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Geophysical Monitoring of Geothermal Fields in the Upper Rhine Graben

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ABSTRACT

In the Upper Rhine Graben (URG), several EGS plants are currently exploiting brines at a temperature higher than 150°C. Other projects are in the drilling phase, others are still in exploration stage, showing that the geothermal activity in the URG is currently on the growing slope. A brief overview of the geothermal sites in the French part of the URG is proposed, with a focus on the environmental monitoring of the project and more specifically on induced micro-seismicity and geodetic monitoring. Because of this growing activity, regulation had to evolve to take into account these new issues and to regulate the building and exploitation of deep geothermal plants by constraining operators to ensure environmental monitoring. We propose in this paper to show the results of more than three years of seismic and geodetic monitoring in the Soultz-sous-Forêts and Rittershoffen plants and to show some perspectives of next geothermal operations that will be monitored in the next upcoming months.

1. UPPER RHINE GRABEN EGS PROJECTS OVERVIEW

1.1 Geological context

The Upper Rhine Graben (URG) is a 300 km long, 40 km wide regional rift zone with an average azimuthal orientation of N020°E between Mainz (Germany) and Basel (Switzerland). It is associated to the Rhine valley, structurally bounded on the South by the folded Jura, on the West by low relief Vosges mountain range, on the East by the Black Forest mountain range and northward by the Vogelsberg volcanic massif.

The western edge of the URG is limited by two major normal faults. The outermost Vosges fault separates Paleozoic series from Mesozoic series and has variable vertical off-sets from several hundred meters to over a thousand meters. The innermost Western Rhine fault inconspicuous on the surface, separates Mesozoic series from Cenozoic series. On the Eastern shoulder of the URG, the Schwarzwald fault and the Eastern Rhine faults are dipping westward with similar vertical off-sets.

Stratigraphically, the uppermost part of the URG is composed by Plio-Quaternary deposits which cover with unconformity Eocene and Oligocene formations whose deposition began during the regional extensional context started 40 My ago. This extension is at the origin of the spacing between the Western and Eastern regional Rhine faults. The sedimentological filling of the basin is syn-tectonic and affected by numerous normal faults resulting from the opening system. Within the Mesozoic era, lack of Cretaceous sequence is observed in the Upper Rhine Graben due to a late Jurassic uplift phase, resulting in a 125 Ma hiatus in the depositional sequence.

The Mesozoic and Paleozoic formations, in continuity with the Paris Basin, are exhumed in the rift flanks and are buried below the Tertiary cover, deeper in the centre of the graben by tilted blocks.

1.2 The geothermal context in the URG

For geothermal issues in the URG, favourable targets are mainly deep and fractured hard rocks. Natural fracture system governs natural permeability and thus natural fluid circulations. Boreholes analysis in the URG has shown that the permeability of the matrix of the deepest formations is too low for a standard geothermal exploitation. Indeed, each borehole with high productivity rates is associated with natural faults/fractures induced by the tectonic evolution of the region.

Depending on the local geological conditions, the permeability of the fracture network is sufficient to allow a water circulation and/or its pumping exploitation (Le Carlier et al., 1994). It explains that the circulation could be at regional scale, allowing fluids to reach greater depths (roughly 4-5km; Sanjuan et al., 2016) and temperatures, generating higher temperature gradients than in a classical sedimentary basin. Geothermal brine acts as a heat transfer fluid by pulling up the heat towards the shallower formations through convection cells. Thus, a litho-stratigraphic knowledge is required for an optimal location of the production platform to reach deep-rooted structures where the potential fractured reservoirs are in the shallowest position.

In the Upper Rhine Graben (URG), several deep geothermal plants, such as those in Soultz-sous-Forêts, Rittershoffen, Landau and Insheim (Figure 1), exploit local geothermal reservoirs trapped in the fracture network in Triassic sediments and the underlying granitic basement (Baumgärtner and Lerch, 2013; Genter et al., 2000; Hettkamp et al., 2013). These projects are based on the Enhanced Geothermal System (EGS) technology. The principle underlying this technology consists of increasing the low initial natural hydraulic permeability of pre-existing natural fractures in the geothermal reservoir via hydraulic and/or chemical stimulation (Schulte et al., 2010).

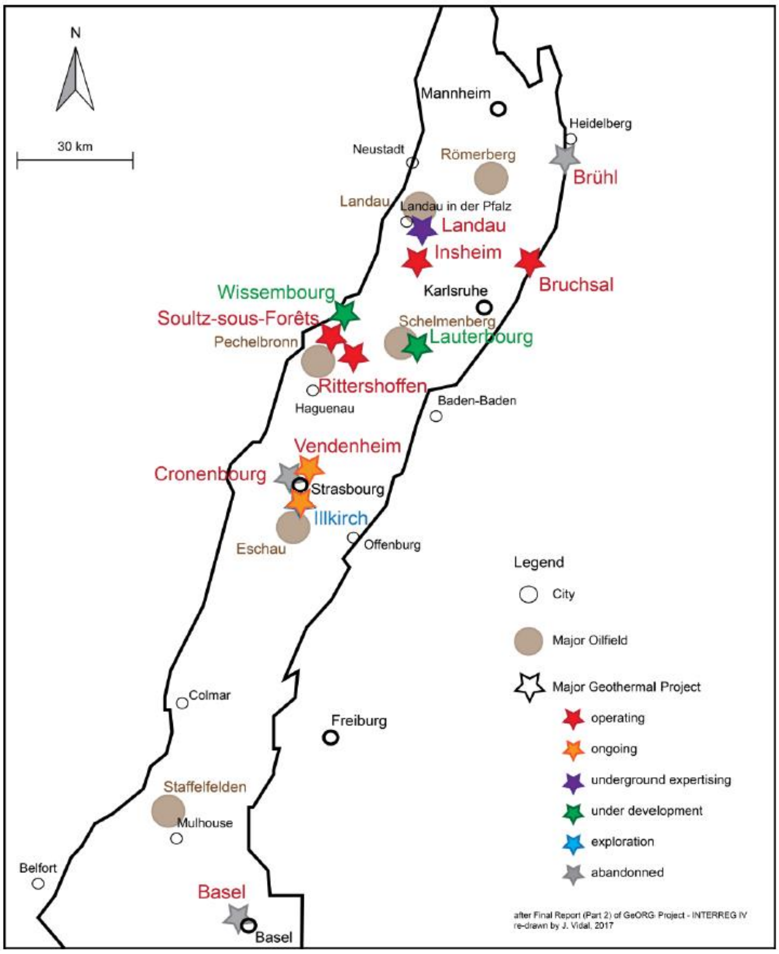

Figure 1: Simplified geological map of the Upper Rhine Graben and status of current deep geothermal projects.

The extensive geological, geophysical and deep drilling data collected in the Soultz and Rittershoffen geothermal wells have led to a better understanding of the deep-seated geothermal resources located at the interface between the sediments and the basement of northern Alsace (Baujard et al., 2017; Dezayes et al., 2010; Genter et al., 2010; Ledésert et al., 1999; Pribnow and Schellschmidt, 2000; Sanjuan et al., 2016; Sausse et al., 2010; Vidal et al., 2016, 2017). The Soultz-sous-Forêts project showed that, from a structural point of view, the best geothermal target of both wells corresponds to a local normal fault showing a significant apparent vertical offset. The next part of the paper is focused on the Soultz-sous-Forêts and Rittershoffen projects, which have been in exploitation in France since 2016. The ongoing Illkirch project, located close to Strasbourg, will also be evocated.

At Soultz, the natural fractures are mainly oriented N0°E, with nearly vertical dipping (Dezayes et al. 2010). At Rittershoffen, the fractures are also N–S striking (N10°E to N20°E) and dip westward in the reinjection well. In the production well, the main fracture orientation is N160°E to N180°E, dipping eastward or westward (Vidal et al., 2016). All these wells were drilled down to the Triassic-sediments and/or the crystalline basement. The Soultz site is located on the western margin of a magnetic body consisting of granitoids, whereas the Rittershoffen site is located more on its center (e.g. Baillieux et al., 2014).

1.3. Projects overview and timeline

The Soultz geothermal project was initiated by a French-German team in 1986 (Gérard and Kappelmeyer, 1987) and has thus been running for more than 30 years. Work at the Soultz site can be divided into three phases: a preparatory phase, a drilling, exploration and reservoir development phase that extended from 1987 to 2007, and the power plant construction phase, which ended up with the commissioning of the plant in 2016 (see **Error! Reference source not found.**). The preparatory phase involved the compilation of existing literature from existing oil industry boreholes and reprocessing and interpretation of old seismic data. The drilling, exploration and reservoir development phase consisted of three sequential campaigns. After an early phase of exploration drilling (GPK-1, EPS-1) at shallow depth (2 km), GPK-1 was deepened to 3600 m and GPK-2 drilled to 3880m. The Soultz project then obtained convincing results between 1991 and 1997. A 4 months circulation test was successfully achieved between these 2 wells in the upper fractured granite reservoir between 3.5 and 3.9 km depth. Based on these encouraging results, GPK-2 was deepened, and two further deviated wells (GPK-3 and GPK-4) were drilled down to 5 km depth in a deep fractured granitic massif between 1999 and 2004, to reach down-hole temperatures of 200°C. The three wells have been stimulated both hydraulically and chemically in order to increase their hydraulic performance (productivity / injectivity index). At that time, geothermal water was pumped out from the production wells (GPK-2, GPK-4) and re-injected at lower temperature into the injection well GPK-3. On a horizontal plan, the 3 deep-deviated wells are roughly aligned with the N170E orientation which is the main orientation of both the fracture network and that of the present-day maximum principal horizontal stress.

Table 1: Timeline of the Soultz-sous-Forêts deep geothermal project

1984-1987	1987-1991	1991-1998	1999-2007	2007-2008	2008-2013	2013-2016
Preparatory phase	Exploration phase	Creation of the two wells system GPK-1/GPK-2 between ~3600 and 3900 m	Creation of the three wells system GPK-2/GPK-3/GPK-4 at ~5000 m	Construction of the first power production unit	Hydraulic Circulations	Dismantling of the previous facilities
		Deepening of GPK-1 at ~3600 m and hydraulic stimulation	Deepening of GPK-2 at ~5080 m and hydraulic stimulation	Power plant design and construction	Circulation tests in 2008, 2009, 2010, 2012 and 2013	Construction of the second production unit
Literature compilation	Drilling GPK-1 at ~2000 m	Drilling GPK-2 at ~3880 m and hydraulic stimulation	Drilling of GPK-3 at ~5100 m and hydraulic stimulation	Installation of the LSP pump in GPK-2 at ~250 m	Production : mostly from GPK-2 (GPK-4 only in 2008 and 2009)	Installation of the LSP pump in GPK-2 at ~350 m in 2016
Seismic survey reprocessing and interpretation	Drilling EPS-1 at ~2227 m (coring between 900 m and 2227 m)	Circulation test between the 2 wells	Drilling of GPK-4 at ~5270 m and hydraulic stimulation	Commissioning and inauguration of the power plant mid 2008	Injection in GPK-3 and sometimes in GPK-1	Commissioning of the renovated plant in July 2016
Permitting and drilling preparation			Circulation test between the 3 wells (5 months)	Installation of the ESP pump in GPK-4 at ~500 m	ESP failed end of 2009	Inauguration of the second power plant in September 2016
			Complementary chemical stimulations	Inter wells circulation tests	Installation of a new LSP in GPK-2 at ~260 m.	Power plant availability since then > 90%

From 2008 to 2013, the commissioning and further exploitation of the first binary power plant at Soultz-sous-Forêts has finally resulted in the development of the EGS (Enhanced Geothermal System) concept. After the dismantling of the previous facilities in 2014-2015 due to corrosion issues related to the geothermal brine, a complete renovation of the plant, with a new geothermal loop and a new ORC (Organic Rankine Cycle) unit, has been built. The commissioning of the renovated plant started in 2016. The plant has been exploiting a geothermal brine at about 150°C with a flowrate of about 30 l/s to produce a net electrical power of about 1.4 MWe since July 2016. The former exploration GPK-1 well was definitively closed in 2018. Currently the brine is pumped out of GPK-2 well and reinjected into two wells, GPK-3 and GPK-4.

The Rittershoffen geothermal plant is located 6 km eastward of the Soultz-sous-Forêts plant. The geothermal plant exploits a geothermal brine trapped in the fractured hard rocks. It is designed to produce a thermal power of about 24 MWth (170°C, 70 l/s) which is delivered to a bio-refinery located 15 km away. Two deep wells have been drilled for targeting local normal-faults located close to the interface between the clastic Triassic sediments and the top crystalline basement. The first well, named GRT-1, reached the final depth of 2580 m end of the year 2012. Various logs and hydraulic tests were performed over the year 2013. As the well injectivity index was quite low, a strategy was defined to carry out operations in order to enhance the fracture permeability and the connection of the well to the reservoir. These operations were applied in two sequences, respectively in April 2013 with a thermal stimulation and in June 2013 with both chemical and hydraulic stimulations. The results obtained were positive since the initial injectivity index was improved by a factor 5 (Baujard et al., 2017,(Baujard et al., 2015; Maurer et al., 2015; Recalde Lummer et al., 2014). Such hydraulic properties were sufficient to reach the expected thermal power, and, right after the operations performed in June, an active reflection seismic survey was achieved. The main purpose of this campaign was to refine the GRT-2 well trajectory. Hence, the drilling of the second well, GRT-2, started in March 2014 and ended in August 2014. GRT-2 is a deviated well of 3200 m length reaching a true vertical depth of 2707 m. Production and circulation tests were performed after the drilling phase. No reservoir development was required since production tests revealed that the initial productivity index was estimated between 2.8 to 3.5 l/s/bar at nominal flowrate (Baujard et al., 2017). The year 2015 was dedicated to the building of the heat transport loop and the building of the geothermal plant, which has been operating since May 2016.

The Illkirch-Graffenstaden deep geothermal project plans the construction of a power plant located 10 km south from the city of Strasbourg to produce electricity and provide heat for a district heating system with a maximum expected thermal power of 20 MWth. The project involves the drilling of two wells (doublet), to produce a geothermal fluid at a flow rate of 70 l/s and a temperature around 150 °C. The targeted reservoir is a fractured zone in the Buntsandstein sandstones and the upper granitic basement. The drilling of the first deep well at 3.8 km in the granite basement is currently ongoing.

2. EVOLUTION OF REGULATIONS

The local tectonic context of the URG shows that many active tectonic faults exist within the basin where natural seismicity is far from being negligible. In addition, it has been shown (Cuenot et al., 2008, Maurer et al., 2015) that stimulation operations, even modest ones, or even exploitation of the geothermal loop are likely to generate induced micro-seismic activity, temporary or continuously, which can be occasionally felt by local population (Charléty et al., 2007, Dorbath et al., 2009). In extreme cases, the occurrence of induced seismicity can even force geothermal operations to be shut down, such as the geothermal project in Basel (Deichmann and Giardini, 2009). As a result, it has become more and more common in deep geothermal energy, exploiting naturally fractured reservoirs, to monitor geothermal activities with high-sensitivity seismological networks. These networks are generally designed not only to accurately assess the state of the natural seismicity before any operation, but also to ensure to be able to detect any emergence of any induced micro-seismic activity attributable to the geothermal operations.

Until 2015, no regulatory framework existed in France to supervise the environmental monitoring of geothermal plant. The deployment of such monitoring networks was left to the goodwill of the operators. With the experience acquired on the Soultz and Rittershoffen geothermal plants as well as the growing number of operators involved in deep geothermal energy, the French mining authorities have express their will to settle clear rules to regulate the construction, the development and the exploitation of geothermal plants. In order to detect any rise of ground motion induced by the geothermal operation, the mining authorities require the deployment of a permanent seismic and geodetic network. At least, five surface stations around each geothermal plant are explicitly required as well as a geodetic station. The goal of this multi-sensors network is to detect any ground motion induced by the geothermal operations at any frequency range.

More precisely, the French mining authorities require that:

- A public information campaign will be organized before the start of the construction of a plant (drilling included).
- At least 6 months before the start of drilling, an operational seismological network of at least 4 short-period velocimetric stations must be set up. A multi-sensors station (broadband velocimeter, accelerometer) must also be installed. A complementary geodetic station including a GNSS receiver and a corner coin for satellite radar interferometry must also be installed on or near the facilities. The data from this station must be connected, sent, processed and archived by a competent independent agency. All the data from this station must be available to the public on the agency website. The monitoring system must remain in place during all operations (drilling potential stimulation, testing and exploitation). A map and the technical information of this network must be communicated to the mining authorities.
- During any well stimulation operations, a real-time physical monitoring of the seismicity must be implemented.

The occurrence of a seismological event, inducing vibrations above a predefined threshold, located in the operator lease and recorded by at least 2 stations, will lead the operator to follow defined, appropriate procedures. Several thresholds have been established in terms of PGV (Peak Ground Velocity) to regulate the exploitation of the geothermal plants in case of occurrence of seismicity (see also the workflow of a seismological alert used for the Rittershoffen and Soultz-sous-Forêts plants shown in Figure 2):

- The threshold of 0.5 mm/s expressed in PGV is defined as the threshold of vigilance from which the operator will continuously monitor the evolution of seismicity and make sure to adapt the operational parameters of the plant to bring it back below this threshold.
- The threshold of 1 mm/s expressed in PGV is defined as the increased vigilance threshold from which mining authorities request the operator to provide to the designated agency with all data from the 4 short-period stations present around the plant, in order to characterize precisely the event. This data will be provided within 24 hours after the occurrence of the event and will cover the 7 days prior to the event. At the same time the operator will take the necessary measures to return below the previous threshold, i.e. the threshold of vigilance.
- The threshold of 1.5 mm/s expressed in PGV is defined as the threshold of progressive and obligatory stop of the installations. From this threshold, the mining authorities will ask the operator to provide to the designated agency with all the data of the 4 short-period stations present around the plant, in order to characterize the event. This data will be provided within 24 hours after the occurrence of the event and will cover the 7 days prior to the event. At the same time the operator will trigger the progressive shutdown of the facilities.

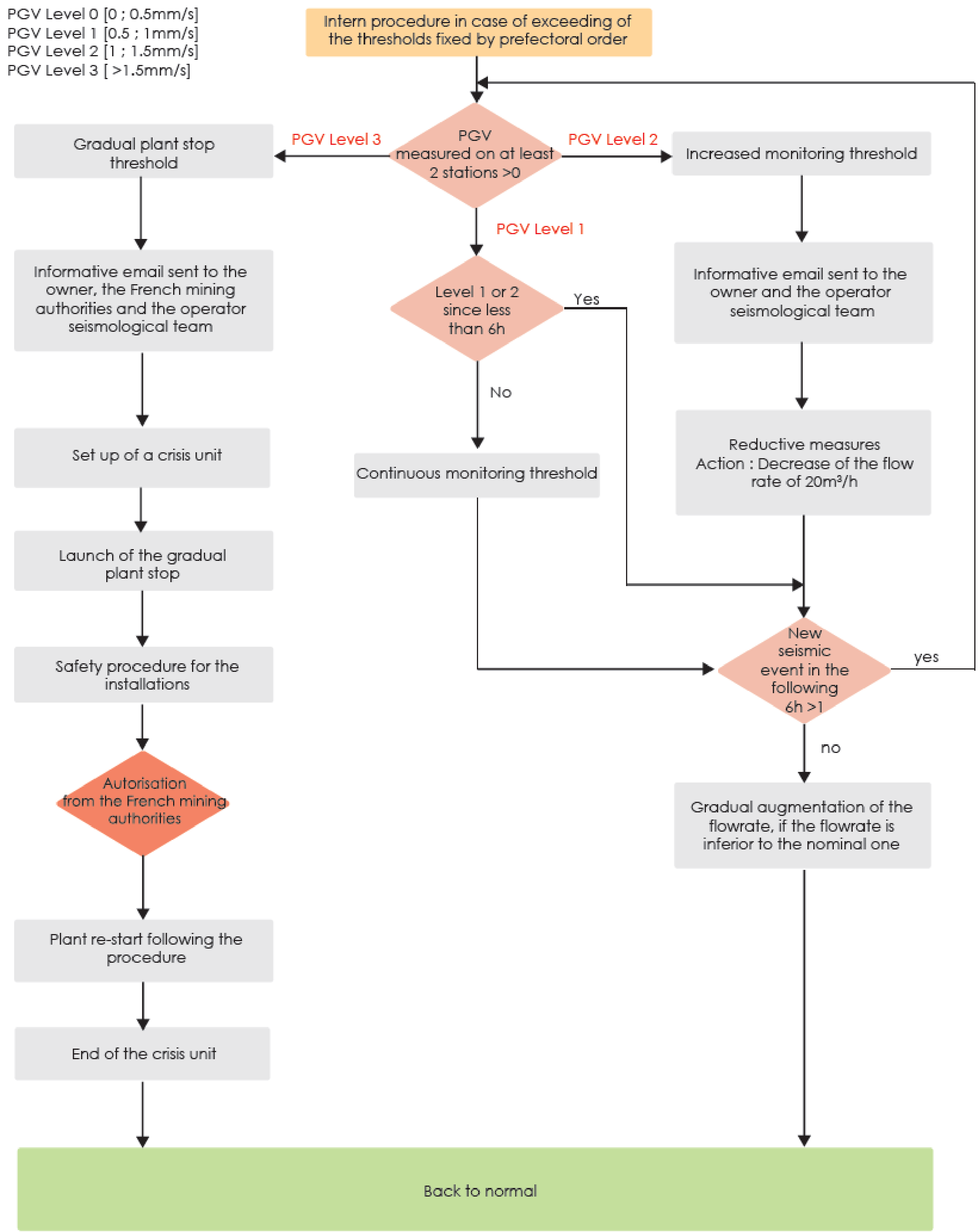

Figure 2: Decisional chart designed by operators in case of occurrence of induced micro-seismic activity, based on French mining authority regulation

Any exceedance of threshold should be immediately reported to the mining authorities and the restart of activities can take place only after approval of the mining authorities, based on the analysis of the event by the agency.

3. RESULTS

3.1 Seismicity associated with exploitation of Soultz-sous-Forêts and Rittershoffen since the commissioning of the plants

Since 2002 for Soultz-sous-Forêts plant and since 2012 for Rittershoffen geothermal plants, the micro-seismicity activity has been monitored by permanent seismic networks (see Figure 3) and by temporary surface networks installed during strategic operations (drilling, reservoir development, commissioning of plant).

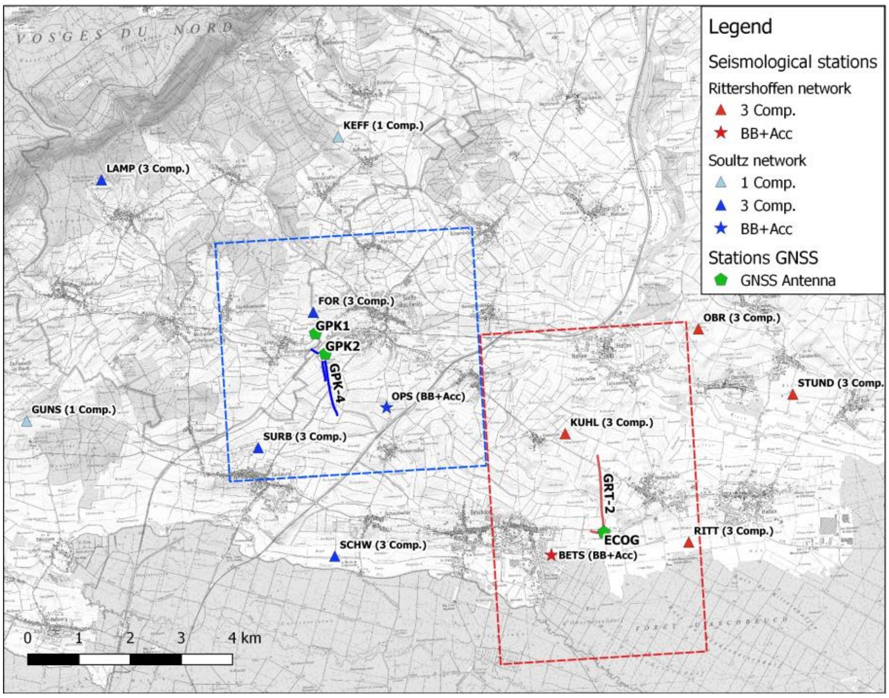

Figure 3: Seismic networks of Soultz-sous-Forêts (in blue) and of Rittershoffen (in red) and geodetic network (in green). Trajectories of wells are also displayed. Dashed rectangle shows Soultz-sous-Forêts (in blue) and Rittershoffen (in red) exploitation licence (concession).

Since 2016, the geothermal plants of Soultz-sous-Forêts and Rittershoffen have been almost continuously operating, with an availability higher than 90%. The micro-seismic activity has been carefully monitored in real–time since the beginning of the production. Since then, a couple of thousands of induced low magnitude earthquakes were detected (Mlmax = 1.7), all located in the vicinity of the injection wells, GRT-1 for Rittershoffen and GPK-4 for Soultz-sous-Forêts.

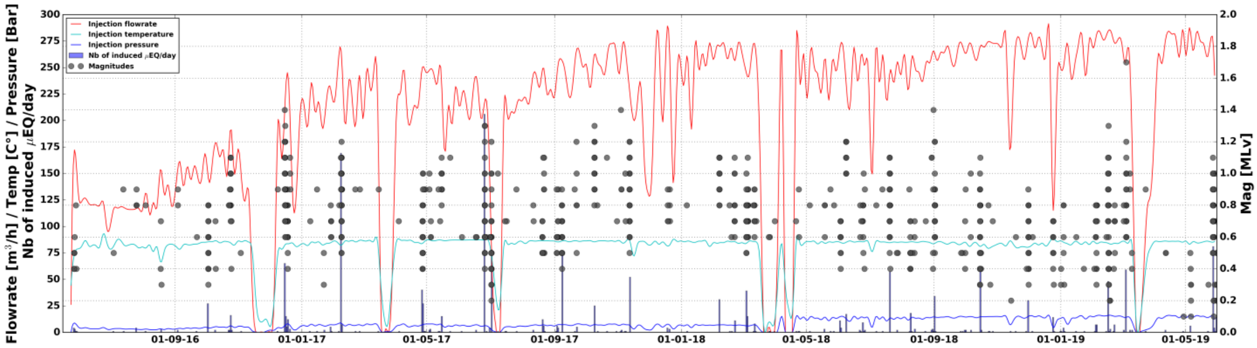

Figure 4: Induced seismicity associated with the hydraulic injection parameters since the commissioning of the Rittershoffen plant

For the Rittershoffen plant (see Figure 4), since the commissioning of the plant, a total of 1680 micro-seismic events have been automatically detected and located in the direct vicinity of the project by the local seismic network. All events have been then manually relocated. Most events are located within a radius of 1 km around the open-hole section of the injection well GRT-1 (see Figure 5). The maximum recorded local magnitude Mlv was 1.7 for an event occurred on the 04th of March 2018. The maximum PGV was 0,506 mm/s associated to that event. No induced seismic event has been felt by the local population around the Rittershoffen plant since operation started. The lowest PGV threshold value (0.5 mm/s) was only reached once, but only on one single station. In terms of focal mechanisms, when it can be measured, it always shows strike-slip faulting. The generated microseismic activity during exploitation is shown in Figure 5.

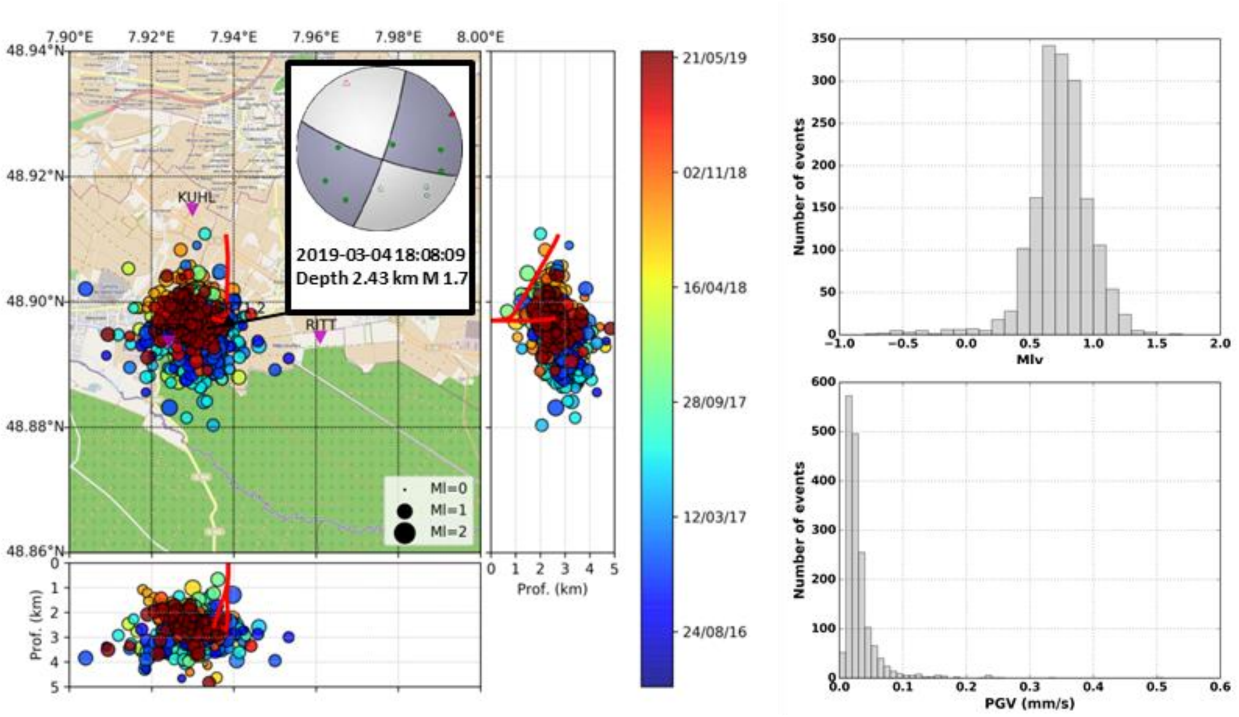

Figure 5: Induced seismicity during geothermal exploitation located around GRT-1 since the commissioning of the Rittershoffen plant

In Soultz-sous-Forêts, induced seismicity has been observed since injection started in GPK4 (see Figure 6). A total of 156 events could be located in the vicinity of the project since the commissioning of the plant in July 2016. The maximum local magnitude Mlv was 1.7. The maximum PGV was 0.173 mm/s associated to that event. The lowest PGV threshold value (0.5 mm/s) was never reached and no induced seismic event has been felt by the local population around Soultz-sous-Forêts since operation started in 2016. In terms of focal mechanisms, it showed either strike-slip or normal faulting. The generated micro-seismic activity during exploitation is shown in Figure 7.

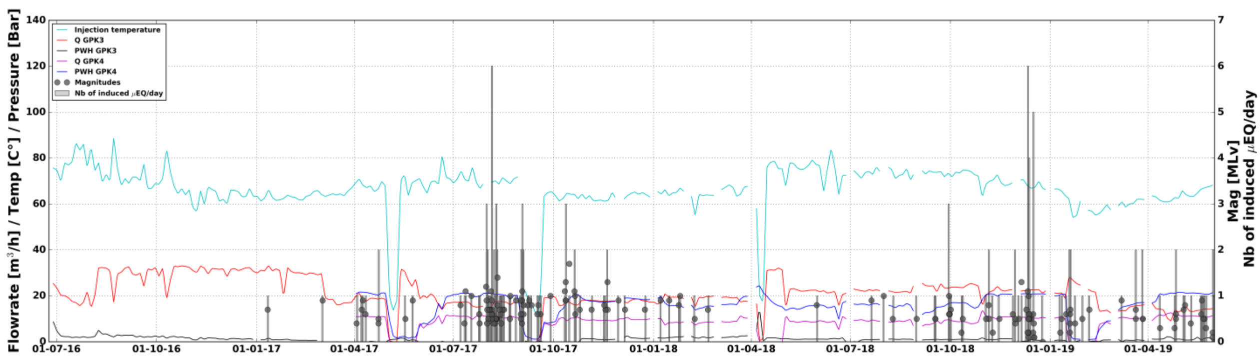

Figure 6: Induced seismicity associated with the hydraulic injection parameters since the commissioning of the Soultz-sous-Forêts plant

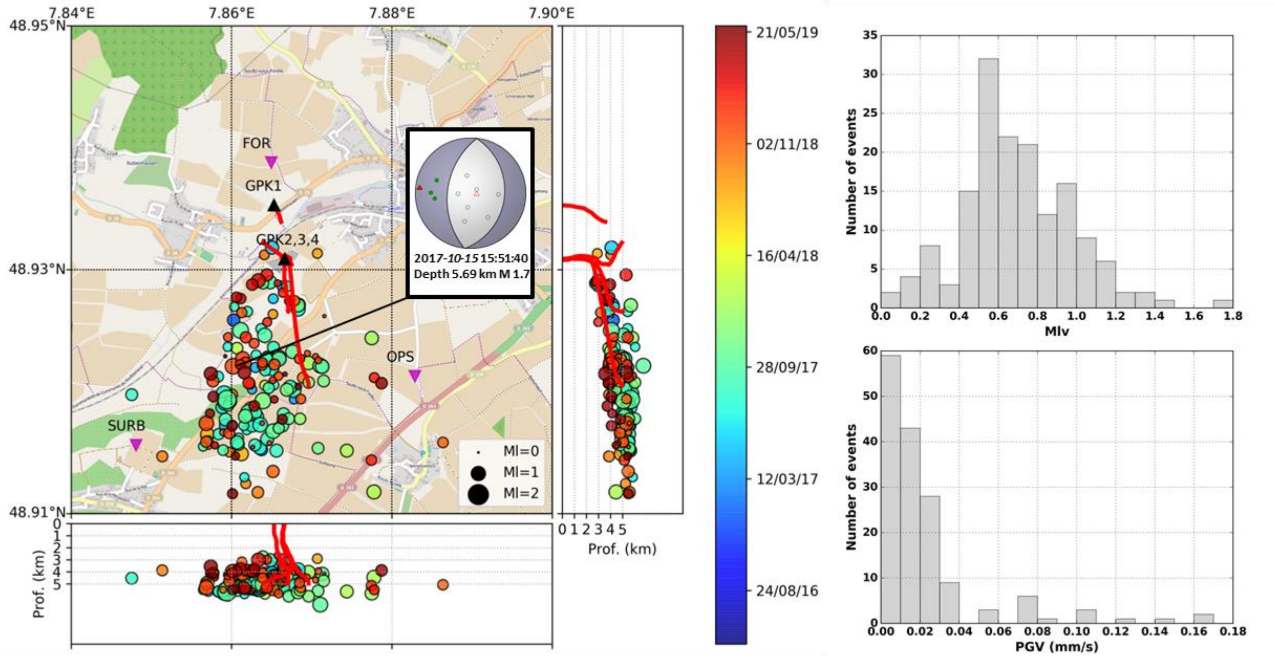

Figure 7: Induced seismicity during geothermal exploitation located around GPK-4 since since the commissioning of the Soultz-sous-Forêts plant

However, even if the induced seismicity observed in Rittershoffen and in Soultz-sous-Forêts was not felt by population, it highlights the need to perform a continuous seismic monitoring, even during the exploitation phase of geothermal plants, which is now explicitly required by the French mining authorities for getting the exploitation license (concession).

4.2 Geodetic evolution

In agreement to the specification of the mining authorities, a geodetic station was installed on each platform in Soultz-sous-Forêts and Rittershoffen. A geodetic station was installed on the GPK-1 platform in Jul. 2013, and in Apr. 2014 on GPK-2, -3, -4 platform (Soultz-sous-Forêts) and on GRT-1, -2 platform (Rittershoffen). Data were processed according to the GNSS PPP method (Precise Point Positioning). Precise Point Positioning (Zumberge et al., 1997) was demonstrated to be a valuable technique for single station positioning over a continental and even global scale (Kouba, 2005). The positioning accuracy in static PPP based on the final products from the GNSS stations can reach a few millimeters horizontally and vertically with daily observations and a few centimeters horizontally and vertically with hourly observations (Geng et al., 2009).

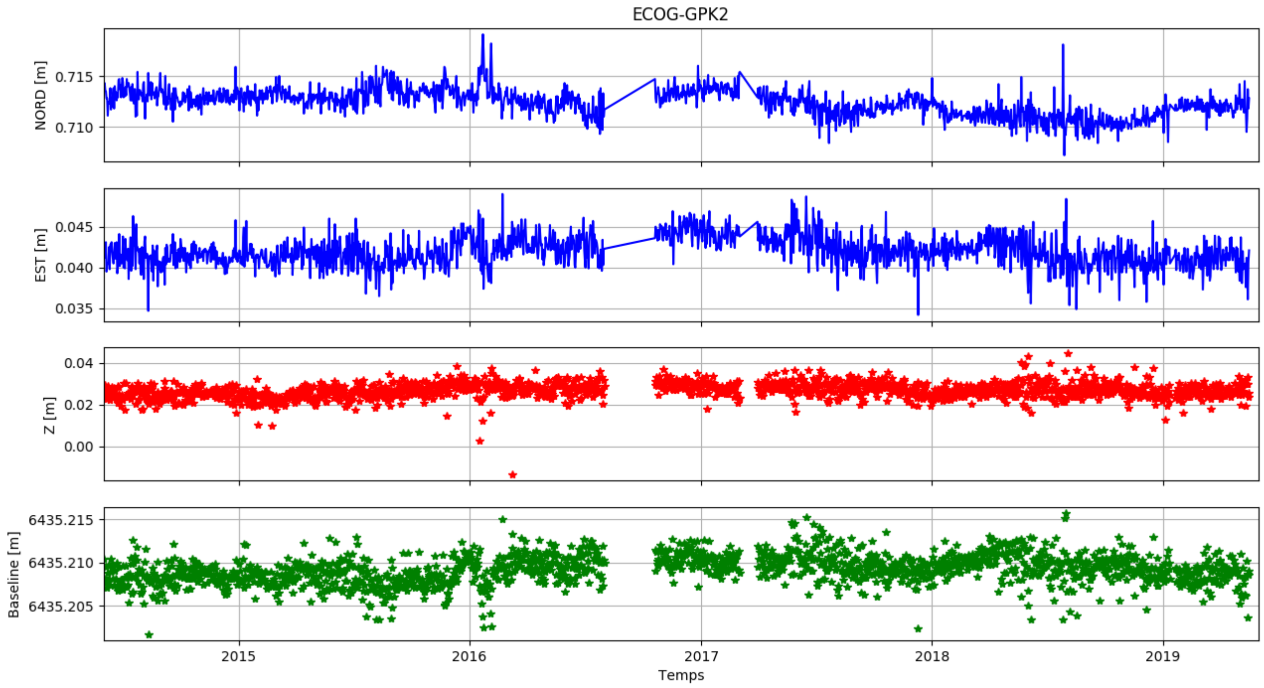

Figure 8: Position of the ECOGI antenna (Rittershoffen plant) relative to the GPK-2 antenna (Soultz-sous-Forêts plant). Results are shown horizontally (blue lines), vertically (red dots) and in baseline (green dots).

The results of the PPP processing (see Figure 8) show that the differences observed between the position of the GPK-2 antenna (Soultz-sous-Forêts plant) and the ECOG antenna (Rittershoffen) is oscillating between ±2.5 cm in the Northern and Eastern direction and ±1.0 cm in the vertical direction. The baseline, which represents the distance in 3D between both antennas, oscillates between ±0.5 cm on a mean distance of 6 435.210 m between the two antennas. The period of time before the commissioning of the two plants is taken as a reference, since no long term circulations have been performed in neither Soultz-sous-Forêts nor Rittershoffen plants before. At that time, both facilities were under construction. The evolution of the baseline between the two antennas does not show any significant variation in the years following the commissioning. Moreover, no clear tendency can be drawn, indicating that no significant vertical and horizontal ground motions can be observed at the surface of each plant (see **Error! Reference source not found.**).

Tableau 1: Evolution of the baseline compared to a reference year (2015)

ECOG-GPK2	North [m]	East [m]	Up [m]	Baseline [m]
Before commissioning	0.713	0.042	0.026	6435.209
2016	0.713	0.043	0.029	6435.210
2017	0.712	0.043	0.028	6435.210
2018	0.711	0.042	0.027	6435.210
2019	0.712	0.041	0.026	6435.209

3.3 Densification of Illkirch seismic network

According to the mining authorities' requirements, the Illkirch geothermal project is monitored by a seismic network. Since 2015-2016, a permanent seismic network composed of four short-period stations and one broad-band station has been installed to monitor the natural seismicity before the start of drilling operations (see Figure 9). The drilling of the first well GIL-1 started in Aug. 2018, and no natural seismicity was detected neither in the close vicinity of the project nor in the targeted fault before the operation. As drilling and reservoir development are strategic operations, in order to closely monitor the seismicity that may occur, the seismic network was densified with 10 broad-band stations installed in a radius of 2-3 km around the drilling platform. So far, no induced seismicity was detected during the drilling of the first well GIL-1 in Illkirch-Graffenstaden.

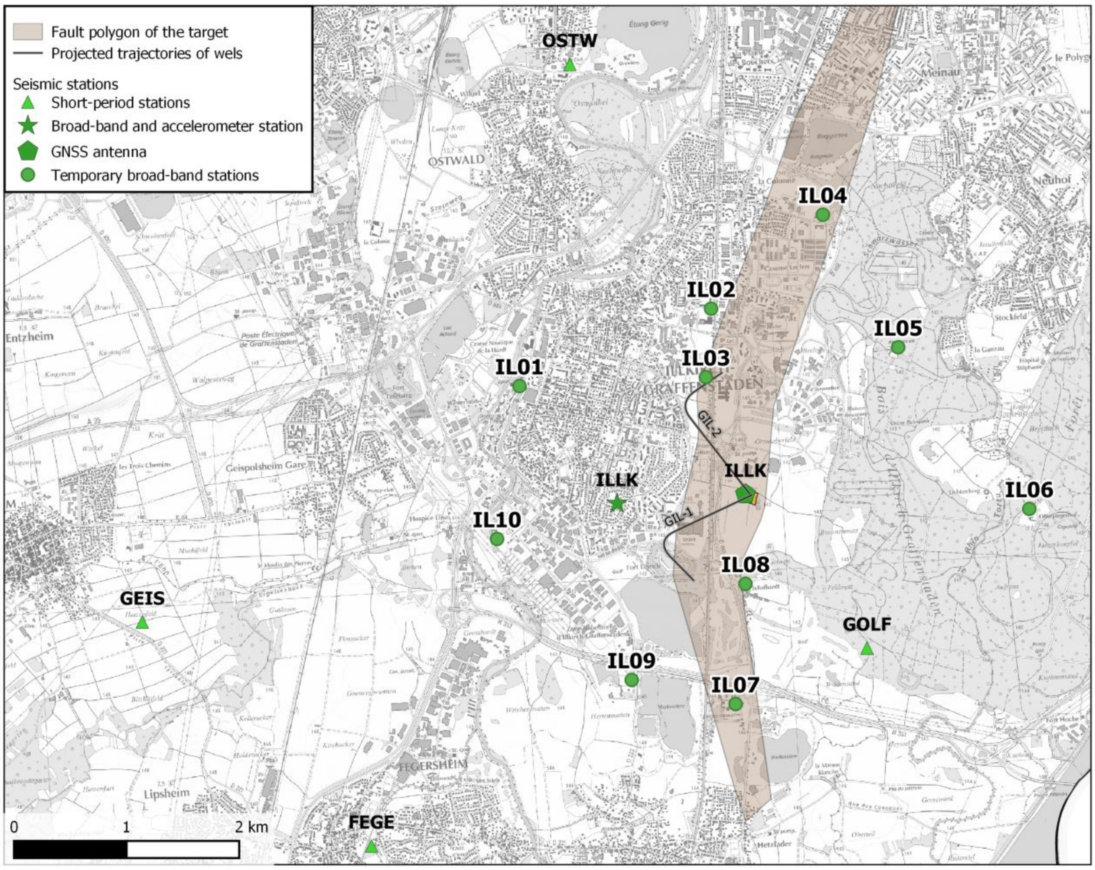

Figure 9: Seismic and geodetic network of the Illkirch geothermal project

4. PERSPECTIVES

4.1 Natural seismicity monitoring in Northern Alsace

Since the installation of the permanent network of Rittershoffen, the magnitude of completeness has been significantly lowered in Northern Alsace allowing to record and detect natural seismicity. If the network is firstly dedicated and designed to detect induced micro-seismicity, natural seismicity is also detected and located all around the drilling platforms.

The URG is one of the largest rift valleys in France. Further inside, the graben is composed of well-individualized structural subsystems. They reflect a growing penetration of the ante-Mesozoic bedrock. Thus, the earthquakes detected in this region reflect the accommodation of the opening of the graben, but with a certain delay compared to faults bordering. In total, more than 100 local natural earthquakes have been detected by permanent or temporary networks dedicated to the monitoring of geothermal activities (see Figure 10). Some clusters of events have been observed. One of them has been observed eastwards from the Rittershoffen plant during a burst of seismicity at about 8 km depth in December 2018. One event reached a local magnitude 1.8 associated with a N20° normal-fault mechanism. Another cluster of seismicity was observed southwards of the Soultz-sous-Forêts plant. This crisis was a bit shallower at about 6 km depth, but the focal mechanism revealed more a strike-slip behavior in this area. These seismic clusters reveal interesting information on the active structure where geothermal fluids are potentially present.

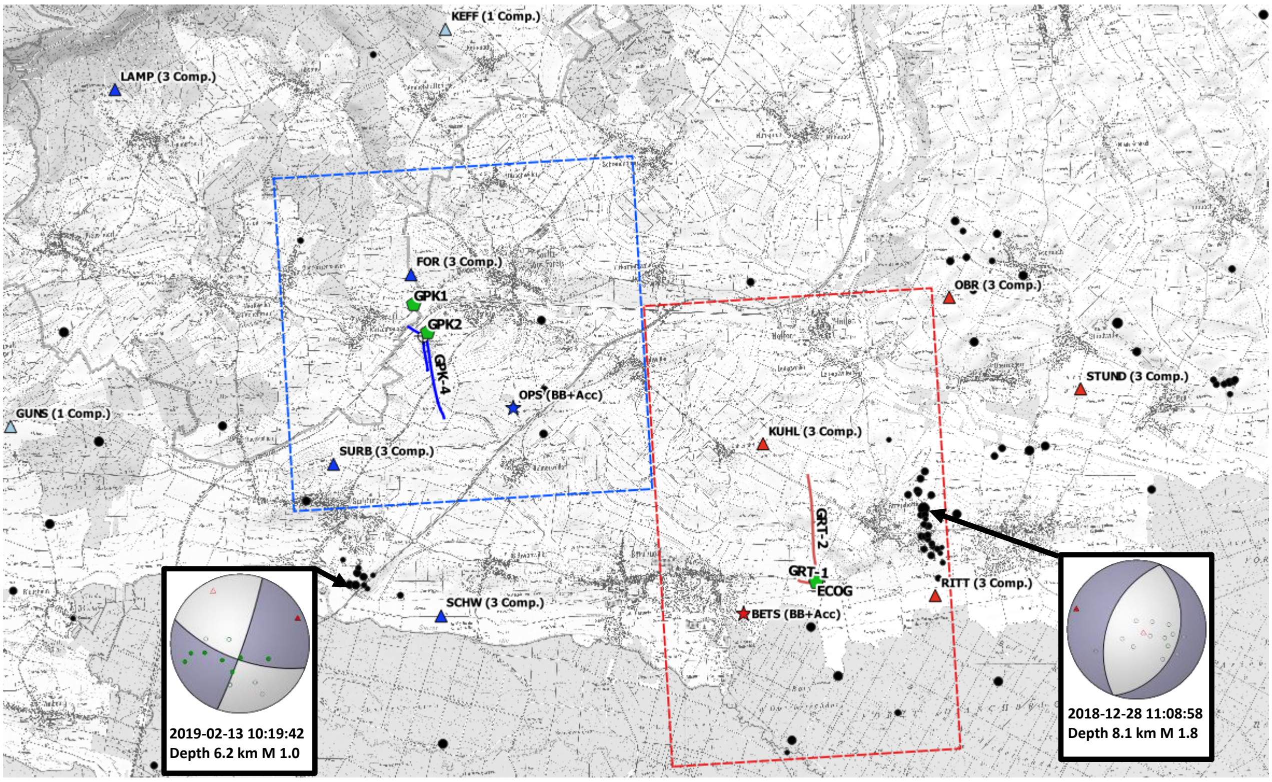

Figure 10: Natural seismicity recorded around the geothermal projects giving some interesting information about the sismo-tectonic activity of the structural subsystems located inside the URG.

4.2 GPK-4 stimulation (DESTRESS)

As part of the Horizon 2020 Destress project, it is planned to carry out in 2019 a soft chemical stimulation of the Soultz-sous-Forêts geothermal well, GPK-4. Destress is a demonstration project (TRL> 7) that aims to make soft stimulation in real conditions while minimizing risks. The GPK-4 well is currently used as an injection well for the Soultz-sous-Forêts geothermal power plant. Its length is 5.2 km MD and is strongly deflected (> 30 °). The open-hole section was drilled in the granitic bedrock. The operation must be innovative by means of gentle stimulation of geothermal wells with products that respect the environment. The proof of the effectiveness of these methods under real conditions in boreholes at 5 km depth will make it possible to de-risk future geothermal drilling in similar conditions. This is a TRL (Technology Readiness Level) greater than 7, and therefore a demonstration project. It is expected that the seismological network will be densified to monitor the environmental impact of these operations.

4.3 FO installation + densification while cold injection (MEET)

One of the objectives of the Horizon H2020 MEET project is to deal with the upscaling of thermal power production for optimized operation of EGS plants in granite in close relation with geothermal site activities. By using an operational plant producing hot fluid from a granitic reservoir, standard flow masses ranging from 30 to 70 kg/s will be reinjected at 40°C. That could thermally represent between 3.5MWth and 8.0MWth of additional produced thermal power for a geothermal site like Soultz and Rittershoffen respectively. This thermal approach for upscaling heat use is new because nobody uses the geothermal heat at low temperature properly in such type of geological conditions. Electricity will be produced as well from small ORC units that could represent between 20 and 40 kWe of additional power for those flow masses. Many possible heat applications could be envisaged such as greenhouses, industrial process for drying cereals, district heating. In parallel to the on-site energy generation, the environmental impact on the fractured granitic reservoir of lower temperature reinjection will be investigated as well as its sustainability from laboratory, analogue studies, on-site fluid reinjection, induced seismicity activity monitoring and advanced hydrothermic modelling. In this framework, a fiber optic survey is planned in the well EPS-1 located at Soultz for monitoring temperature and deformation and evaluating the thermo-mechanical impacts on the reservoir of the reinjection at lower temperature. A temporary network of seismological stations will be deployed during the reinjection test at high flow rate for monitoring the thermo-mechanical response of the reservoir.

CONCLUSION

In the Upper Rhine Graben (URG), several deep geothermal projects (Soultz-sous-Forêts, Rittershoffen, Landau and Insheim), are currently in exploitation of local geothermal reservoirs trapped in the fracture network in Triassic sediments and the underlying granitic basement. These projects are based on the Enhanced Geothermal System (EGS) technology even if some wells, like the second well of the Rittershoffen project GRT-2 showed economically viable production flowrates right after the drilling and no reservoir development was required. The monitoring of the geothermal plants currently in exploitation in the French side of the URG showed that induced seismicity occurred in both Rittershoffen and in Soultz-sous-Forêts. It highlights the need to perform a continuous seismic monitoring, even during the exploitation phase of geothermal power plants, which is now explicitly required by the French mining authorities for getting the exploitation license. As well as seismic monitoring, a geodetic monitoring is also required by the authorities in order to cover all the frequency ranges, from milliseconds to days, in terms of ground motions. New technologies, like fiber optics are being tested to complete the actual way of monitoring projects. A densification of the seismic network with temporary networks installed during strategic operations of a normal life-cycle of a geothermal project (drilling, reservoir development, commissioning of plant) or during research and development actions done to upscale the power of a geothermal plant (injection at colder temperature) allows to have better idea of the reservoir behavior. Such networks are also able to detect natural seismicity and give some precious information on the current seismo-tectonic activity in the URG, and may be a criterion to select some zones of interest to set up some future geothermal projects.

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