EXPERIENCES AND CHALLENGES IN GEOTHERMAL EXPLORATION IN THE UPPER RHINE GRABEN

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ABSTRACT

The Upper Rhine Graben is one of the main regions in Europe for geothermal exploration and utilization. Key deep geothermal projects like Soultz-sous-Forêts, Basel, Landau, Insheim, Brühl, Trebur and Rittershoffen document significant increase in knowledge on how to face exploration and production challenges. Some projects are successful, some failed due to various reasons. Exploration strategies for commercial deep geothermal projects require a sensitive momentum of financial and technical risk analysis and risk management. Much is written on successful projects, less on the failures and open challenges.

We focus on the developer's perspective of commercial deep hydrothermal projects within the Upper Rhine Graben by reviewing successful and failed projects. Special attention will be paid to the lessons learned and how to mitigate the associated risks through adjusted exploration strategies in future projects.

1. INTRODUCTION

The Upper Rhine Graben (URG) has a proven large geothermal potential. Nevertheless, the number of geothermal boreholes e.g. in the German Molasse basin is significantly higher than in the URG. The complex internal structure and recent tectonic activity implies high exploration risks as long as it is not sufficiently understood. At the same time it holds promising possibilities for geothermal utilization when the reservoir properties and architecture are understood.

Geothermal exploration of hydrothermal systems is primarily aimed at the two main relevant parameters temperature and flow rate, which highly influence the output of the geothermal plant. While the temperatures and the geothermal gradient are relatively good predictable due to the meanwhile high number of temperature measurements in boreholes and the well-developed understanding of the underlying processes, the prognosis of the flow rate and the productivity is still subject to significant uncertainties. In formations with low porosity and permeability, productivity mainly depends on a pronounced open fracture network. Fractures can significantly improve the feed volume and thus the contribution of matrix porosity to production. Fracture systems are typically associated with faults which can be mapped in 3D through seismic exploration. Furthermore productivity is also a function on how a borehole is draining a fracture system. Well path, well design and technical operations such as stimulation or drilling lateral wells can have a significant impact on success.

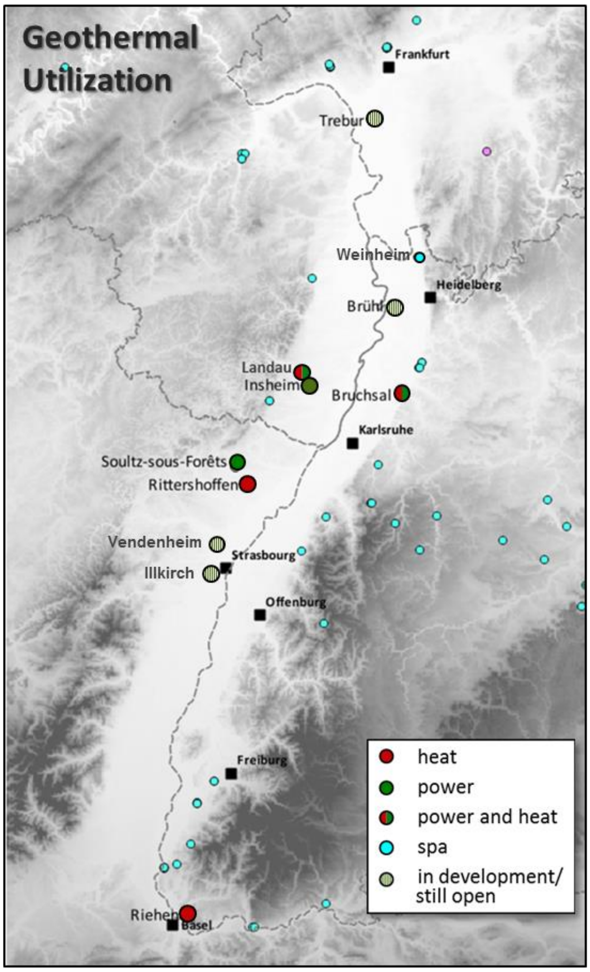

Figure 1: Overview of geothermal utilization in the Upper Rhine Graben.

Although the URG has a large geothermal potential, only relatively few projects have been implemented to date. These include the projects Bruchsal, Landau, Insheim, Weinheim, Soultz-sous-Forêts, Rittershoffen and Riehen (Fig. 1). Others are currently in the planning stage (e.g. Graben-Neudorf, Neuried) or at an advanced stage of implementation (Brühl, Illkirch, Vendenheim). Early projects have failed due to insufficient surface exploration, inappropriate target definition and technical problems (e.g. Bellheim, Offenbach a. d. Queich). A more recent project failed due to unexpected alterations within the reservoir formation (Trebur).

2. PREDICTING TEMPERATURE AND FLOW RATE

Temperature and flow rate cannot be considered as independent parameters. Assuming an open system with permeabilities enabling fluid flow, a lateral temperature gradient will initiate convection due to lateral differences in fluid density. In case fluid flow is driven by a lateral gradient in hydraulic head due to topography, the temperature field will be affected by infiltration of cold water in higher elevated areas and upwelling of warmer water in the valleys/lowland. Lateral differences in fluid density may also be derived by solution processes from fluid-rock-interactions and increasing total dissolved solids (TDS). Furthermore, fluid flow will be directed through the permeability structure and preferred horizontal or vertical pathways such as fault zones. Taking all of this into account, prediction of temperature and flow rate is not as straightforward as often assumed and much more experience and investigations are needed to minimize uncertainties.

2.1 Vertical temperature gradient

Temperature gradients in the URG are among the highest in Germany. The median geothermal gradient in the northern part of the URG is 4,8 K/100 m modelled at 3 km depth and 4,1 K/100 m at 5 km depth (Freymark et al. 2017). This general trend of increased gradients in the upper part to lower gradients beneath is explained by thermal blanketing of the Tertiary clay rich sediments with low thermal conductivity (Freymark et al. 2017). The two most important geothermal anomalies in the URG are located in the Landau region and around Soultz-sous-Forêts with geothermal gradients of up to 12 K/100 m within the Tertiary sequence (e.g. Agemar et al. 2013). To the east of the mentioned two anomalies, the geothermal gradients decrease with increasing thickness of Tertiary sediments. First of all, this trend reflects the relatively low thermal conductivity of the clay rich Tertiary sediments. In addition, regionally different heat flows from the pre-Tertiary subsurface, especially the radiogenic heat production rate of the crystalline basement (Freymark et al. 2017), and convective heat transport via fault zones may influence the subsurface temperature field significantly. For example, some temperature profiles in geothermal wells indicate a significant decrease of the geothermal gradient at top Muschelkalk and in the vicinity of hydraulic active fault zones to a normal (i.e. 3 K/100 m) or even a very low value (e.g. 0,3 K/100 m). An example for this behaviour is well documented for the Rittershoffen GRT-1 and GRT-2 wells (Baujard et al. 2017). Unsteady effects such as erosion, uplift or paleoclimate are not relevant in the region of the URG.

2.2 Reservoir temperature

Temperature gradients in the URG are based on in-situ measurements in boreholes. Unfortunately, there are not many wells drilled by the hydrocarbon industry to depths of geothermal reservoirs in the area of interest. Most hydrocarbon exploration wells are focused on hydrocarbon reservoirs at shallower depths within the Tertiary. Therefore, the available information on temperatures at greater depths is sparse.

Typically, temperature measurements in boreholes are carried out immediately after the drilling work has stopped. As these temperatures are affected by the mud circulation, a correction of the measurements is necessary. This is done typically for total depth of the well, since the disturbing influence of the mud circulation on the temperature field is lowest at the deepest point of the borehole. In spite of the corrections applied, these results, in contrast to undisturbed temperature logs, are still affected by an error of approx. ± 8 K (Agemar et al. 2012).

Due to the nature of temperature measurements in the wells, the distribution of wells being drilled, the availability of the data and the possibilities to correct the measured temperature for mud circulation, the spatial distribution of data sets (including temperature, location and quality) with differing quality is very heterogeneous. Within the GeotIS project, the 3D temperature field was modelled by weighted inter- and extrapolation using 3D geostatistics (3D-kriging) for the prediction of subsurface temperatures at unsampled locations (Agemar et al. 2012). The modelling does not respect varying geological settings and therefore may not reflect the true temperature distribution from local convection like in hydraulic active fault zones. Additionally, a linear temperature/depth correlation is applied and the effect of varying thermal conductivity is ignored. More details describing data collection, treatment of the data, philosophy and modelling of the subsurface temperature field can be found in Agemar et al. (2012).

Temperatures data of the GeotIS project are made publicly available via a cartographic web query (Agemar et al. 2014, www.geotis.de). This is a valuable data source but care has to be taken in order to respect influences from structurally controlled convection in the subsurface.

2.3 Flow rate

Flow rate is a function of reservoir permeability, physicochemical properties of the fluid, the hydraulic connection between well and reservoir (i.e. well path and well design), and the maximum drawdown limited by the installation depth of the pump. For a lineshaft pump installation, depth is limited to about 640 m (technically proven in Insheim). Maximum drawdown may not be lower than 50 m above the topmost bowl of the pump.

Reservoir permeability is highly dependent on the internal reservoir structure, the interactions between the reservoir fluid and the reservoir formation, the fault activity to create new fractures and re-open clogged fractures, and may vary significantly laterally within short distances. Therefore, there is no single number for a specific reservoir formation.

The production index (PI) describes the flow rate in relation to the applied drawdown in the well. The PI values scatter very strongly in the URG even within the same reservoir formation. Low PI values are often derived in wells exploiting the basement. Higher PI values of up to 20 l/(s·bar) (Brühl GT1) have been realized in wells exploiting fault zone related to Buntsandstein reservoirs (Fig. 2). Please note that the PI value only reflects the flow rates the well has been tested for and that the PI value may not be linearly extrapolated to higher flow rates.

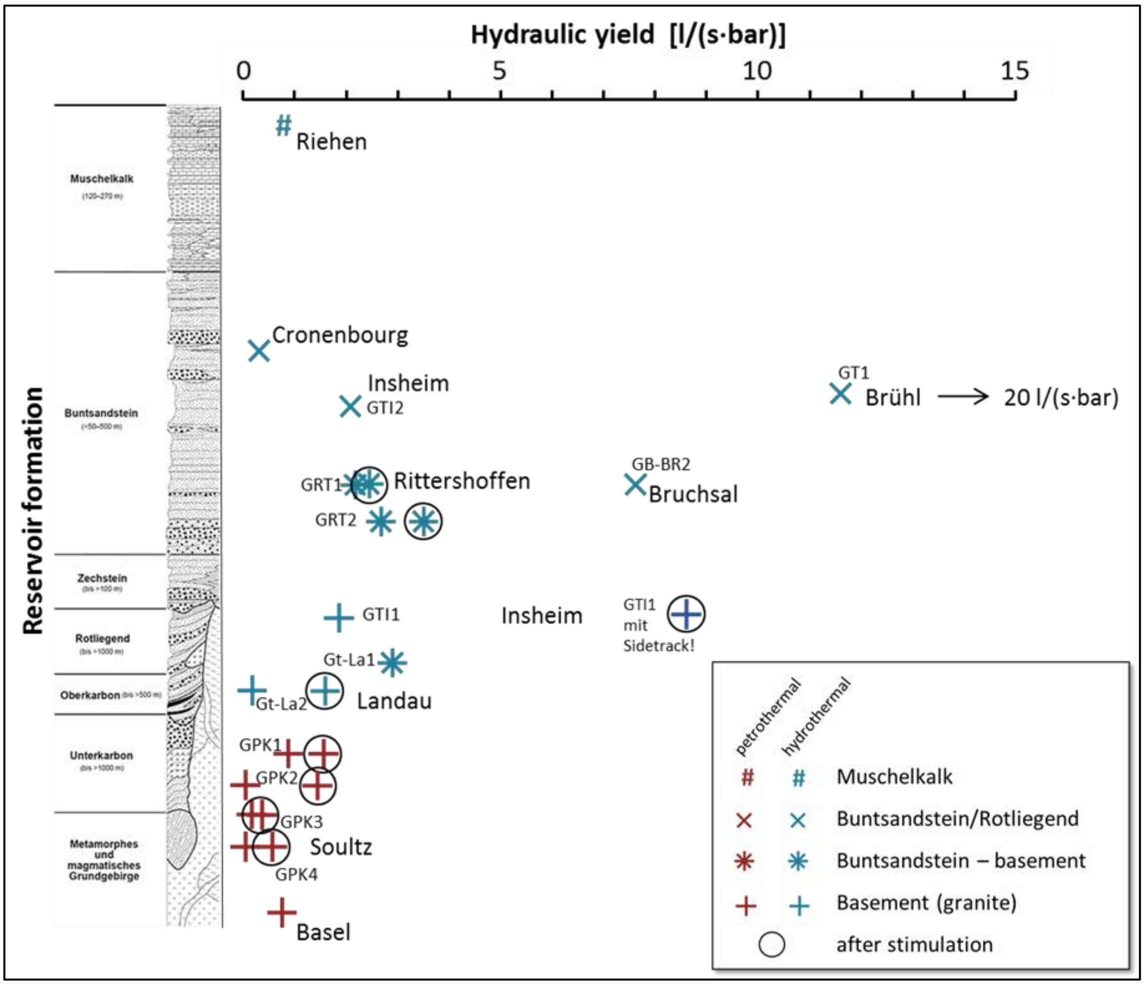

Figure 2: Hydraulic yield of geothermal wells versus reservoir formation in the Upper Rhine Graben.

Variation in PI is often due to the fact that the associated productive open hole sections vary in size and well paths encountering the fracture network. Furthermore, it should be noted, that the reservoir exploration and targeting strategies have been improved over time with gathered experience. 3D seismic exploration and high resolution reservoir characterization including geomechanical modelling etc. allow targeting fault zones with potentially high permeability. Low flow rates were typically measured when no fault zones were targeted. Higher productivities exceeding >2 l/(s·bar) were found, when permeable fault zones were exploited.

Before hydraulic well testing, it is not possible to assess the flow rate that could ultimately be achieved for a specific project. Existing geothermal projects in the Upper Rhine Graben operate with a flow rate between 20 l/s (Riehen) and approx. 70 l/s (Insheim, Rittershoffen). Significantly higher flow rates can be achieved if some of these existing producing or injecting wells would be enhanced by drilling a lateral well into the productive fault zone. For economic hydrothermal utilization, a PI value of >2 l/(s·bar) assuming a maximum drawdown of 50 bar (feasible with a lineshaft pump installation depth of 600 m) is needed to gain sufficient flow rates.

Beyond the primary achievable flow rate by just intersecting a fault zone with one well, production and injection may be enhanced through different (stimulation) operations. The following options are given:

- Acidification (chemical stimulation) in order to dissolve mineralization and re-open clogged fractures.
- Hydraulic stimulation in order to enhance fracture aperture and generate additional fractures for a better hydraulic connection between well and reservoir.
- Injection of cold water, which would result in cooling and contraction of the host rock and in opening new fractures.
- Drilling a lateral well from the primary well to enlarge the total length of the open hole within the same reservoir formation and exploit a neighbouring section of the fault.
- Drilling a lateral well to tap other reservoir formations to enlarge the total length of the open hole and exploit a neighbouring section of the fault.

2.4 Internal reservoir structure

The internal reservoir structure is determined by the discrete fault plane geometry, the fracture network of the deformation zone and the thickness of the reservoir formation. The width of the fracture network is scaling with accumulated true offset whereas the vertical fracture extend is controlled by the rheological stratification, i.e. interbedded strata of clay-/marlstone and sandstone. Fracture propagation is hindered or even stopped at boundary surfaces of clay-/marlstone (in which cohesion is high). In case of the Middle and Lower Buntsandstein, very thick layers of sandstone with only thin layers of clay-/marlstone in between are typical, resulting in very well connected fracture networks over large vertical extend.

A common observation in outcrops suggests that fracture networks are more intense and wider in the hanging wall of the fault (typically two to three times wider compared to the footwall; (e.g. Reyer et al. 2012) (Fig. 3). We therefore rank the part of the reservoir in the hanging wall higher than the part in the footwall of the fault. This is especially of interest when exploitation of both hanging and footwall with one well is not feasible and one has to decide which part serves as the primary target.

An additional feature of the reservoir structure is the fault core. In case of high true offset (i.e. deformation), the host rock will be intensely crushed/milled along the plane of maximum shear deformation forming a so called ‘fault gouge’. High amounts of fault gouge will significant decrease permeability of the fault core leading to a hydraulic border and compartmentalization of hanging and footwall. The same might result from clay smear (i.e. incorporation of clay or shale in the fault core during faulting of a layered sand-clay or limestone-marl sequence).

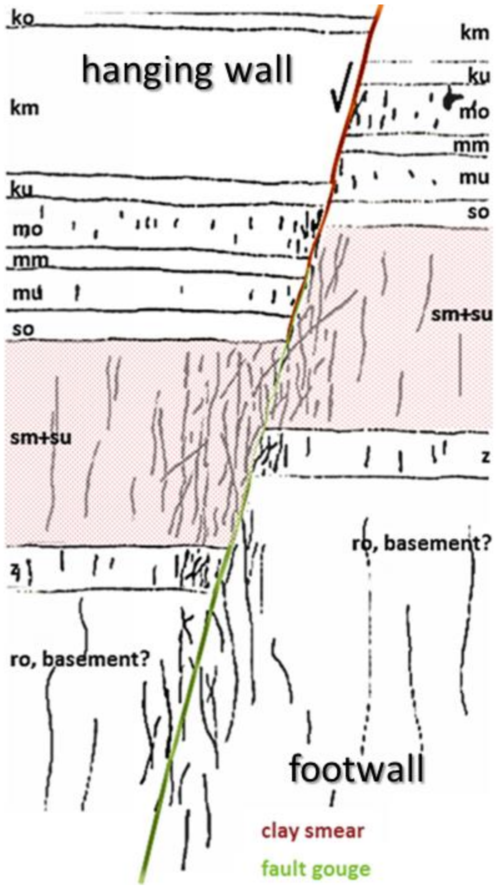

Figure 3: Illustration of fracture networks in the hanging wall and footwall along a vertical transect through a fault zone. The Buntsandstein formation is highlighted.

3. LESSONS LEARNED FROM FAILED PROJECTS

3.1 Offenbach GT1 and Bellheim GT1

In the projects Offenbach (drilled 2005) and Bellheim (drilled 2005/2006) drilling aimed to exploit fractured reservoirs in the Muschelkalk and Buntsandstein. High mud losses while encountering the Muschelkalk formation indicated high permeability in a nearby hydrocarbon well. However, despite hydraulic stimulation, the well Offenbach GT1 did not find the desired permeability within the Muschelkalk. Deepening the well into the Buntsandstein was not successful in encountering an open fracture network above percolation threshold. Sidetracks, which should open up the Muschelkalk in the vicinity of a larger fault zone, failed technically. The well Bellheim GT1 did not reach its target in the Muschelkalk formation close to a fault zone due to technical problems, so that proof of an existing hydrothermal reservoir is still pending here. Lessons learned from these projects are:

Only fault zones yield sufficient permeabilities for economic success and target definition should be based on 3D seismic surveys to map and evaluate fault zones.

3.2 Trebur GT1

In the project Trebur (drilled 2016), the expected fractured reservoir at approx. 3.500 m depth was defined by a sequence of volcanic rocks (basaltic lavas/sills and rhyolithic tuffs) intercalated in siliciclastic sediments of Permian age (Donnersberg formation, Rotliegend) crosscut by a fault zone proven to be active during the Tertiary. The average geothermal gradient derived from offset wells is in the order of 5 K/100 m. At reservoir depth, a formation temperature of up to 170 °C has been expected. Flow rates of 60 to 80 l/s have been assumed to be realistic in highly fractured reservoirs associated with fault zones.

When drilling the first well Trebur GT1 in 2016, stratigraphy and structures have been encountered as predicted. From image logs, open fractures in basaltic lava/sill were proven to be oriented in the same direction as predicted by the geomechanical model. However, in contrast to the expectations, the open fractures within the envisaged reservoir were hydraulically inactive. Additionally, formation temperature and mean geothermal gradient were significant lower than expected (i.e. 139 °C @ 3.400 m depth and about 4 K/100 m respectively).

Both, relatively low temperature and absent hydraulic conductivity correlate with the occurrence of massive alterations encountered in the volcanic tuffs of the Donnersberg formation. These alterations were not known from offset wells in this extent and the nature of occurrence as well as the controlling factors of these alterations is still under investigation. We assume that these alterations hinder or limit the growth of discrete fracture networks, the associated percolation and convective heat transport (i.e. hydrothermal convection).

About 3.5 km further to the north of Trebur GT1 the hydrocarbon well Königstädten 3 has been drilled in 1957 into the same structure as the Trebur GT1. Königstädten 3 encountered top Rotliegend down to a total depth of 2.492 m. The temperature at bottom hole (BHT) was 152 °C (corrected). Assuming temperature as a proxy indicating hydrothermal convection, one can come to the conclusion that there are major differences in hydraulics along strike of the fault with hydraulic convection in the northern part and missing convection in the southern part. Unfortunately the well Königstädten 3 has not reached the Donnersberg formation and was not drilled through the fault zone as the well Trebur GT1 was.

We have learned from Trebur that the link between temperature and hydrothermal convection along a fault zone is more complicated than previously assumed. Along the same fault zone the situation can obviously change at short distances. In geothermal exploration prior to drilling, a well-established approach to map hydrothermal convection along fault zones is still lacking. To date high resolution structural mapping using 3D seismics together with information from offset wells are thought to be sufficient in enhancing the probability of success. After drilling the well Trebur GT1 into highly altered volcanic rocks, this approach seems not to be sufficient in the northern URG. Geophysical datasets based on surface seismics alone is insufficient to map alterations. Mapping alterations is furthermore complicated by laterally varying intensity of alteration regardless of their primary pedogenetic or later hydrothermal origin. The intensity of alteration may however manifest itself by a shift in electrical resistivity of the host rock as proven in numerous studies of high-enthalpy resources around the world. Electromagnetic methods aiming at mapping earth resistivity may therefore provide the missing link for alteration mapping also in the case of low-enthalpy resources. However, resistivity structures are typically imaged at lower resolution than seismics and non-unique results due to the diffuse nature of the EM wave propagation in the subsurface. This limitation can be overcome by adding structural and stratigraphic information. Within the submitted R&D project proposal “ConvEx” (acronym for convection exploration) the combination of high resolution 3D datasets (e.g. 3D seismic) with low-resolution EM (e.g. CSEM, Ritter et al. 2017) and temperature gradient data (from gradient wells) will be tested to provide a robust approach for mapping high saline thermal fluids along fault zones, i.e. hydrothermal convection. Testing case will be Trebur, where a high resolution 3D seismic is available.

4. TRACE: LOOKING FOR DEEP REACHING FLUID PATHWAYS

Deep reaching faults serve as potential fluid pathways in the URG and may host hydrothermal convection cells. A pre-requisite for this is sufficient permeability through continuous fracture networks in the deformation zone of the fault. (For deep reaching faults the fault core, where most of the slip takes place, is often characterized by fault gouge and clay smear making the fault core impermeable.) How to prove continuous permeability along the fault when typical surface manifestations such as hot springs are lacking?

The TRACE project (2012-2015), funded by the Federal Ministry for Economic Affairs and Energy (funding code 0325390), presented a low-cost strategy for characterizing deep hydro-geothermal reservoirs using a combination of methods from hydro-geochemistry and isotope geochemistry on fluid samples mainly taken from shallow groundwater wells (Kraml et al. 2016). The main goal is to confine the area of interest for further geophysical investigation, as already done in the exploration of high-temperature resources around the world. For this purpose, naturally occurring geochemical and isotopic tracers like noble gases and radiogenic isotopes of strontium and lithium have been investigated. Noble gas isotopes provided most promising results from all natural tracers under consideration.

Noble gas isotopes (especially the $^3He/^4He$ ratio) can be used as tracers for fluids derived from mantle, crustal or meteoric origin. Investigations of noble gas isotopes in groundwater samples taken near faults allow for identifying deep-reaching permeable fault sections as viable targets for geothermal development. The noble gas tracer is therefore representing the only direct indicator for qualitative prediction of actually existing fracture permeability in the subsurface before drilling. Noble gas isotopes also enable a ranking of prospects and an optimized planning of e.g. the 3D seismic survey design with sufficient coverage and focus on the most promising target zone within the exploration license area (i.e. cost reduction by narrowing down the extension of cost-intensive 3D seismic surveys). The identification of promising prospects at the beginning of surface exploration studies is therefore saving time and money of the project developer and investor. It can also be part of the financial risk mitigation strategy i.e. a positive “TRACE result” could even convince insurance companies to insure the reservoir-related risk (Kraml et al. 2016).

5. NORM AND HYDROCHEMISTRY

Naturally occurring radioactive materials (NORM) in the produced brine might be enriched in scales precipitating during circulation in the geothermal plant (e.g. in the heat exchanger; Degering & Köhler 2015). The only way to handle NORM is to keep them dissolved in the circulated brine by inhibiting scaling (Seibt et al. 2013). The quantity of dissolved NORM is depending on the type of the reservoir rocks. Brine circulating in the granitic basement and Rotliegend formation has generally more NORM (Degering et al. 2016). However, overlying formations up to the Muschelkalk are hydraulically connected to the basement via permeable faults and therefore also affected by significant NORM.

Not only scales containing NORM but also scales in general can be a problem in geothermal utilization. Therefore, it is advantageous to assess the expected hydrochemistry (including gas content and composition) and related physico-chemical parameters (specific heat capacity, density, viscosity) of the target formation in the pre-drilling exploration stage. Since published hydrochemistry data is available, a data base with validated compositions can be established and regularly updated.

Due to the generally high CO_2 content of the URG fluids (up to > 4 liter/liter water at surface conditions), the planning of a pressure maintenance is essential for preventing degassing and related carbonate scaling.

Corrosion effects have also to be considered in the exploration phase, which are mainly due to the comparably high (≥100 g/l) NaCl content of the URG hydrothermal fluids. The drilling company has to be aware of the enhanced salinity and it is advisable to establish a groundwater monitoring prior to drilling to protect the near-surface groundwater aquifers.

6. INDUCED SEISMICITY

Perceptible seismicity is of major concern in the context of public acceptance and may hinder the development of a deep hydro- and petrothermal projects significantly. It is therefore necessary already during exploration to develop a concept on how to mitigate perceptible induced seismicity.

By far most of the induced seismicity is observed in projects circulating through crystalline basement rocks (e.g. Evans et al. 2012). All projects injecting into the crystalline basement produce seismic events (Basel, Soultz-sous-Forêts, Landau, Insheim, Rittershoffen) albeit with mainly very low magnitude, whereas circulation through sedimentary rocks tends to be less seismogenic. However, the presence of faults allows pressures to penetrate significant distances vertically down into the basement and increase the risk of induced seismicity (Evans et al. 2012). It is therefore advisable to keep distance to the crystalline basement, to operate with rather low pressures and explore for faults with very high permeability in sedimentary rocks. Only with high structural permeability it will be possible to keep pressures low while circulating with high flow rates.

Mapping critically stressed faults with a potential for perceptible induced seismicity is limited by the resolution of seismic surveys. And even a 3D seismic survey will not necessarily detect all faults of a size that is relevant for the seismic hazard (Baisch et al. 2016).

7. PUBLIC ACCEPTANCE

Besides geological and technical challenges, geothermal development in the URG faces major problems regarding public acceptance. Starting point were negative events like in Staufen, where drilling for a shallow geothermal project caused swelling of anhydrite in the underground leading to substantial damage of buildings in the historic city center, or in Basel, where hydraulic stimulation for a deep petrothermal project caused induced seismicity with a maximum magnitude of 3,4. These events caused basic fears among the population, fomented by citizens' initiatives against geothermal that often argue on a non-factual level. As is so often the case, people focus on the few critical aspects and ignore the learning curve over time and recent successful projects implemented without any incident (e.g. Rittershoffen).

In practice, in some municipalities in the German part of the URG opposition exists against the development of geothermal projects locally. As a consequence, delays arise during licensing procedures, exploration campaigns are hindered, project developers have to exclude some areas within their concession field and finding of project sites is often difficult.

To develop new geothermal projects, high efforts in public relations are necessary. It is to be hoped that new successful projects will reduce general anxieties and strengthen the public acceptance of geothermal project development in the URG.

CONCLUSIONS

For economic geothermal project development in the URG, fault zones play a central role. This is why recent hydrothermal geothermal projects without exception focus on such zones during exploration. Matrix-permeabilities are of fundamental importance with regard to sustainable heat utilization. For the high flow rates, the increased structural permeability in the deformation area of a fault zone is the decisive factor.

The depth and thickness of targeted reservoir formations as well as the location, orientation and width of fault zones can be explored with sufficient precision using 3D seismic surveys. The difficulty now lies in estimating the hydraulic permeability in the area of a specific fault zone and proving this estimation with data, usually performed during a detailed reservoir characterization study. A simple extrapolation or up-scaling of reservoir characteristics is generally not reasonable due to the heterogeneity, anisotropy and scale dependent variations of the structures. In addition, a prognosis is complicated due to the specific deformation history of a fault, since changes in tectonic deformation style and involved geomechanical processes cause temporal and spatial changes in porosity and permeability within the fault zone.

Despite the complexity and uncertainties, it is essential for successful exploration to collect and evaluate all known factors influencing the permeability structure of a fault zone and the associated temperature field. Only a synopsis and evaluation of these factors can provide an indication of potential hydraulic pathways within a fault zone. This is the only way to increase the probability of success.

The need for a well-founded geoscientific database for the identification of geothermal fluid-bearing fault zones is countered by the demand for cost-effective and efficient exploration methods. For economic reasons, a compromise must be found which, at an acceptable financial cost, creates a sufficient data base to reduce the exploration risk to an acceptable level. Methods developed in projects like TRACE or ConvEx will help to achieve this task.

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