4

# Towards a revisited geothermal conceptual model in the Upper Rhine Graben

A. Genter, C. Baujard, C. Glaas and V. Maurer

New concepts of deep geothermal energy in Western Europe were mainly initiated by a French-German consortium in the Upper Rhine Graben, at Soultz-sous-Forêts, France. A series of deep boreholes were drilled till 5 km deep within a crystalline basement, reputed tight and lying below the former Pechelbronn oil field where the first electric log was achieved for detecting petroleum in sedimentary reservoirs in the 1920s.

The main geothermal concept developed at Soultz-sous-Forêts, was to create from scratch, a down-hole heat exchanger by injecting water via a vertical borehole in a very low matrix porosity crystalline rock and by pumping it out hotter via deviated boreholes. It was derived from geothermal projects developed worldwide (US, Japan, Germany, UK), called Hot Dry Rock (HDR). However, after the achievement of several deep drilling at Soultz, the HDR concept slightly evolved to become Enhanced or Engineered Geothermal Systems (EGS), consisting of pumping hot


DOI: https://doi.org/10.1051/978-2-7598-3752-6.c004

water already present in the underground. Based on an extensive deep geoscientific characterization including geophysical exploration and geophysical logging, this chapter explains how a better knowledge of the geothermal resource allows improving the conceptual model of this deep resource and thus how to optimize geothermal targets by derisking drilling depths and well design.

## 4.1 Geothermal development in the Upper Rhine Graben

In Western Europe, deep geothermal energy started in the 90s by a French-German scientific cooperation in the Upper Rhine Graben, at Soultz-sous-Forêts (SsF), France. This research site was the location of many deep geothermal wells reaching 5 km in the Carboniferous crystalline basement, various geophysical logging including borehole imagery logs, well testing and hydraulic circulation. After an extensive phase of purely scientific research on the underground, the site slowly evolved to a pre-industrial site by building a first binary plant producing electricity in 2008. However, due to severe corrosion induced by the high salinity of natural geothermal fluids, after the dismantling of the first plant, a second but more robust binary plant was constructed and operated in 2016 by Electricité de Strasbourg. Since, it has been producing electricity on the French grid with an installed capacity of 1.7 MWe.

From the SsF experiment, many spin-offs have been created or new competitors tried to duplicate the Soultz concept in the Upper Rhine Graben, mainly in France, Germany and Switzerland. Thus, Landau and Insheim geothermal plants were developed in the Rhine-Palatinate in Germany whereas Rittershoffen plant and Illkirch sites were developed in Alsace (Figure 4.1). Rittershoffen, which is a real SsF cousin, is producing 24 MWth of energy since 2016 to a biorefinery with geothermal wells having a reservoir depth divided by two in comparison with SsF reservoir depth. Therefore, after several decades of geothermal research, exploration and development in Northern Alsace, two geothermal plants are commercially operating in France (SsF and Rittershoffen). In the German part of the URG, three plants are also operating (Landau, Insheim, and Bruchsal) (Figure 4.1). The Bruchsal geothermal doublet was drilled in the 80s in a fractured reservoir on the Eastern side of the URG and penetrated Permo-Triassic sandstones considered as a hydrothermal fractured/faulted reservoir (Kolbel et al., 2020). Those sites have penetrated the sedimentary formations of the graben and, for some of them, the deeper crystalline basement (Soultz, Rittershoffen, Insheim, Landau). In Switzerland, at Riehen, a heat plant has been operating from several decades but is located on the Eastern shoulder of the URG (Figure 4.1). This site deliver heat from geothermal hot water pumped in the Middle Triassic reservoir composed of fractured carbonates. In the past, for various reasons, several geothermal projects were stopped in the URG (Trebur, Brühl, Cronenbourg, Basel). For instance, at Cronenbourg in the suburb of Strasbourg, the unique deep geothermal well at 3220 m, drilled in 1980, was not permeable enough in the Permian sandstones and this site was abandoned without any attempt of flow enhancement. In Basel, the occurrence of an induced seismic event was felt during the shut-in of a post-hydraulic stimulation operation done in a 5 km geothermal well drilled in a granite. A magnitude higher than 3.4 was then felt in 2006 causing the full stop of the Basel geothermal project (Häring et al., 2008).

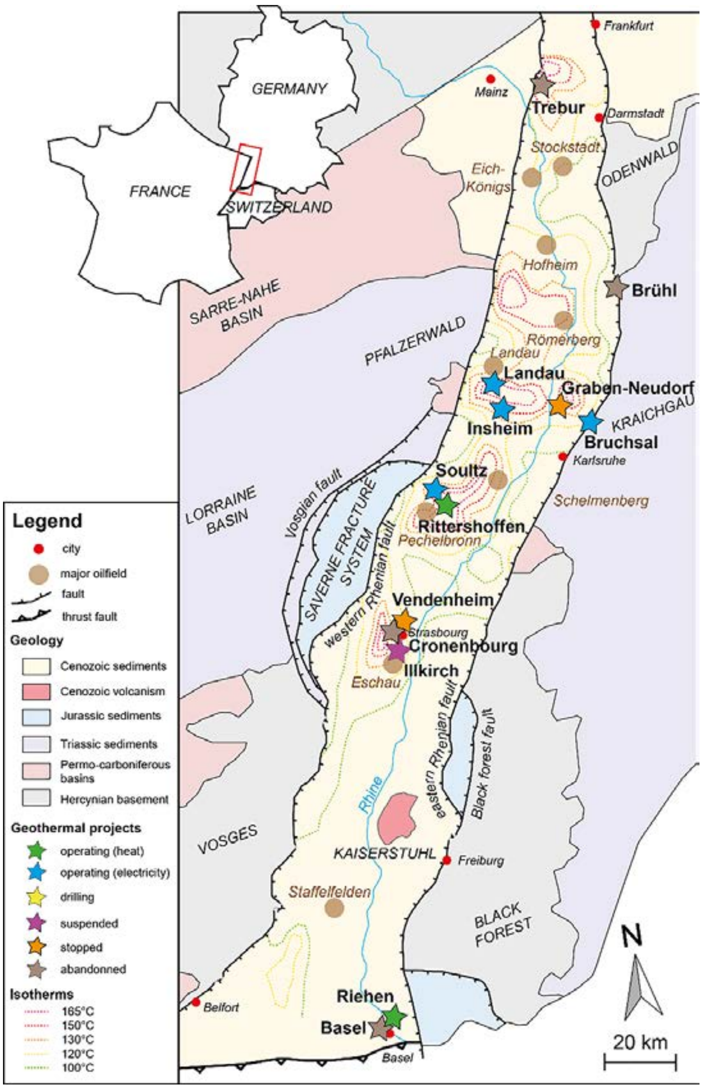


Figure 4.1 *Geothermal projects in Northern Alsace, and Southern Rhine Palatinate and Baden Wurttemberg.*

More recently, in the Strasbourg area (Vendenheim), a new competitor came for developing geothermal projects for producing electricity. However, after the drilling of two deep wells at about 6 km measured depth, a series of man-made seismic events were felt on surface during well testing or various operations between 2019 and 2021 with a local maximal magnitude of 3.9 (Schmittbuhl et al., 2021). It turned out that social acceptability became a real issue in this urban area because some structural damages were observed on houses around Strasbourg as well as on the German side around the city of Kehl. About 4000 requests from inhabitants have been made due to the occurrence of cracks observed on the walls of their houses. In parallel, by using the precautionary principle, the Illkirch geothermal project which was under development South of Strasbourg at the same time, was suspended by the French mining authorities in order to anticipate any further issue related to man-made seismicity. Now, the Vendenheim project has a new geothermal owner, but the site is still stopped by the mining authorities. In parallel, the Illkirch project is still suspended even if it did not cause any nuisances. The operator is waiting for the possibility of drilling at least a second geothermal well if the social acceptability is acceptable. Moreover, new geothermal projects are under development in Northern Alsace in the area of SsF with a geothermal well that could be planned for 2025 for exploiting the reservoirs at the fractured interface between the deep sediments and top basement.

In parallel to the geothermal development of the URG, a new era is rising with the booming of geothermal lithium. Several French and German companies aim to extract the geothermal lithium which is dissolved into the geothermal brine with a concentration ranging between 160 and 210 mg/L. After a phase of research for extracting lithium from the brine and then producing lithium carbonate of battery grade quality, several companies are currently obtaining geothermal and lithium leases in order to conduct pre-feasibility and feasibility studies before investment decisions for conducting industrial projects for producing lithium.

## 4.2 Evolution of the geothermal concept during the SsF adventure

The basic concept started on the Hot Dry Rock (HDR) concept considering that many geothermal wells reached interesting temperatures, but their flowrates were too low, even though fully dry, for reaching viable economic balance. Therefore, based on previous geothermal research dealing with the creation of artificial heat exchanger by hydraulic fracturing in US, UK, Japan or Germany (Figure 4.2), a jointed European research site was selected in Alsace, Eastern part of France, based on well-known temperature field measured in the former oil mines and oil wells close to Pechelbronn where the Schlumberger brothers did their first geophysical well logging in 1927 for detecting hydrocarbon reservoirs based on electrical measurements.

Firstly, the French-German SsF project started based on the Hot Dry Rock (HDR) concept. It consists in exploiting the vast energy resource that resides as heat in the low-permeability rocks which underlie most continental regions of the Upper crust at practically drillable depths. Thus, it was planned to drill a vertical well in the area of SsF because the geology was very well-known from several thousand of former petroleum wells mainly drilled in the Cenozoic reservoirs where interesting temperatures could be accessible at low drillable depths (Figure 4.2). Therefore, a first vertical well, called GPK-1, was planned to intersect about 1400 m of Cenozoic and Mesozoic sediments before to penetrate into the Carboniferous top crystalline basement.

In such theorical HDR concept, at the end of each drilling operation, it was planned to inject fresh water under pressure in order to create artificial fractures that can be used as a heat exchanger. Then, it is needed to drill and then to inject under pressure in a second vertical well for connecting hydraulically the first one by creating newly-formed planar fractures in the deep heat exchanger. Considering the absence of natural permeability, fresh water must be injected from one well (injection well), and by heat transfer taken on the newly created artificial fractures, the cold injected water becomes hotter and could be produced at surface in the second well (production well) for producing steam and thus electricity. The SsF project started with this HDR concept by developing permeability in a crystalline basement lying below the super-hot sedimentary cover.

After the drilling of the GPK-1 well in 1987, the main findings were a very high geothermal gradient in the first km with about 110 °C. However, below those depths, the geothermal gradient declined sharply indicating the occurrence of natural fluid circulations within the natural fractures inside the Triassic formations and the crystalline basement, the uppermost sedimentary cover acting as a thermal insulator. It turned out that 140 °C was measured at 2000 m depth in the granite instead of the 200 °C planned initially. The second main finding is the occurrence of a native brine within the crystalline basement proving that the top basement between 1400 and 2000 m depth was not tight as anticipated by many geoscientists (Vuataz et al., 2000). By taking into account those findings, the capacity to develop post-stimulation permeability was investigated considering two cases. First, the top basement was considered as a medium with a residual permeability due to individual natural fractures partly sealed by hydrothermal deposits. Its stimulation could lead to preferential flow paths and thus a rapid cooling. Therefore, a second option was also considered. Indeed, the deepest depths probably correspond to complex fractured rock where closed natural fractures took place within brittle crystalline rocks (Gerard et Kappelmeyer, 1987). In this deeper case, it would be possible to stimulate a volume of fractured rocks and thus to engineer structural linkages between the future doublet for extracting large amounts of heat by circulation through this created down-hole heat exchanger.

However, before to drill at great depths, it turned out that for better exploring the Soultz basement an old petroleum well was deepened and fully cored in 1990-1991 from the Middle Triassic limestone to the deep granite from 930 till 2230 m depth.

This newly exploration well with a low borehole diameter brought new geological characterization about the natural fracture system. The main finding was the confirmation of highly fractured zones with associated hydrothermal alterations in this shallow basement reservoir. Natural fractures are organized in clusters and intense argillic hydrothermal alteration took place in the granite evidencing the impact of paleo or recent fluid circulations (Genter et al., 2010). It was also shown that the natural fracture density in the granite was more than three times higher than in the Permo-Triassic sandstone (Genter et al., 1997).

Then, in order to achieve hotter temperature conditions, it was planned to deepen the GPK-1 geothermal well from 2000 to 3600 m in 1992 and to drill a second geothermal well, GPK-2, from surface to 3890 m in 1995 which is located about 500 m apart from GPK-1. The temperatures measured at total depth of those two wells GPK-1 and GPK-2, were around 160 °C and thus still far from the 200 °C expected. Many tests were conducted in those wells including hydraulic testing, tracer tests, hydraulic stimulations and circulation tests in this intermediate reservoir (Schill et al., 2017). Induced seismicity was monitored both in surface but also in some former oil wells deepened till the top basement (Cuenot et al., 2008; Dorbath et al., 2009).

Finally, GPK-2 was deepened to 5058 m measured depth for reaching 200 °C at total depth and two additional deep geothermal wells, GPK-3 and GPK-4 were drilled to about 5000 m and reached 200 °C (Genter et al., 2010). As the HDR concept was still in mind, it was planned that GPK-2 and GPK-4 would be two production wells and GPK-3 an injection well. All these new drill pads were drilled from the same platform for optimizing the geothermal operations (stimulation, circulation test and future exploitation). Natural permeability was observed in the granitic sections of all wells mainly related to hydrothermally and fractured sections (Evans et al., 2005). Even if permeability indicators were observed in each well, natural artesian flowrate was too low for a viable economic production. Therefore, each well, which has an open-hole section between 4500 and 5000 m, was hydraulically and chemically stimulated. These stimulations enhanced significantly the hydraulic yield of the three reservoir sections (2000 m, 3500 m, 5000 m), in some instances by about two orders of magnitude (Schill et al. 2017). Kohl et al. (1997) shown that complex hydraulic flow regimes are not restricted to near-well vicinities but rather extend large distances until reaching high capacity far-field faults. The most effective method for enhancing the flow, was the hydraulic stimulation rather than the chemical ones.

In the follow-up geothermal projects such as at Landau and Insheim, the concept of enhancing the naturally most productive reservoir level at the top of the granitic basement was applied, as well as specific hydraulic stimulation techniques (Schindler et al., 2010). Several long-term circulation tests including tracer tests were carried out at SsF for demonstrating that the deep wells are connected after stimulation on a large open geothermal reservoir producing a very saline brine (Sanjuan et al., 2006).

From 2011, the new Rittershoffen geothermal project, located less than 10 km from SsF, was launched for producing heat at high temperatures (170 °C) and high flowrate (>70 L/s) for providing geothermal heat to a biorefinery. The first vertical well was drilled at 2560 m and targeted a local normal fault steeply dipping in the fractured granite. This first well, GRT-1, was not permeable enough and was thermally, chemically and hydraulically stimulated. Its hydraulic performance was enhanced by a factor 5 and was considered as a successful geothermal well (Baujard et al., 2017). Then, the second well, GRT-2, was drilled to 3200 m and inclined from the same pad and targeted the same permeable normal fault which was better defined thanks to a new 2D seismic survey (representing 16 km length) done in 2013 calibrated with the geological results of the first well. The highly deviated well, GRT-2, crosscut this local fault and its damage zone and was immediately permeable at the end of the drilling operation without any stimulation operations (Baujard et al., 2017). Thus, the first vertical well could be considered as an EGS-like well whereas the second one was fully hydrothermal because several permeable channels bearing by the normal fault were crosscut and contributed to the flowrate. This Rittershoffen EGS project demonstrated that permeable faults took place at great depth, but the main challenge is to adapt the well trajectories with the complex geometry and internal architecture of those local faults. To fill the gap between the lack of deep knowledge of the geothermal resource (lithology, fault geometry, permeable features) and the design of future geothermal wells, innovative geophysical exploration is one of the main tools.

From 2016, GPK-2 is the unique production well at SsF with a mass flowrate of about 30 kg/s. Therefore, both GPK-3 and GPK-4 could be used as reinjection wells. It turns out that it is easier to produce a geothermal fluid with a relevant flowrate, assisted by a production submersible down-hole pump because the wells are artesian, than to reinject in one well only. Thus, it is the reason why GPK-4 became an injection well. Moreover, the fact to use two reinjection wells limits the seismic activity and consequently the occurrence of large felt seismic event. In parallel, from 2016 the geothermal doublet at Rittershoffen is producing a brine at 168 °C in surface with an average flowrate of 80 kg/s.

From 2010 to 2019, a new geothermal project was launched close to Strasbourg at Illkirch (Figure 4.1). It targeted a deep normal fault having a vertical off-set of about 800 m located at the interface between the Lower Triassic sandstone and the top crystalline basement. Thus, a new 2D seismic reflection survey (35 km) was acquired in 2015 as well as other geophysical methods (gravity, aeromagnetic). However, this faulted interface was tight during drilling operation. It could be interpreted as the occurrence of secondary argillic clay halo that plugged this fault due to the past activity of the hydrothermal system (Glaas et al., 2021a). Thus, this first highly deviated well, GIL-1, was deepened to 3800 m depth in the crystalline basement which evidenced some permeability indicators and a high fracture density (Baujard et al., 2022, Glaas et al., 2021b). A stimulation program including hydraulic and chemical operations was developed for enhancing the initial productivity conditions. However, due to felt induced seismicity taking place at Vendenheim (Figure 4.1) and generated by another geothermal operator, the local mining authority suspended unilaterally the Illkirch project, and the second well is still pending to the Alsace prefecture decision.

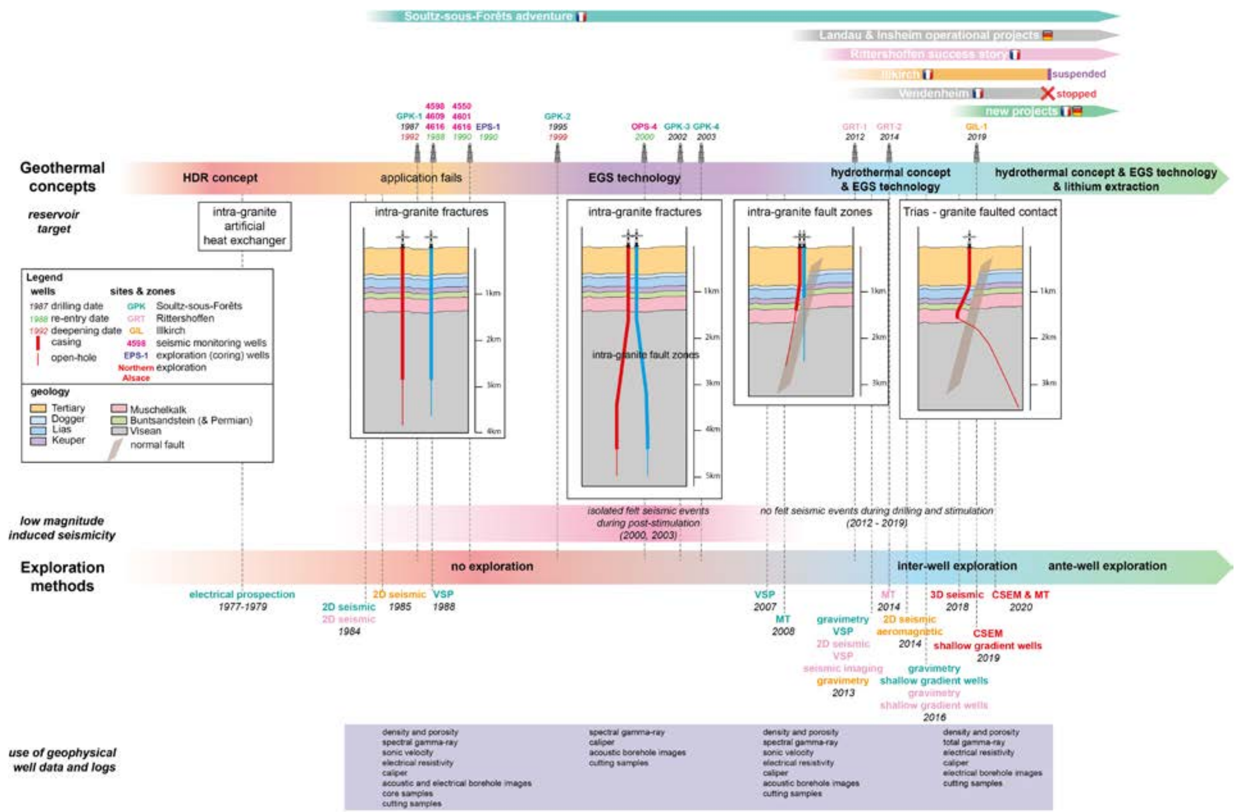


Figure 4.2 *Evolution of the geothermal concepts in the Upper Rhine Graben based on the Soultz-sous-Forêts pioneered geothermal project.*

Therefore, EGS sites in the URG could be considered as convective-dominated systems characterized by the occurrences of some open natural fractures. The natural fluids circulating within the fracture/fault system could be pumped via suitable borehole trajectories. The shallower Soultz wells were drilled till 2000 m vertically intersecting a steeply dipping fracture system. Therefore, the probability that vertical boreholes intersect subvertical natural fractures was quite low and complex stimulation strategies were needed to connect the open-hole section of the geothermal wells with the partly permeable natural fracture system.

For more recent and future projects in the URG, inclined or deviated wells could be drilled into the nearly vertical fracture system that allowed easier connections to the most convective and permeable fractures (Vidal and Genter, 2018). Then, from the purely HDR concept developed at SsF for creating from scratch a down-hole heat exchanger, the occurrence of natural brines trapped with complex steeply dipping fractures, the initial geothermal concept evolved to Enhanced or Engineered Geothermal Systems (EGS) in order to enhance the hydraulic flowrate. Generally, there is no need to restimulate the geothermal wells during long-term exploitation. There is no decline of the production neither increases of the reinjection pressure, which is below 20 bars both at SsF and Rittershoffen. Then, the stimulated fractured reservoir acts as a hydrothermal reservoir partly reconnected to the far-field due to the impact of the stimulation techniques. Therefore, we can state that there is a kind of physical continuum between EGS, with no or low initial permeability and hydrothermal system, which are prone to be hydraulically improved by post-drilling stimulations.

## 4.3 Pre-exploration phase

The structural and geological context of the SsF area in the URG can be outlined by a thick sedimentary cover of 1400 m made of Mesozoic (Permo-Triassic to Middle Jurassic) and Cenozoic formations lying on the top of a Carboniferous granite horst, limited by local faults striking NNE-SSW to NE-SW dipping 60 to 70° West. There is a huge unconformity between the Mesozoic and the Cenozoic sedimentary successions due to an emersion or an uplift before the Cenozoic. By comparison with the Paris Basin geology, that means that many Mesozoic sedimentary units are lacking like the top Jurassic and all the Cretaceous. As this area was characterized by several tectonic phases during the emplacement of the Rhine Graben, the geophysical methods deployed on surface and sometimes in the wells must consider the specific geological background of this area.

During purely HDR development at SsF, geophysical exploration was rather limited because the basic idea was not to find an aquifer or a specific geological unit but deep-seated brittle rocks showing very low matrix porosity and high temperature conditions. Therefore, there was no real geophysical exploration phase at SsF even if research based on surface electrical methods were done between 1977 and 1979 in order to target deep geothermal resources in the basin (Baudu et al., 1980).

However, for designing properly a vertical deep drilling operation, which is risky and costly, there was a strong need to characterize the overlying sedimentary units. Thus, 2D vintage seismic reflection profiles done for oil exploration in 1984 mainly to image the Mesozoic and the Cenozoic formations were reprocessed and reinterpreted for geothermal targets at the sedimentary-basement interface (Munck et al., 1979). Moreover, a series of former oil wells was used for calibrating the reprocessed 2D seismic profiles and stratigraphy. Therefore, the provisional geological profile of the first well GPK-1 between surface and the top basement was very accurate thanks to the high density of old petroleum wells drilled in this area. At regional scale, older public gravity and magnetic measurements (Rotstein et al., 2006) indicated that the Bouguer anomaly was delineating a large area corresponding to a granite batholith already proved by a core taken in the old petroleum well, 4616, located at SsF that reached the top of the granitic basement at 1380 m depth.

With the drilling of GPK-1 and its stimulation in 1988, three old petroleum wells surrounding the site (4598, 4601, 4616) were reopened in order to instrument down-hole three-directional permanent probes for monitoring induced seismic activity during stimulation operation. Those probes were designed to withstand high temperature (125 °C) and severe corrosion conditions at the bottom of the holes.

In parallel to the coring of the HDR exploration well (EPS-1), three old petroleum wells, 4550, 4601 and 4616 were deepened in 1990 to about 1500 m in order to instrument down-hole seismic sensors. The fact that those sensors would have been installed in the deep Triassic sandstone or the Carboniferous basement, allowed enhancing detection of very low magnitude events and reducing the uncertainty on the location of the induced events. An additional peripheral seismic observation well, OPS-4; was drilled in 2000 and located less than 2 km south of GPK-2. It started from surface to 1540 m in the Lower Triassic formation in order to reduce azimuthal bias during the seismic monitoring. In parallel, a permanent network of surface seismic stations was installed and regularly densified according to stimulation and circulation phases.

The drilling of the first well GPK-1 to 2000 m and its later deepening to 3600 m were also a good opportunity to use innovative image log tools based on acoustic (BHTV, UBI) and electrical methods (FMS, FMI, ARI). In 1987, FMS tool was used probably for the first time in continental Europe for characterizing the fracture depth, the fracture azimuth and their dip in the granite section. Moreover, drilling induced tensile fractures were also characterized for measuring the orientation of the main horizontal stress. Detailed interpretation of standard geophysical logs in the basement of GPK-1 (Traineau et al., 1991) was achieved as well as detailed comparison between borehole image logs and continuous coring done in EPS-1 (Genter et al., 1997). During this early phase of reconnaissance (1987-1991), VSP (Vertical Seismic Profiling) was carried out to better image the fault structures close to the GPK-1 well and for improving the velocity model allowing an accurate location of seismic events to be recorded during stimulation experiments. Moreover, results of VSP were used to reprocess two vintage reflection seismic lines crossing the SsF area. Based on the interpretation of five 2D seismic lines, a 3D geological model was built in a geomodelling tool (Renard and Courrioux, 1994). After drilling operations, various geophysical logging tools were used in the geothermal wells mainly at SsF. They aimed to characterize both the petrography of the crystalline basement (bulk density, sonic velocity), the hydrothermal alteration due to severe geochemical interactions with natural fluids (spectral gamma ray with U, K and Th, resistivity logs), and temperature and flow logs for identifying discrete permeable fractures. For example, the most striking observation derived from spectral gamma ray, was the significant increase of K related to argillic alteration within fractured zones (Traineau et al., 1991). It corresponds to the precipitation of clay minerals bearing potassium like illite related to fluid circulation.

Acoustic and electrical resistivity image logs were also extensively used for mapping in situ, the orientation of natural fractures as well as orientation of the principal horizontal stress field based on the observations of drilling induced tensile fractures or borehole breakouts (Figure 4.3). Caliper logs were also used systematically during the technical phases for cementing operations. By using various geophysical logs acquired in the Soultz wells, many research attempts have been done by using statistical tools like Principal Component Analysis, Hierarchical Ascending Classification or neuronal network for mapping clay-rich zones in the basement.

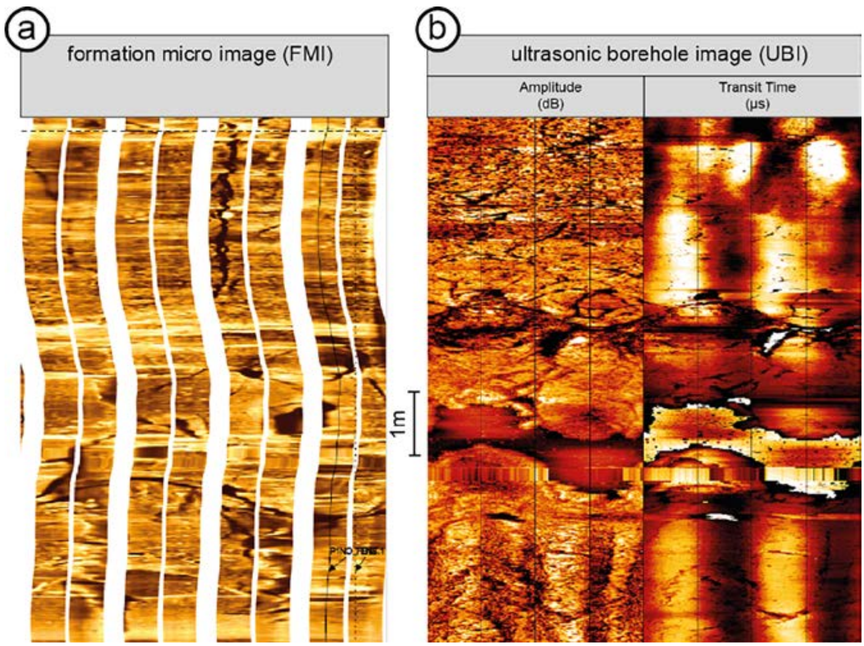


Figure 4.3 *Example of borehole imagery logs acquired in the Lower Triassic sandstone (left) or crystalline basement (right) of the geothermal well GRT-2. Natural fractures appear as sinusoidal traces on both electrical and acoustic borehole image logs. Nearly horizontal stratification, and vertical induced drilling fractures are also visible on the electrical image log (left).*

During the development of the Rittershoffen project, again vintage 2D seismic lines were used for targeting the first vertical well GRT-1 drilled at 2560 m in the granite. However, those reflection seismic data were mainly acquired for imaging oil embedded in Cenozoic sedimentary reservoirs. Thus, the deepest sediments and the related fault network were not imaged properly. It is the reason why a new reflection seismic campaign was achieved at Rittershoffen as well as a three-component VSP for better targeting the second well, GRT-2, drilled to 3196 m. Then a new 3D geological model was built, and the second deviated well was targeted to the North with the same technical design as the first well (Baujard et al., 2017). This well was drilled parallel to the main local fault and about six permeable fractures crosscut the GRT-2 well in the sandstone and in the granite. This highly deviated well became the production well in which a down-hole line shaft pump was set. Consequently, the first well, GRT-1, became the reinjection well which is mainly crosscut by a branch of the local fault in the granitic section. From 2016, geothermal exploitation is running properly by using this doublet.

After this success story in Rittershoffen, the Illkirch project started in 2010. From the lessons learned at SsF and Rittershoffen, two main sets of geophysical exploration methods were carried out. First, vintage 2D seismic lines were reprocessed and additional new 2D seismic lines were acquired. It aimed to better define the geological and structural properties in this part of the Rhine Graben where the sedimentary layers are rather thick. In this part of the Rhine graben, this sub-basin could reach more than 4000 m thick. In parallel to this new seismic acquisition campaign, two gravity data acquisitions were made in 2013 and 2016 for refining the existing datasets. Moreover, a high-resolution aeromagnetic survey was conducted in 2015 in this area. Both geophysical methods aimed to determine the nature of the deep basement (granite, schist, metamorphic rocks, …), which was only known from outcrops lying in the Vosges mountains. Therefore, a better image of the local faults and layers was achieved by combining in a geomodeller, both vintage and recent 2D seismic lines. Then, a combined interpretation of gravimetric and magnetic data correlated with a structural interpretation of 2D seismic lines made it possible to highlight nature and the structure of the deep basement (Edel et al., 2018). Moreover, the drilling of the deepest part of the GIL-1 is well confirmed that the deepest basement is characterized by brittle crystalline formation. The drilling of this deviated well perpendicular to a local fault at Illkirch between 2018 and 2019 demonstrated that the faulted interface between the Triassic sandstone and the granite was tight, that the basement was made of granite as predicted by aeromagnetic results and that permeable fractures took place in the crystalline basement. Because of felt induced seismicity triggered by another competitor at Vendenheim in the northern part of Strasbourg during this period, the Illkirch geothermal project was temporarily suspended by local mining authorities in 2021 till now.

In Northern Alsace, a 3D seismic reflection campaign was carried out in 2018 over a surface of about 180 km² in superimposition with the geothermal licenses and concessions hold by Électricité de Strasbourg. It was the first 3D seismic survey done in France for deep geothermal energy. The large surface of the 3D seismic acquisition allowed having an underground image at a regional scale rather than at the level of a single project, which helped in terms of interpretation of the continuity of the structures and of the horizons. The target is to obtain a better geological and structural image of the sedimentary layers and the fault system by focusing on the deep formations in the basin, e.g. the Lower Permo-Triassic sandstone and the top crystalline basement. Therefore, special attention has been paid on the faults intersecting the top basement for evaluating how they rooted into it (Figure 4.4). The main striking parameters of this 3D acquisition correspond to broadband seismic ranging from 2 Hz up to 96 Hz delivered by 62000 lbs vibro-trucks and 27000 vibrated points. Various former old petroleum wells, used for the seismic interpretation, are clustered around the SsF and Rittershoffen geothermal wells (Figure 4.4). The two operational EGS sites of SsF and Rittershoffen were comprised within the 3D acquisition area. It represents a tangible advantage for better calibrate the 3D results from seismic in terms of geology by comparison with the geological layers observed in the boreholes of SsF and Rittershoffen. In order to assess the imaging quality of the deep faulting, the pre-processing flow chart was validated by a 3D migration of the full cube. Iteratively built from picked faults and key horizons on delivered volumes, the 3D structural model was built according to the results of an Advanced Fault Enhanced volume. To refine the fault definition and location, a fault-oriented velocity model was carried out (Toubiana et al., 2020).

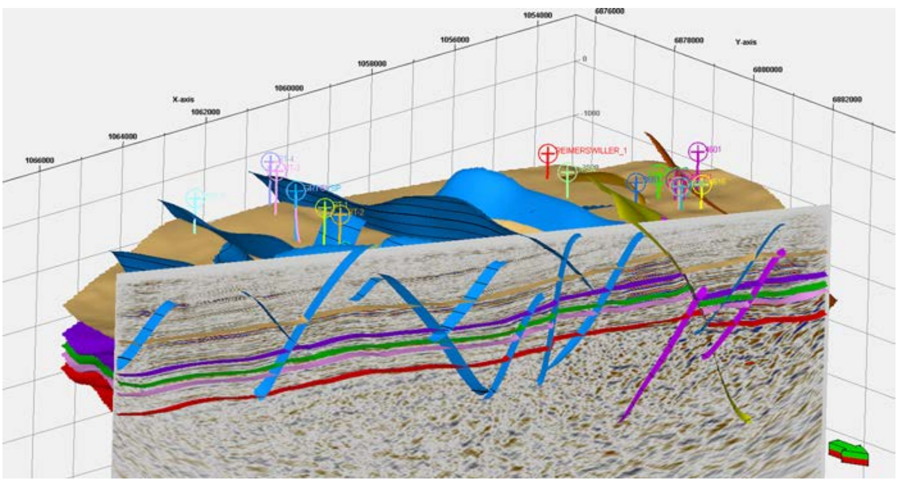


Figure 4.4 *Local 3D model of the geological layers and the main steeply dipping faults in Northern Alsace derived from 3D seismic interpretation. The green arrow indicates the North, and X and Y axes the geographic coordinates. On surface, geothermal and former oil well names from Rittershoffen (left) and SsF (right) geothermal sites are represented. Geological legend for the layers from surface to the deep basement: (brown) Eocene with top of the Dolomitic Zone, (purple) Upper Trias with top of the Keuper, (green) Middle Trias with top of the Muschelkalk, (pink) Lower Trias with top of the Buntsandstein, (red) Carboniferous with top of the crystalline basement.*

Based on new gravity data acquired in Northern Alsace and their comparison to the older Bouguer anomaly, a qualitative data analysis reveals several negative Bouguer anomalies suggesting a decrease of the bulk density at the depth that fits with potential geothermal reservoirs like the Lower Trias and the top basement (Abdelfettah et al., 2020). A more quantitative analysis of gravity data combined with 3D geological models outlined areas with low density values that could be explained either by the variation of petrography within the basement and/or the occurrences of highly fractured zones associated with geothermal fluid affecting the bulk density values.

Due to their sensitivity to fluids and particularly brine water in rocks, passive electromagnetic (EM) techniques (e.g. Magnetotellurics or MT) or active (Controlled-Source Electromagnetic or CSEM) have been traditionally used to investigate the subsurface conductivity. Therefore, MT surveys were conducted in Northern Alsace, respectively, close to Soultz in 2007-2008 and Rittershoffen in 2013-2014. MT data collected in the Soultz area were combined with other geophysical data for estimating temperatures at depth below the existing geothermal wells drilled at 5000 m. The main result of this analysis based on MT, was the forecast of a very deep convective cell below GPK-2 at around 6000–8000 m. Results from continuous MT measurements done at Rittershoffen in 2013-2014 suggested transient variations in subsurface conductivity due to the occurrence of fluids at depth. Furthermore, by using MT response versus time, it revealed that fluids could migrate in a NE direction from the injection well GRT1. Therefore, MT is not only a method for geothermal exploration or for assessing temperatures at depth but could be used as a monitoring tool during hydraulic stimulation or geothermal exploitation.

EM methods have shown to be effective to characterize geothermal reservoir geometry in volcanic area, hydrocarbon reservoir geometry in offshore sedimentary area or onshore mineral exploration but not really in EGS. Nevertheless, the ability of EM methods to image targets with high geothermal potential in deep fractured reservoir and in a high man-made noise environment still needs to be demonstrated. Indeed, CSEM sources must compete with high noise levels and a conductive sedimentary cover resulting in low signal to noise ratio. At SsF, a full-scale 3D CSEM campaign done in 2020 demonstrated the ability of the technique to image resistivity variations underneath a thick sedimentary cover (>1400 m).

An assessment of subsurface rock mineral compositions derived from their physical properties measured through geophysical logging, employing a combination of statistical and machine learning techniques has been applied to the Triassic sedimentary reservoirs from the URG (Pwavodi et al., 2024). Based on various geophysical data from the geothermal SsF and Rittershoffen wells, mineral composition was spatially predicted and compared with existing mineral descriptions. This approach based on machine learning helps in deciphering complex mineralogical compositions and geological structures within subsurface geothermal reservoirs from the URG.

A methodology was established by using the thermal logs of the deep geothermal wells of Rittershoffen and SsF and applied to the temperature profiles measured in the gradient wells as an exploration tool. The basic idea is to try to estimate the temperature at the top of the geothermal reservoir. Thus, a series of seven shallow wells (<200 m) were drilled in Northern Alsace and temperatures were measured at equilibrium. Then, by using detailed lithostratigraphy and other relevant geological information, temperatures were extrapolated linearly till the top of the Middle Triassic limestone (Maurer et al., 2018). Above this geological interface, the geothermal gradient is conductive and shows a very high slope. This method is effective in volcanic environments for locating the heat source. It has been adapted to the URG reservoirs for delineating hottest zones related to local faults at the depth corresponding to Middle Triassic layers.

## 4.4 Optimizing borehole design according to the geological knowledge of the reservoir

Geophysical exploration was not really used for HDR because there was no need of reconnaissance of a deep heat exchanger nor to identity geothermal permeable reservoirs. However, based on extensive structural characterization by drilling in the URG, faults and fractures are highly dipping (>70°) and drilling vertical wells present a high probability to not cross these nearly vertical structures. Some recent wells in the URG (GRT-2 in Rittershoffen, GIL-1 in Illkirch, two wells in Vendenheim) are deviated in order to intersect a maximum of nearly vertical faults and fractures. However, a deviated well is more complicated to drill, to log and to exploit, and consequently more expensive. Insofar the cost of the drilling follows an exponential law corelated to the drilled length. It is the reason why the most recent wells are not drilled into the deep granitic basement only like in SsF but target the fracture network in the overlying Lower Triassic sandstones as well as the first kilometer of crystalline basement just below the interface with the sedimentary cover. It has been demonstrated from extensive structural analysis of the SsF wells that the first km of the top crystalline basement is much more naturally fractured than the overlying Triassic sandstones as well as the deeper basement.

By discovering that the fractures are highly dipping and locally permeable, well design evolved from vertical to deviated or even inclined wells trajectories. Therefore, the first wells were vertical at Soultz (GPK-1, GPK-2) but slightly evolved to a more complex design like GRT-2 in Rittershoffen that was deviated and drilled parallel to the main local faults identified by 2D seismic. The hydraulic performance of this second well was so good, that stimulation operations were not needed (Baujard et al., 2017). The open-hole sections of the geothermal wells are generally aligned with the orientation of the principal horizontal stress (SsF, Rittershoffen). Some wells in Brühl, Insheim or Rittershoffen were not stimulated and presented a sufficient natural permeability for industrial exploitation (Vidal and Genter, 2018). They are classified as hydrothermal and not strictly EGS wells. Their trajectories were well designed according to the geological and structural context because they crossed out several permeable fractures. The absence of stimulation is a substantial advantage for reducing cost as well as induced seismicity, main nuisance for public acceptance. However, all the geothermal projects in the URG are considered as EGS because they will need to use a reinjection well and to develop induced seismicity related to the geothermal exploitation (Maurer et al., 2020).

## Conclusion and perspectives

In the Upper Rhine Graben, since the earlier development of matrix porosity geothermal projects in sandstones (e.g. Cronenbourg) and HDR projects in deep granitic basement (e.g. SsF) in the 90s, the geothermal concept evolved towards EGS projects by considering the geological properties of the deep geothermal system. The occurrence of fractured reservoirs characterized by natural brine circulations with fractured zones obliged developers to adapt geophysical exploration methods, geophysical well logging strategies as well as technical well design for reaching hydrothermal or EGS geothermal targets.

Therefore, by improving the conceptual model of deep geothermal resources in the URG, well productivity has been improved either by stimulation or by optimizing geothermal targets by derisking drilling depths and well design. The depths of the wells have been divided by factor 2 between SsF and Rittershoffen, the first km of the top basement being highly fractured, hydrothermally altered and permeable. Consequently, the flowrate is higher than 70 kg/s at Rittershoffen compared to the 30 kg/s at SsF only.

In terms of surface geophysical methods, only 2D seismic reflection was used in the past for shallower petroleum targets. By considering the importance of the fractured reservoirs, 2D or even better 3D seismic is now routinely used for deep geothermal resource exploration in the URG for imaging the top basement as well as the fault system at seismic scale. In terms of depth penetration, some progresses were also done from surface to great depths. For instance, some years ago, at Rittershoffen the second well, GRT-2, was targeted based on a specific 2D seismic line. For new geothermal projects based on a doublet, well design and their geothermal targets are defined before any drilling operation based on surface geophysical methods and specific treatments (inversion, machine learning, 3D modelling, …).

Permeable faults or fractures lying into a deep basement hidden by a thick sedimentary cover are still challenging to image based on surface geophysical methods. Thus, there is a real need for combining various geophysical methods and treatments to propose a multi-physics image of deep fractured geothermal reservoirs in the URG in order to explore with low risks and thus exploit more sustainably the deep geothermal resource.

## Acknowledgments

This contribution has partially received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101147171 (FINDHEAT project). This research is also part of the SIMGEO project funded by ADEME (French Agency for Ecological Transition).

## References

Abdelfettah Y., Hinderer J., Calvo M., Dalmais E., Maurer V., Genter A. (2020) Using high accurate land gravity and 3D geological modeling to discriminate potential geothermal areas: Application to the Upper Rhine Graben, France, *Geophysics* 85(2), 35-56, https://doi.org/10.1190/GEO2019-0042.1.

Baudu R., Bernard J., Georgel J.M., Griveau P., Rugo R. (1980) Application des méthodes de prospection électriques dipolaires à l'étude géothermique du Fossé rhénan supérieur, BRGM Open file report, 80 SGN 586 GPH, 64 pages.

Baujard C., Dalmais E., Glaas C., Maurer V., Genter A. (2022) Evaluation du risque géologique, retour d'expérience du projet Illkirch (Strasbourg, France), Journées de la Géothermie 2022, Aix les bains, France, 09 et 10 juin 2022.

Baujard C., Genter A., Dalmais E., Maurer V., Hehn R., Rosillette R., Vidal J., Schmittbuhl J. (2017) Hydrothermal characterization of wells GRT-1 and GRT-2 in Rittershoffen, France: Implications on the understanding of natural flow systems in the Rhine graben, *Geothermics* 25, 255-268.

Cuenot N., Dorbath C., Dorbath L. (2008) Analysis of the microseismicity induced by fluid injections at the EGS site of Soultz-sous-Forêts (Alsace, France): Implications for the characterization of the geothermal reservoir properties, *Pure and Applied Geophysics* 165, 797-828.

Dorbath L., Cuenot N., Genter A., Frogneux M. (2009) Seismic response of the fractured and faulted granite to massive water injection at 5 km depth at Soultz-sous-Forêts (France), *Geophysical Journal International* 177(2), 653-675, https://doi.org/10.1111/j.1365-246X.2009.04030.x.

Edel J.B., Maurer V., Dalmais E., Genter A., Richard A., Letourneau O., Hehn R. (2018) Structure and nature of the Paleozoic basement of the Central Upper Rhine Graben derived from new and old magnetic, gravimetric and seismic investigations. Zoom on the deep geothermal project of Illkirch-Graffenstaden (S. of Strasbourg, France), *Geothermal Energy Journal* 6, 13, https://doi.org/10.1186/s40517-018-0099-y.

Evans K.F., Genter A., Sausse J. (2005) Permeability creation and damage due to massive fluid injections into granite at 3.5 km at Soultz: part 1 - Borehole observations, *Journal of Geophysical Research* 110, B04203.

Genter A., Castaing C., Dezayes C., Tenzer H., Traineau H., Villemin T. (1997) Comparative analysis of direct (core) and indirect (borehole imaging tools) collection of fracture data in the Hot Dry Rock Soultz reservoir (France), *Journal of Geophysical Research* 102(B7), 15419-15431.

Genter A., Evans K., Cuenot N., Fritsch D., Sanjuan B. (2010) Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems (EGS), *Comptes Rendus Geoscience* 342, 502-516. https://doi.org/10.1016/j.crte.2010.01.006

Gerard A., Kappelmeyer O. (1987) The Soultz-sous-Forêts project, *Geothermics* 16(4), 393-399.

Glaas C., Patrier P., Vidal J., Beaufort D., Genter A. (2021a) Clay mineralogy: a signature of granitic geothermal reservoirs of central Upper Rhine Graben, *Minerals* 11, 479, https://doi.org/10.3390/min11050479

Glaas C., Vidal J., Genter A. (2021b) Structural characterization of naturally fractured geothermal reservoirs in the central Upper Rhine Graben, *Journal of Structural Geology* 148, 104370, https://doi.org/10.1016/j.jsg.2021.104370.

Häring M.O., Schanz U., Ladner F., Dyer B.C. (2008) Characterisation of the Basel 1 enhanced geothermal system, *Geothermics* 37, 469-495, https://doi.org/10.1016/j.geothermics.2008.06.002.

Kohl T., Evans K., Hopkirk R., Jung R., Rybach L. (1997) Observation and simulation of non-Darcian flow transients in fractured rock, *Water Resource Research* 33, 407-418.

Kölbel L., Kölbel T., Wiegand B., Sauter M., Schäfer T., Siefert D. (2020) Identification of fractured zones in geothermal reservoirs in sedimentary basins: a radionuclide-based approach, *Geothermics* 85, 101764.

Maurer V., Aichholzer C., Richard A., Harlé P., Hehn R., Genter A., Duringer Ph. (2018) Geothermal reservoir temperature estimation derived from gradient wells in a continental rift context (Upper Rhine Graben), Stanford Geothermal Workshop 2018, Stanford, California, USA, 12-14 February 2018.

Maurer V., Gaucher E., Grunberg M. Koepke R., Pestourie R., Cuenot N. (2020) Seismicity induced during the development of the Rittershoffen geothermal field, France, *Geothermal Energy* 8, 5, https://doi.org/10.1186/s40517-020-0155-2.

Munck F., Walgenwitz F., Maget P., Sauer K., Tietze R. (1979) Synthèse géothermique du Fossé rhénan Supérieur, Commission of the European Communities, BRGM Service Géologique Régional d'Alsace, Geologisches Landesamt Baden-Württemberg.

Pwavodi J., Marquis G., Maurer V., Glaas C., Montagud A., Formento J.-L., Genter A., Darnet D. (2024) Rock mineral volume inversion using statistical and machine learning algorithms for Enhanced Geothermal Systems in Upper Rhine Graben, eastern France, *J. Geophysical Research: Machine Learning and Computation* 1, e2024JH000154, https://doi.org/10.1029/2024JH000154

Renard P., Courrioux G. (1994) Three-dimensional geometric modelling of faulted domain: The Soultz horst example (Alsace, France), *Computer Geoscience* 20(9), 1379-1390.

Rotstein Y., Edel J.-B., Gabriel G., Boulanger D., Schaming M., Munschy M. (2006) Insight into the structure of the Upper Rhine Graben and its basement from a new compilation of Bouguer gravity, *Tectonophysics* 425, 55-70, https://doi.org/10.1016/j.tecto.2006.07.002

Sanjuan B., Millot R., Innocent Ch., Dezayes Ch., Scheiber J., Brach M. (2016) Major geochemical characteristics of geothermal brines from the Upper Rhine Graben granitic basement with constraints on temperature and circulation, *Chemical Geology* 428, 27-47, https://doi.org/10.1016/j.chemgeo.2016.02.021

Sanjuan B., Pinault J.-L., Rose P., Gerard A., Brach M., Braibant G., Crouzet C., Foucher J.-C., Gautier A., Touzelet S. (2006) Tracer testing of the geothermal heat exchanger at Soultz-sous-Forêts (France) between 2000 and 2005, *Geothermics* 35, 622-653.

Schill E., Genter A., Cuenot N., Kohl Th. (2017) History performance history at the Soultz EGS reservoirs from stimulation and long-term circulation tests, *Geothermics* 70, 110-124.

Schindler M., Baumgartner J., Gandy T., Hauffe P., Hettkamp T., Menzel H., Penzkofer P., Teza D., Tischner T., Wahl G. (2010) Successful hydraulic stimulation techniques for electric power production in the Upper Rhine Graben, Central Europe, in Proceedings of World Geothermal Congress 2010, WGC2010, Bali, Indonesia.

Schmittbuhl J., Lambotte S., Lengliné O., Grunberg M., Jund H., Vergne J., Cornet F.H., Doubre C., Masson F. (2021) Induced and triggered seismicity below the city of Strasbourg, France from November 2019 to January 2021, *Comptes Rendus Géoscience* 353, 561-584, https://doi.org/10.5802/crgeos.71.

Toubiana H., Salaun N., Mitschler J.B., Carriere X., Gigou G. (2020) Upper Rhine Graben deep Geothermal reservoir imaging, *EAGE Annual*, 82nd EAGE Conference & Exhibition 2020, 8-11 June 2020, Amsterdam, The Netherlands.

Traineau H., Genter A., Cautru J.P., Fabriol H., Chevremont P. (1991) Petrography of the granite massif from drill cutting analysis and well log interpretation in the HDR borehole GPK1 (Soultz, Alsace, France), *Geothermal Science & Technology* 3(1-4), 1-29.

Vidal J., Genter A. (2018) Overview of naturally permeable fractured reservoirs in the Upper Rhine Graben: Insights from geothermal wells, *Geothermics* 74, 57-73, https://doi.org/10.1016/j.geothermics.2018.02.003.

Vuataz F.-D., Brach M., Criaud A., Fouillac Ch. (1990) Geochemical monitoring of drilling fluids: A powerful tool to forecast and detect formation waters, *SPE Formation Evaluation* 5(2), 177-184.