic signals to characterize the fracture/fault system and to monitor stimulation progress and processes (understanding source physics)

- This likely requires optimizing (i.e. cost/result) seismic monitoring networks and velocity calibration. As noted in the reservoir characterisation roadmap, the inclusion of a downhole sensor, or even better, a string of seismic sensors, in the array would be beneficial, but would require that an exploration well exists. Seismic sensor strings suitable for short-term operation are commercially available. Robust seismic sensors that are suitable for *long-term* borehole operation are not yet 'off-the-shelf' items, but the technology appears to be mostly “ready”. However, it is not clear that the considerable costs of development and deployment would be justified by the benefits.

Recommendations for short- and medium-term action for reservoir creation and stimulation modelling

As outlined above, the mutual hydro-mechanical interactions between intact rock, pre-existing fracture networks and fluid pressure during fluid injection are complex and very difficult to predict, monitor, and analyse in actual reservoir targets at great depth. Two main, complementary roads to significantly improve our understanding can be defined:

- *Scaled analogue experiments*. While actual stimulation experiments in a deep borehole are very expensive and typically lack detailed knowledge of the underground conditions, much better control and insight can be achieved in scaled experiments in rock volumes with better accessibility.
  Therefore, an initiative to perform in situ experiments in *underground rock laboratories* (URL) on the scales up to 100 m has been launched and will be led by researchers at ETH Zurich. Such experiments will allow the complex interactions that occur during stimulation to be studies under controlled conditions. The experiments will identify and quantify the contribution of factors such as natural fracture network distribution and connectivity, stress field, initial fracture properties (aperture, infillings, alteration etc.) in controlling the creation of new fractures vs. the reactivation of existing ones and in controlling the degree of effect permeability enhancement.
- *Improved numerical simulation tools*. In the framework of SCCER-SoE and NFP70, a multidisciplinary team from several groups at ETHZ, USI, UNINE and collaborating international institutions has formed to *develop and apply the next generation reservoir modelling tools* for this purpose. Building on their already existing simulation code platforms the group will tailor the simulation capabilities towards the particular needs of EGS development in Switzerland. These tools will be validated during the above mentioned controlled underground experiments, which will connect actual measurements to an in-depth analysis. We anticipate that the scenario testing and data integration capabilities of the modelling codes will make them a central tool for future integrated workflows from reservoir exploration through reservoir characterization and stimulation to optimizing and managing production.

5. Power Plants roadmap

Workgroup Participants

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Polydynamics Ltd.:	Robert Hopkirk

Scope

Geothermal heat can be used directly (i.e. supplying heat to a district heating system, greenhouse complex or fish farm), or it can be used to generate electricity, or a mixture of both. Simplified we can say that if the well production temperature is below 130°C, then feeding a district heating system is the optimal solution. Deep Geothermal Energy (DGE) systems are envisage to produce fluid at temperatures higher than 150°C, which is hot enough to give reasonable turbine efficiencies for electricity generation. Above roughly 150°C, combined heat and power system are optimal. The design and the dimensioning of the turbine depends upon whether a district heating system has to be served. This has to be taken into account optimizing the heat and power system.

This chapter considers only geothermal plants that generate electricity. There are two reasons for this. Firstly, the DGE roadmap concentrates on EGS systems with production temperatures above 150°C, and secondly, the construction of a district heating system needs high investment cost and redundancy of the heat generation must be guaranteed.

Conversion efficiency of geothermal power plants

Importance and state of current knowledge

The conversion efficiency from heat to electricity depends upon the temperature of the fluid and the conversion technology. The maximum isentropic efficiency η_{is} of a process is called the Carnot efficiency and is defined as

$$\eta_{is} = W / Q_H = 1 - (T_C / T_H)$$

where

- W is the work done by the system (energy exiting the system as work),
- Q_H is the heat put into the system (heat energy entering the system),
- T_C is the absolute temperature (Kelvin) of the cold reservoir,
- T_H is the absolute temperature (Kelvin) of the hot reservoir.

As an example, the maximum efficiency of a cycle with an inlet temperature of 160°C and a condenser temperature of 50°C is 25%.

The effective efficiency of a standard steam turbine with inlet temperatures of 130 to 180°C is considerably lower than the Carnot efficiency, because the temperature of the production fluid is only slightly larger than the boiling temperature of water at atmospheric pressure. For this reason, binary plants that use working fluids whose boiling point is significantly lower than water to drive turbines are commonly used in geothermal plants. Broadly speaking, there are two types that differ in the working fluids that are used:

- The Organic Rankine Cycle (ORC) systems use fluids that have a higher molecular mass and a lower boiling temperature compared to water. Isobutane is commonly used as a working fluid for inlet temperatures of 160°C. This cycle is the standard cycle in use.
- The Kalina cycle is using a solution of two fluids, normally water and ammonia. This cycle has often a slightly higher efficiency than ORC systems, but is normally more expensive.

With today's technologies a maximal turbine thermal efficiency of about 75% of the Carnot efficiency can be achieved, leading to a cycle efficiency of up to 19% for our example above, with 160°C inlet and 50°C condenser temperature. If we take into account the electric power required to run the plant and the pumps needed to produce and/or inject the geothermal fluid, net efficiencies of 10% to 14% are commonly achieved, depending on the specific conditions.

Innovative technologies for future geothermal power plants

Increasing the efficiency of a geothermal power plant improves the economic value of the plant directly. Thus, a considerable research effort is being directed towards the development of more efficient technologies. The following is a summary of technologies currently under development:

Hybrid systems (for example, combined geothermal and biomass combustion to produce superheat steam)

In the optimal case, the geothermal heat is used to preheat the water, and the biomass combustion serves to superheat the steam. Such a scheme could potentially increase the turbine efficiency-from approximately 75% to 85%. The challenge is not the process itself, but to maintain a constant supply of heat from both sources at the rates that maximize the efficiency of the system.

Thermoelectric converter power generation

Thermoelectric generators (also called Seebeck generators) are devices that convert heat, or more precisely, temperature differences, directly into electrical energy. They use a phenomenon called the Seebeck effect, which is a form of thermoelectric effect.

The efficiency of the process using currently available materials is only of the order of a few percent. However, there is hope of finding better materials in the next few years that could yield efficiencies of 10% for inlet temperatures of 160°C and condenser temperatures of 50°C. This efficiency is still considerable lower than achieved by ORC or Kalina systems at these temperatures. Thermo-electric systems require further fundamental research.

Magneto-caloric energy conversion

Magnetic energy conversion makes use of materials that show a dependence of magnetization on temperature. First trials to practically implement this effect in a mechanical design have been conducted. The effect cannot generate efficiencies higher than the Carnot efficiency. Currently available materials yield efficiencies of around one percent. With improved materials and optimized designs, it is hoped to reach efficiencies up to 10% for 160°C inlet and 50° outlet temperature.

Osmotic power plant or salinity gradient power plant

This process utilizes a contrast in salinity between two solutions. A startup company, OsmoBlue, has developed a system that uses a proprietary concentrate in a closed loop cycle. The pressure difference developed between solution with different concentrations drives a turbine. The solution on the low pressure side of the turbine is split into high and low concentration solutions with heat using a patented process. The main challenge is to upgrade the process to power levels of interest.

Recommendations for short and mid-term actions for power plants

Future work should include:

- Continue to monitor R&D progress in the fields of thermo-electric power conversion, magneto-caloric energy conversion and osmotic power generation. Become involved if good progress has been achieved.
- Work towards installing an experimental geothermal facility, fed by heated water (i.e. 10 l/s at 180°C), to test technologies to achieve overall higher efficiency, reduce corrosion downgrade, improve reliability and operation time of all components, test solutions to handle different chemical composition of the geothermal brine, test solutions for heat exchange and cooling.

6. Economic Modeling roadmap

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Scope

The technology to produce electricity from geothermal reservoirs through EGS is still being tested and has high costs, owing to the limited experience gained so far and to the uncertainty in underground conditions. However, there exists a reasonably clear understanding of the system concept and the target performance characteristics of demonstration two-well systems. Therefore the goal of this chapter is to provide a framework for calculating the cost structure for deep geothermal power plants, and present a reasonable scenario for the evolution of the main cost drivers, so that the evolution of the electricity generation cost can be estimated. An extensive sensitivity analysis is provided in the TA Swiss report: Energy from the Earth: Deep geothermal as a resource for the future, published in November 2014.

Technical specifications for the baseline geothermal plant

The baseline concept consists of a two wells system (doublet) accessing a reservoir at a depth of 5km and temperature of 165°C, with a flow rate of 50 l/s. The parameters used in the plant power calculation are given in Table 1.

Parameter	Units	Pilot plant: baseline concept
Number of wells	-	2
Well depth	km	5
Production temperature	°C	165
Reinjection temperature	°C	50
Reservoir impedance	MPa*s/L	0.15
Flow rate (injection)	L/s	50
Gross electricity plant power	MWel	3.54
Gross thermal efficiency	%	14.8
Pump power for geothermal fluid	MWel	0.44
Net plant power	MWel	3.1
Net thermal efficiency	%	13

Table 1: Technical specifications for the baseline geothermal plant

An organic Rankine cycle (ORC) system is used. The reinjection temperature of the brine is fixed at 50°C and the pressure in the primary loop is maintained sufficiently high to avoid an injection pump and prevent the geothermal brine from flashing. This is thought to avoid scaling effects and is consistent with the use of a hybrid condenser in the secondary loop of the power plant. A standard value for the reservoir impedance of 0.15 MPa/l/s is chosen. The gross thermal efficiency of the plant reaches 14.8%, derived from the Carnot efficiency of 26%, and a turbine and cycle efficiency of 75% each. The gross electric power of the plant (i.e. excluding power lost for geothermal fluid pumps) is 3.54 MWel. Subtracting the estimated power required for injection and production pumps for the geothermal fluid of 0.44 MWel (for example, the power needed by a downhole pump operating at a depth of 500 m and providing a surface pressure of 1 MPa), a net plant power output of 3.1 MWel is achieved.

Cost elements for the baseline geothermal plant

The investment cost includes exploration costs, drilling costs, stimulation costs and power plant construction costs, see Table 2. The listed drilling costs are for sub-horizontal wells, and are higher than those for vertical wells owing to the limited experience of drilling deviated wells in crystalline rock. The reservoir stimulation costs include completion with a packer-based zonal isolation system, facilitating multi-zone stimulation. Since these technologies still have a pioneering character for Switzerland and Europe, the more uncertain cost elements are given as a 10%-90% cost range.

Parameter	**Units**	**Baseline geothermal plant**
Exploration costs	mln CHF (MCHF)	5
Well cost 1st/2nd well	mln CHF	20-40 / 15-35
Hydraulic stimulation cost per well	mln CHF	3-5
Cost of power plant (gross power)	CHF/kWel	4000
Plant cost	mln CHF	14
Maintenance and operational costs	mln CHF/yr	2
Levelized net electricity generation cost	**Rp/kWh**	**28-42**

Table 2: Cost elements for the baseline geothermal plant

The economic model determines the net present value (NPV) of the levelized electricity generation cost, resulting in a break-even of the project over its projected lifetime of 20 years. The baseline model considers investment costs and the maintenance and operation costs, but does not take into account any additional cost resulting from technical risks and overhead, or the generation of profits. Financial costs and depreciation over 20 years are considered, and the interest rate respectively the weighted average cost of capital (WACC) is arbitrarily set at 5%. The technical specifications and cost elements assumed for the baseline geothermal plant result in a levelized net electricity generation cost range of 28-42 Rp/kWh.

It should be noted that no revenues from the provision of housing or district heating is taken into consideration in the above calculations. The main reason to include only electricity generation is that the energy consumption for housing or district heating is expected to sharply decrease by 2050, owing to improvements in isolation and efficiency (Energy Strategy 2050). Decoupling electricity production from the proximity of heating applications will also serve to reduce possible risks.

Projected evolution of costs

The plan for successful development of DGE in Switzerland foresees the installation of 3 pilot geothermal plants in the next decade. As geothermal technologies and installations develop around the world, efficiency is expected to increase and costs to decrease.

Table 3 shows a plausible evolution of the technical parameters and cost elements during the pilot phase. The experience gained with the first pilot plant is used to improve the design of the second and subsequent plants so that higher flow rates are achieved. Well costs are expected to decrease significantly as experience is gained around the globe in drilling and completing the boreholes. It is also assumed here that sufficient experience and knowledge will be gained in the next ten years to enable the exploitation of a larger EGS reservoir with two doublets feeding one plant.

The standard plant has a net electricity power output of 20MW (after accounting for power for geothermal fluid pumps) and a levelized net electric generation cost of 10 Rp/kWh. It is based on the lower bound of plant #3 and will be depreciated over 30 years. The standard plant is expected to be reached in the time frame of 2025 to 2035.

Parameter	**Baseline**	**Plant #2**	**Plant #3**	**Standard Plant**
Number of wells	2	2	4	7
Production temperature (°C)	165	175	185	185
Reinjection temperature (°C)	50	50	50	50
Flow Rate (L/s)	50	60	130	235
Gross plant electric power (MWel)	3.6	4.9	12.2	22.1
Net plant electric power (MWel)	3.1	4.4	11.1	20.0
Operational hours/year	7500	8000	8200	8200
Plant cost (CHF/kW)	4000	4000	3000	3000
Exploration costs (mln CHF)	5	5	4	4
Well costs (mln CHF)	35 – 75	30 - 50	55 - 80	96
Stimulation costs (mln CHF)	6 – 10	5 - 8	8 - 12	14
Plant cost (mln CHF)	14	17	28	65
Operational and maint. costs (mln CHF/year)	2	2	3	4
Duration of depreciation (years)	20	20	20	30
Levelized net electricity generation cost (Rp/kWh)	**28 – 42**	**17 - 23**	**12 - 15**	**10**

Table 3: Evolution of the levelized net electricity generation for pilot plant #1 to #3 and standard plant

The levelized electricity generation cost depends on a number of technical parameters and cost elements, and even a marginal improvement in any of the elements contributes to an overall decrease of the projected generation cost. Using the evolution of the technical parameters and cost elements defined in Table 3, the levelized electricity generation cost range of the standard pilot plant reduces to 10 Rp/kWh, less than one third of the cost range of the first baseline plant.

Projection to 2050

The Energy Strategy 2050 target for DGE is of 4.4TWh/yr, or about 7% of Switzerland's present electricity needs, of which half to be reached by EGS technology. As this target corresponds to an installed capacity of 500 MWel, to be reached by 2050, requiring in turn the installation of additional 20 MWel capacity or one standard plant every year after 2025, at the conclusion of a successful pilot phase with the installation

As Switzerland, Europe and the global geothermal industry install further EGS-based geothermal plants and technologies become more standardized, we expect substantial improvements in the technical specification and reductions of the cost elements to take place, in line with the numbers given in Table 3.

The growth rate in capacity of DGE plants will heavily depend on the capacity needed to build future plants, the market price for electricity consumption and the evolution of policy measures to support the introduction of deep geothermal energy power plants (e.g. feed-in tariffs, technology stimulus, etc.).

At this early stage, simple extrapolations can be used to estimate the investments needed to meet the energy strategy 2050 target. Following the numbers in Table 3, if industry will be able to reach a target standard of 20MWel installed capacity per plant at a cost of 10 mlnCHF per installed MW, an investment of around 5 Mia CHF will be required to meet the 2050 target.

7. Risk Governance roadmap

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Scope

This chapter of the roadmap addresses issues and research needs for risk governance of future deep geothermal projects. The primary risk to the investors arises from the failure to create an economically-viable system. A substantial part of that risk arises from project termination due to induced seismicity, which is the primary accident and environmental risk, although other risks exist (e.g. borehole blowout, water contamination).

Introduction and context

The exploitation of deep geothermal energy resources is, like all energy technologies, not risk free. The primary risk in the public eye is induced seismicity but other risks (e.g. borehole blowout, environmental risks such as water contamination) exist. While the assessment of the hazard is the starting point and has been the focus of past research, risk, the product of hazard, exposures and vulnerability, is generally the more meaningful parameter to consider. In addition to the safety of operation, environmental risks and risk of accidents, the financial risk to the operators and investors is critically important. Likewise, future projects should not only consider the risk to an individual project as part of their license to operate, but also the ‘transfer risk’ that an accident at one site may have severe impact on the entire technology.

How these risks potentially impact our society, is, of course dependent on the vulnerabilities of our buildings, our infrastructure and our communities. Moving towards a safe and more resilient geothermal energy sector requires better calibrated tools for hazard and risk assessment, including the low probability-high consequence event settings. Furthermore, the tools have to be closely integrated with related communication and public engagement strategies, as perceived risk actually strongly impacts energy source design and mitigation strategies. Therefore, a quantitative and holistic risk governance framework for deep geothermal energy projects is necessary, but only partially existing. Risk Governance is by definition cross-disciplinary, and the consideration of multi-risk, feedback loops and cascading events is important. It is also an international challenge where synergies exist to many other nations.

To prepare for future projects, we need to develop such a holistic concept of risk governance from a truly multi-disciplinary perspective, that embraces a broad picture of risk: one that not only includes risk assessment and assessment of ability to recover from accidents, of both the industry and the impacted communities, including insurance related issues, but it also looks at how risk perception, perceived benefits and risk-related communication can be organized.

There are a number of potential hazards associated with geothermal activities, which range in severity from little or no effect, to worst-case events of multiple fatalities and extensive asset and environmental damage. Operators need to demonstrate how any adverse effects associated with these risks are going to be managed, thus reducing the risk to ALARP ('as low as reasonably practicable'). This entails implementation of preventive and mitigating measures. Preventative measures include, for example, real time monitoring of seismicity, measures of ground motion, and responsive measures to predetermined thresholds. Mitigating measures could include discontinuing hydraulic stimulation operations, bleeding-off of excess pressure, and possibly activating emergency response plans and evacuations. It is worthwhile noting that there is currently no single measure that will ensure safety, but a wide range of activities is needed.

Stakeholder roles

It is important to recognize that many stakeholders with different roles (Figure 1) are involved in the planning and execution of a deep geothermal project. These stakeholders bring to the process often quite different interests and backgrounds, making for a complex mesh of stakeholder interactions. While some stakeholders have clearly defined and limited roles, others may have overlapping responsibilities and interests. It is important to reflect on the roles and responsibilities of the different stakeholders early in the process. It is particularly important to do so within the SCCER environment, since the SCCER brings together academic players, industry, funding agencies and, to a lesser extent, regulators, in a consortium that to the outside may seem as one single group. It is also important that all stakeholders have access to a common and consensus-oriented knowledge base for their decision-making processes, although they may need to extract different kinds of risk metrics (e.g., financial losses, ground motion thresholds, damage probabilities etc.).

Below is an incomplete list of the major stakeholders and their roles:

1) **Industry/Operator**: Proposes projects and executes them. In general, it will be industry that is ultimately responsible for the project and applies for a license to operate, implying also liability for potential damages.
2) **Consultants.** Can assist industry/operators in the preparation of environmental impact studies or the execution of the plant. Or they may act for regulators as reviewers.
3) **Academia**: Advances the state of knowledge but also may advise industry and support regulators. If researchers participate directly in geothermal projects, their role as authoritative and independent experts is diminished.
4) **Funding agencies:** Review the scientific and economic viability of projects before supporting a project. Funding agencies are often closely related to regulators and should strive to be largely independent. They can influence 'best practice' through constraints on funding (e.g., open data policies).
5) **Regulators:** Will grant a license to operate and review the environmental impact and safety of the operation, based on existing legislation. Independence from operators is critical. Regulators may rely on academia/federal offices/consultants for guidance and review of risk studies.
6) **Politicians:** Will likely balance risks and perceived benefits (including economic impact, climate change etc.) for decision-making. They must have access to authoritative, independent information.
7) **Insurance companies:** Provide the operators for a fee with of part of the financial risk. Need to perform an independent review of the risks in order to assess insurance rates.
8) **Public and Media:** Will report on the projects, integrating different sources of information and opinions.

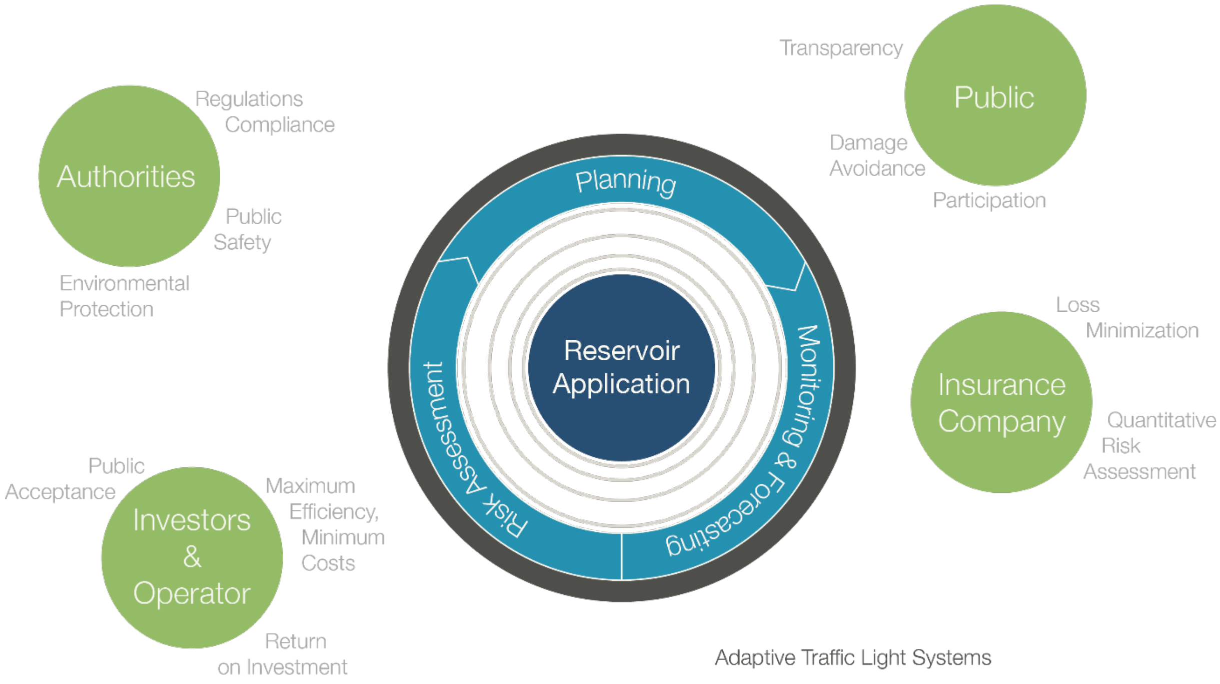

Figure 1: Schematic view of some of the stakeholders and their interest involved in risk governance and project management.

TA Swiss study on deep geothermal energy

The most comprehensive review of risks related to deep geothermal energy exploitation in Switzerland was recently conducted as part of the TA-Swiss study ("*Energy from the earth: Deep geothermal as a resource for the future?; editors Hirschberg, Wiemer and Burgherr, 470 pages*). Work package 5 of this study addresses in about 100 pages of text and figures separately the areas "*Accident Risk*", "*Seismic Risk*" and "*Risk Perception*". This study forms also an excellent and comprehensive baseline for this roadmap on risk governance of deep geothermal projects. With respect to accidental risk, the study analyzed:

- Blowout (drilling and operational phase)
- Drilling muds (drilling phase)
- Hydraulic Stimulation (stimulation phase)
- Working fluids (operational phase)
- Cooling system (operational phase)
- Geofluids (operational phase)
- Induced Landslides
- Induced Seismicity

Overall, the study concludes "*that the seismic risk dominates the environmental risk profile as well as the public perception of risk. The potential for geothermal reservoir creation and operation to trigger felt events is likely to be location-dependent, and is generally not well defined for most areas of interest in Switzerland. More work is needed to understand the factors that promote the generation of felt events".*

The study points out a number of areas where research activities are need, which form the baseline of the recommendations of short-term actions given below. It is currently unknown if the inevitable increase of seismicity during reservoir creation and operation is acceptable from an economic, insurance, regulatory and public perception point of view.

Interfaces with other roadmap chapters

Risk assessment and the demonstration of operational safety are essential for companies for obtaining a license to operate a future deep geothermal plant. In this sense, risk assessment is also standalone activity and part of a regulatory process. However, risk assessment is also closely connected to other roadmap activities. Risk management impacts heavily also the geothermal reserve assessment.

The primary focus of the SCCER activities is on accidental risk, environmental impact and risk perception, not on economic risks. Nevertheless, there is a strong feedback between risk minimization and mitigation and the chance of economic success of a project. For example, a more conservatively tuned traffic light system will reduce the risk of a potentially damaging event occurring, but at the same time reduce the chance of creating a economically-viable system in the underground. Therefore, risk governance cannot be simply reduced to minimizing the risk (do nothing, and nothing will happen), but must allow for balancing risks and benefits. There is also an obvious conflict between the most effective way to reduced risk, which is to stay away from populated areas, and the important economic benefit of using heat for district heating without having to construct expensive geothermal pipelines.

In the same spirit, risks may be a major constraint on the available deep geothermal reserves and on the exploration techniques to be applied. While there is general agreement that geothermal resources in Switzerland are large, limits on exploitability may result from the acceptable seismic risk associated with EGS reservoir creation and long-term operation. For example, it is possible that safety considerations will require exclusions zones for EGS development around population centers, or certain geological features such as active faults, thereby limiting the deployment possibilities of EGS technology. Risk assessment and reduction must thus be an important element within modeling and reservoir characterization. Finally, real-time monitoring is an integral element if risk mitigation strategies.

Induced seismicity related challenges for deep geothermal application

The problems encountered in the Basel petrothermal and St Gallen hydrothermal projects clearly identify induced and triggered seismicity as a major component of risk for the successful development of deep geothermal energy in Switzerland. Beyond the risk to buildings and human beings, it is also a major contribution to the risk for investors, because damaging and even non-damaging earthquakes may reduce the acceptance of the local population and thus threaten the success of a project.

Induced seismicity is not at all exclusive to deep geothermal energy exploitation. However, deep geothermal energy production is especially challenged right now by induced seismicity, for the following reasons:

1) Deep geothermal energy projects are often located *near urban areas*, because it facilitates the sale of heat, which may be the primary objective, or the secondary objective after electricity production, since the use of waste heat greatly enhances the economics of the systems. Because in this context the risk is defined as the product of hazard, exposure and fragility, the seismic risk of deep geothermal projects near urban areas is much higher. While some nations, such as Australia, have opted to minimize the exposure and hence the risks by avoiding settlements, this alternative is only partially viable in nations such as Switzerland where potential reservoirs are located primarily near the densely populated areas in the Alpine Foreland, and because potential users of heat from combined heat and power plants must be local.

2) In the case of petrothermal systems (also known as EGSs), induced earthquakes are *an essential tool* for creating a reservoir, and the economic success in terms of the heat output

is to some degree dependent on the number and size of induced events, and the fraction of permeability creation that is occurring aseismically. The balancing of reservoir creation and seismic risk represents a major scientific challenge.

3) In the case of deep hydrothermal projects, target zones are often *major fault zones*, because here the permeability is typically much higher. Because the existing pre-stresses and the potential for unwanted reaction cannot be imaged directly through geophysical methods, there is a danger that targeted fault zones may turn out more seismogenic than hoped for (e.g., St. Gallen, 2013).
4) Deep geothermal energy, especially EGS, is a new technology, triggering a different and generally more skeptical risk perception from established technologies such as mining or oil and gas production. There is also limited experience, empirical evidence and best practice to draw from.

Currently, risk management of induced seismicity is also a scientific challenge, because reliable and validated methodologies and tools to assess and monitor the risks do not exist. This is a consequence of two factors: our limited understanding of the physical processes taking place, but even more so, our limited knowledge of the physical conditions (i.e., 3D stress and strength heterogeneity, pre-existing faults, permeability distribution etc.) at the depth where the reservoir creation is taking place. However, it is important to remember that while the direct and indirect economic impact of induced earthquakes on geothermal projects has been substantial in Switzerland, they have so far very minor damages and no injuries. Also on a world-wide scale, there have been no injuries or casualties linked to deep geothermal projects. This compares to more than 15'000 people dying on average every year through natural earthquakes and earthquake related effects (tsunamis, landslides, fires).

Conclusions and recommendations for short-term actions

I. Appropriate risk governance is essential for the commercial and scientific success of future deep geothermal energy projects and P&D projects.-Risk governance should be considered a *process* that needs to be included consistently in all phases of future projects (e.g., exploration, reservoir creation, communication, etc.). Resilience, the ability of a single project to continue despite an accident and also of the entire technology to continue, is a concept that should be an integral part of risk governance.

II. A clear and transparent definition and separation of the roles of the various stakeholders is important and should be carefully and explicitly considered very early in the project planning. The role of SCCER-SoE scientist as compared to the project operators in a P&D project needs to be clarified.

III. Because of past failures of geothermal projects due to induced seismicity, and the problems with the gas kick in St. Gallen, it is vitally important that the safety of operations and risk governance takes priority over commercial aspects in the next P&D projects. This will be more costly in the short run, but will likely pay dividends in the long run. For example, careful data analysis and modeling once a test injection has been completed will take additional time, which is expensive because of drilling rig standby costs or adjustments to the planning.

IV. Insurance is key element of risk governance and public acceptance, but the geothermal industry is currently experiencing challenging conditions in the insurance market. Here academic research can make an important contribution over the next 1-2 years, by developing tools and calibrations that can be use by insurance companies and regulators as an input for loss calculations. For example, better-calibrated fragility curves for minor, cosmetic damage are needed.

V. Deep underground laboratories can play an important role in the validation of risk management tools, such as codes that forecast the reservoir evolution induced seismicity and mitigation strategies. Studying induced seismicity in such labs offers an opportunity to significantly enhance the understanding and management ability of induced seismicity related to reservoir creation in a repeatable, controllable and safe environment. Most of the processes relevant for induced seismicity are scale invariant – so they are amenable to study at reduced scales of 1:10 or 1:100.

VI. Future P&D project should reduce the risk by reducing exposure; areas with low population density are preferable, even if the opportunities to derive economic benefit from district heating sales is limited. Otherwise, it may be possible to increase the resilience of the impacted communities through preparedness, early warning, engineering improvement, insurance and other actions.

VII. The exploitation of deep hydrothermal resources targeting large and potentially active faults is complicated by the fact that a reliable assessment of the re-activation potential and hence the seismic hazard is difficult. Geophysicists are not able to image the level of tectonically accrued stresses on faults, and it is thus difficult to assess with confidence the probability of a run-away rupture on such systems. Therefore, petrothermal systems that deliberately avoid such large structures are, from a seismological point of view, the more promising target for a future pilot and demonstration projects.

VIII. We currently lack calibrated and validated tools for hazard, risk and vulnerability and resilience assessment, particularly (but not exclusively) in the 'low probability - high consequence' event setting. For example, the maximum possible earthquake that can be triggered or induced through deep geothermal activities is highly uncertain. It should be a priority of the research in underground labs and Pilot and Demonstration sites to reduce the uncertainty in the assessment of Mmax and other hazard relevant parameters. 3D seismic imaging pilot and demonstration sites may also provide important constraints on the location, scale and orientation of large discontinuities (i.e. faults) in the underground, which is relevant to hazard assessment (see exploration roadmap).