Experience Learnt from a Successful Soft Stimulation and Operational Feedback after 2 Years of Geothermal Power and Heat Production in Rittershoffen and Soultz-sous-Forêts Plants (Alsace, France)

Clément Baujard[1], Albert Genter[1], Nicolas Cuenot[1], Justine Mouchot[1], Vincent Maurer[1], Regis Hehn[1], Guillaume Ravier[1], Olivier Seibel[1], Jeanne Vidal[1]

[1] ES-Géothermie, Bat Le Belem, 5 rue de Lisbonne, 67300 Schiltigheim, France

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ABSTRACT

The deep geothermal industrial sites of Rittershoffen and Soultz-sous-Forêts are located within the French side of the Upper Rhine Graben. A brief overview of the sites is proposed, with a focus on well treatments, especially on the successful stimulation in the injection well of Rittershoffen , as a lot of data is available. The stimulation efficiency of every reservoir development phase could be precisely quantified. Combined seismic and hydraulic data analysis lead to a better understanding of the reservoir development processes. In the end, an extensive feedback after more than 2 years operations of both sites is proposed, as a detailed monitoring (including chemical, seismological and production/injection parameters) is carried out in Soultz and also in Rittershoffen.

1. Site Overview

1.1 The Upper Rhine Graben

Geothermal energy for electricity production or heat generation from deep crystalline basement rocks has been under development from decades in Western Europe, mainly in the Upper Rhine Graben (Vidal et Genter, 2018). URG is part of the European Cenozoic rift system that extends from the Mediterranean to the North Sea coast (Ziegler, 1992). The URG started to form during

Late Eocene in response to NNE trending Alpine compression. The URG's deep thermal structure, which is likely to be related to mantle uplift, was investigated by deep seismic surveys (Brun and Wenzel, 1991). Relief of the rift borders is still important and the Moho topography shows an important rise up to 24 km depth in the southern URG (Dezes et al., 2004; Edel et al., 2007). The shallow heat flow in the graben ranges between 100–120 mW/m^2 (Pribnow and Schellschmidt, 2000). Extensive borehole data show that the temperature within the graben at depths of 1 km is highly variable, the thermal anomaly at Soultz and Rittershoffen (France) or in Landau (Germany) being particularly high.

Generally old oil well data as well as vintage 2D seismic profiles were available for starting to explore the deep-seated geology of hidden basement lying underneath the basin. After an intense phase of scientific researches characterised by a strong evolution of the geothermal concept, it turns out that several industrial projects are now emerging in this area, due to the occurrence of natural geothermal fluid circulations of brines through a multi-scale permeable fracture system. The Soultz-sous-Forêts and Rittershoffen geothermal plants operating plants are striking examples that producing energy from deep crystalline basement is a reality in this geological area. Other geothermal projects are already operating in the German side of the URG and new projects are under development in the Strasbourg area with recent drilling operations (Reichstett, Illkirch) targeting a geothermal faulted resource located at the interface between the sediments and the basement.

1.2 Soultz-sous-Forêts

The Soultz-sous-Forêts geothermal power plant has been under geothermal exploitation from June 2016. The binary plant on surface was fully renovated in 2015-2016. The geothermal loop is composed of one production well GPK-2 and two reinjection wells GPK-3 and GPK-4. All three wells are 5km deep and are cased to roughly 4.5 km in the granitic section. Below that depth, the reservoir is made of crystalline basement and underwent various kinds of hydraulic and chemical stimulations in the past and several periods of long-term circulations (Cuenot et Genter, 2015; Schill et al., 2017). However, GPK-4 still shows a poor injectivity index. Temperature at reinjection is typically around 60-70°C. Due to its low hydraulic performance, the reinjection well GPK-4 has been chosen to be chemically stimulated for enhancing its injectivity index, in the frame of the European project DESTRESS. Induced seismicity monitoring of the site is permanently performed through a network of seismological stations installed on surface.

1.3 Rittershoffen

In Rittershoffen, two deep wells were drilled in 2012 and 2014 respectively. Both wells target a normal fault zone in the crystalline basement (Baujard et al., 2017). Due to a low natural injectivity index, the first well was thermally, chemically and hydraulically stimulated. In this injection well, post-stimulation injectivity was improved by a factor 5 resulting in an operation flowrate higher than 70L/s. Moreover, this soft stimulation program was carried out with low environment impact, as no induced seismicity was felt during hydraulic stimulation, and environmentally friendly acids were designed and used to dissolve secondary sulfates and carbonates clog existing fractures. The second well showed a very high productivity from the first hydraulic tests. A 24MW heat plant and a transport loop, delivering process heat at high temperature for a bio-refinery located in the vicinity of the plant, were built in 2015 and began operating in 2016.

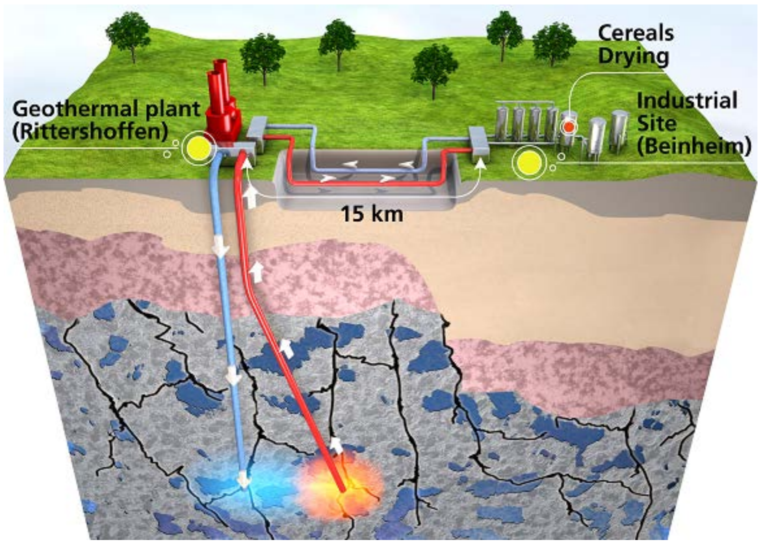

Figure 1: Sketch of the Rittershoffen geothermal project

The geothermal brine with a surface temperature of 168°C is very similar to that at Soultz: a Na-Cl-Ca dominated brine, with a salinity of 100 g/L and a gas-liquid-ratio of 1:1 (Sanjuan et al, 2010). Even if the production well GRT-2 is artesian, this brine is pumped by a downhole Line Shaft Pump installed, consuming about 420 kW at 75 L/s. Since it is not technically feasible to transport brine to the factory due to its corrosivity, the heat is transferred to a transport loop containing fresh water, via twelve heat exchangers having only 4°C of pinch (Ravier, 2016).The temperature at the inlet of the bio-refinery is 159,5°C, meaning that thermal loses on the transport loop is only 4,5°C on 15 km (Ravier et al., 2017).

Due to a high injectivity index of the GRT-1, no injection pump is required to pump back the fluid into the reservoir. In contrast, it was necessary to install an injection column in early 2018 to create pressure drop to maintain a well head pressure higher than the degassing pressure.

After three month of commissioning, the Rittershoffen geothermal plant is commercially operational since September 2016. In 2016 and 2017, about 630 000 m^3 and 1 960 000 m^3 of brine was pumped in order to supply respectively 34.5 GWh and 142.8 GWh of heat the bio-refinery. This geothermal heat replaced a part of the bio-refinery's natural gas consumption and saved about 8 570 tons of CO_2 emissions in 2016 and 34 600 tons of CO_2 in 2017 (Pratiwi et al, 2018). In 2017, the thermal efficiency of the transport loop was about 92%. Total electrical consumption of the Rittershoffen geothermal plant and of the transport loop was about 4.8 GWh in 2017, giving a ratio between the geothermal heat energy supplied with the electrical energy consumption of nearly 30

2. Rittershoffen well GRT-1 Soft stimulation

2.1 Stimulation overview

GRT-1 well was stimulated in order to enhance the well injectivity. A thermal stimulation (low-rate cold water injections), a targeted chemical stimulation and a hydraulic stimulation were applied to the well. The results were very positive as the initial injectivity increased from a 0.5 L/s/bar to more than 2.5 L/s/bar. The stimulation process is detailed in Baujard et al., 2016. The injectivity evolution of the well is showed in Figure 2. On the contrary, GRT-2 appeared to be a very good producer from the first production tests after it was drilled in 2014.

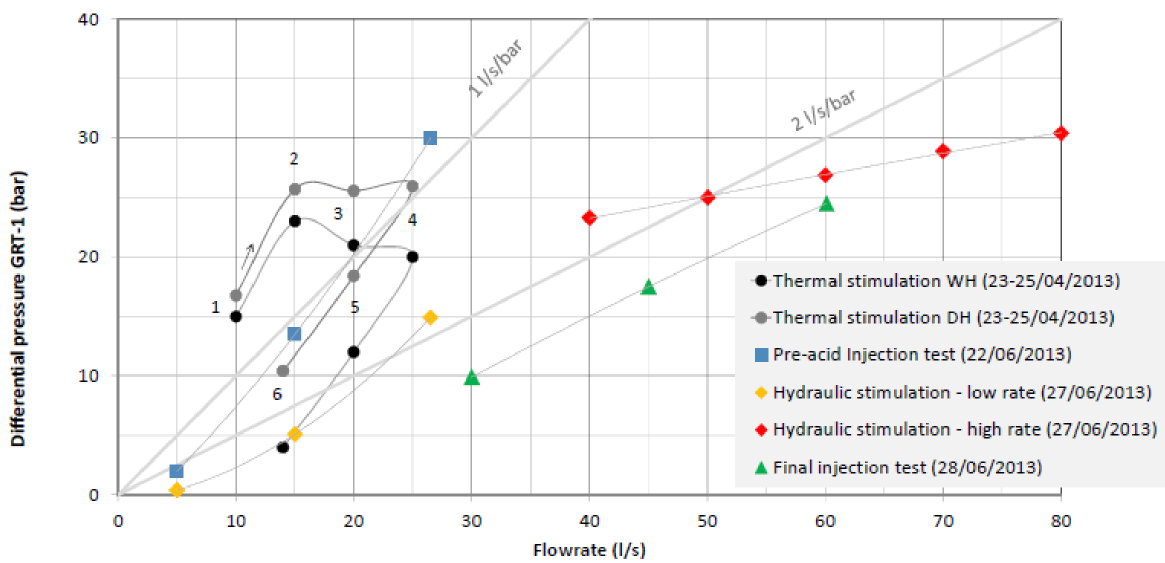

Figure 2: Injectivity evolution of GRT-1 during the different injections (from Baujatd et al., 2016).

2.2 Interpretation

An extensive work has been carried out in order to interpret and understand the efficiency of well GRT-1 stimulation. Vidal et al. (2016) quantified the impact of different stimulations on the different sections of well GRT-1 and concluded that the permeability increase in the Triassic sandstones of the Buntsandstein was essentially due to the chemical injections. The mechanical behavior of the regional fault zone and the associated generated micro-seismicity could be reproduced using a numerical model (ECLIPSE) by Sosio et al., 2018 (see Figure 3).

Further investigations have been realized in order to better understand the process involved in the increase of well injectivity (see Meyer et al., 2017) during hydraulic stimulation. The observation of the injection pressure showed that after reaching a certain injection flowrate, the injection pressure starts to decrease slowly as the time increase on each flowrate steps (Figure 4). The observation of the seismic activity during the same phase showed that the seismic activity starts at the same flowrate at which the pressure starts to decrease (Figure 4).

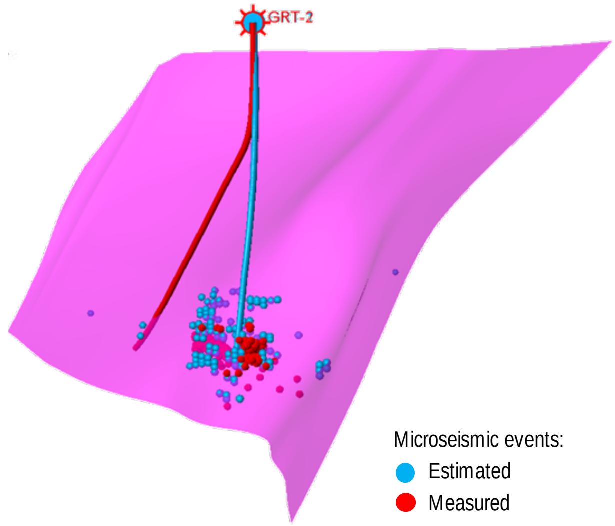

Figure 3: Geomechanical simulation results: simulated and measured microseismic events during the injector well stimulation. The main fault crossing the site is shown in the background (From Sosio et al., 2018).

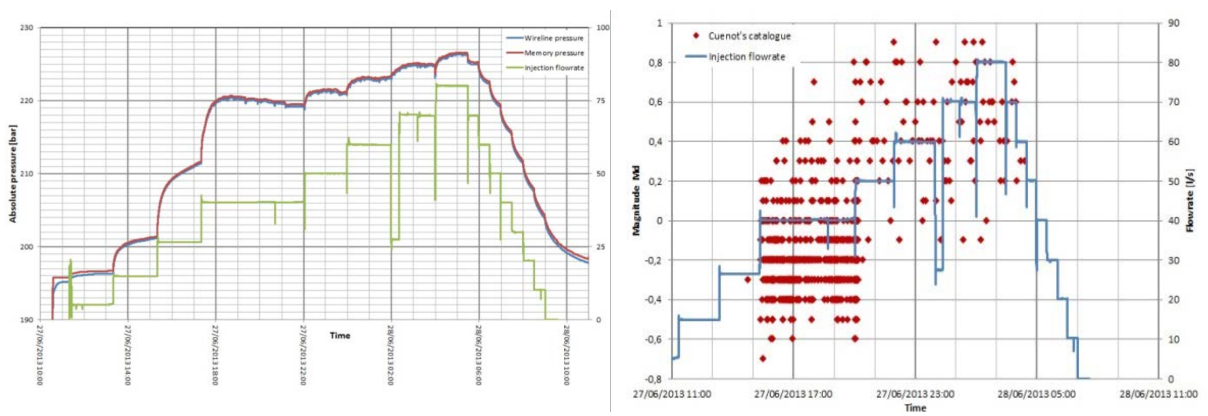

Figure 4: Left: Pressure data recorded by the wireline sensor (blue) and memory (red). As they are very similar, the catalogue with the smallest time step has been chosen (Baujard et al., 2017). Right: MP catalogue of induced seismicity during the hydraulic stimulation (Meyer et al., 2017).

Based on those two facts, the assumption that seismicity was linked to pressure decrease behavior has been made. A zoom in on the injection pressure showed that the slow decrease in injection pressure is actually the consequence of several small pressure drops and that pressure drops are correlated with cluster of induced seismicity (Figure 5).

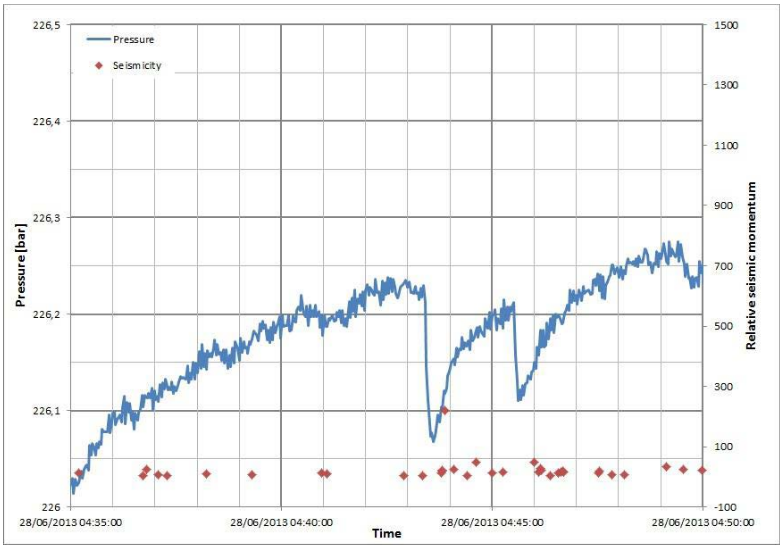

Figure 5: Two examples of pressure drops and their associated burst of seismicity at Rittershoffen (Meyer et al. 2017).

The models of the phenomenon made with the 2D finite elements simulator CFRAC showed the following results:

- the pressure drop could be a consequence of the opening of a wing-crack;
- the seismic burst may be created during the pressurization of another fracture, after it has been reached by the previously created wing-crack.

Nevertheless, the model assumptions were too restrictive to conclude on the real process behind those pressure drops and the associated micro-seismicity. Further study of the focal mechanism would be an interesting follow up of those researches to better characterize the type of seismicity related to the pressure drops and to increase in injectivity.

3. Operation monitoring

3.1 Soultz-sous-Forêts power plant

<u>Power plant operation</u>

A new ORC module was installed in Soultz-sous-Forêts in 2015 and 2016. Commercial operation of the power plant started by the end of June 2016. The production flowrate is 30L/s. From June 2016 to February 2017, the flowrate was reinjected in GPK3 only. Since March 2017, GPK4 was also used as a reinjection well. The plant was running in 2017 90% of the time over the whole year.

The long-term exploitation of the geothermal plant is plotted from June 2016 to February 2018 on Figure 6. During the first 8 months of exploitation, the geothermal fluid was reinjected only into the GPK-3 well, which showed a quite low wellhead overpressure (Figure 6). No induced seismic activity was observed during this period. Then, in order to test the global hydraulic response of the geothermal system, it was decided to share the reinjection between GPK-3 and GPK-4 wells. Then, about 2/3 of the produced fluid volume was reinjected in the GPK-3 well for 1/3 in the GPK-4 well (Figure 3). From March 2017, the wellhead overpressure of GPK-3 well has been very low but that of GPK-4 well has increased to an average value of 17 bar, highlighting the poor injectivity index of this well. The consequence was a more significant hydro-mechanical response of the granite reservoir with the emergence of a moderate induced seismic activity (Figure 3). It must be noticed that none of those events were felt. In 2017, the geothermal plant availability reached 90% of the time, including several weeks of planned maintenance stop. In the coming months, a chemical stimulation is planned in the GPK-4 well in the framework of the DESTRESS project. It is the reason why a series of well logging has been in January 2018 in order to check the integrity of this reinjection well. The planned chemical stimulation will be targeted for dissolving appropriate secondary minerals filling the natural fractures, such as carbonates or other minerals.

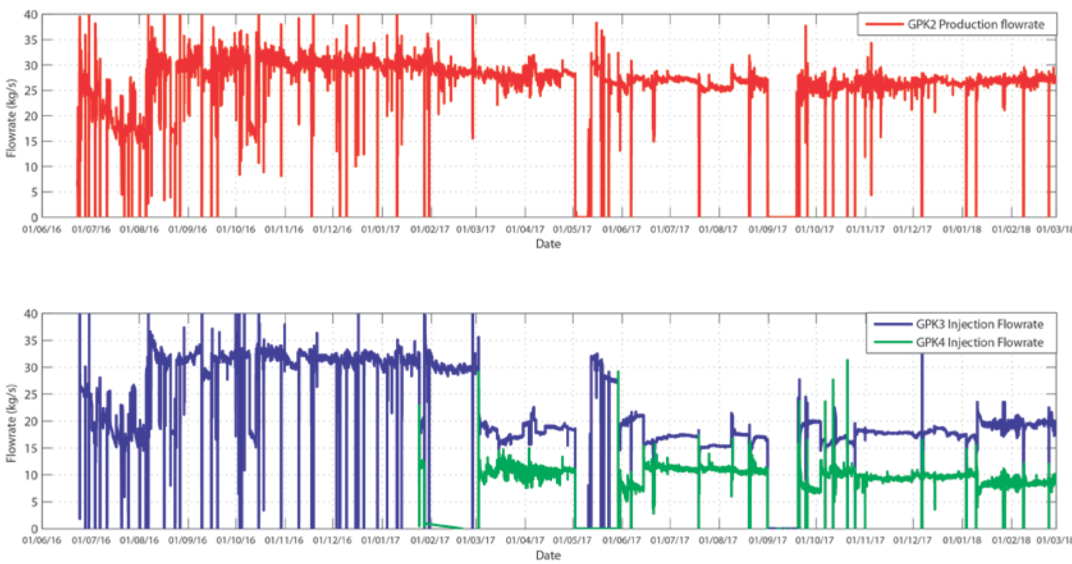

Figure 6: Production flowrate from GPK2 (red curve), injection flowrate in GPK3 (blue curve) and GPK4 (green curve) between June 2016 and September 2017.

Seismic monitoring

Induced seismicity has been observed since injection started in GPK4. A total of 70 events could be located in the vicinity of the project. The maximum local magnitude Mlv is 1.7. The maximum PGV is 0,17 mm/s. No induced seismic event was felt by the local population around Soultz-sous-Forêts since operation started in 2016. The generated microseismic activity is showed in Figure 7.

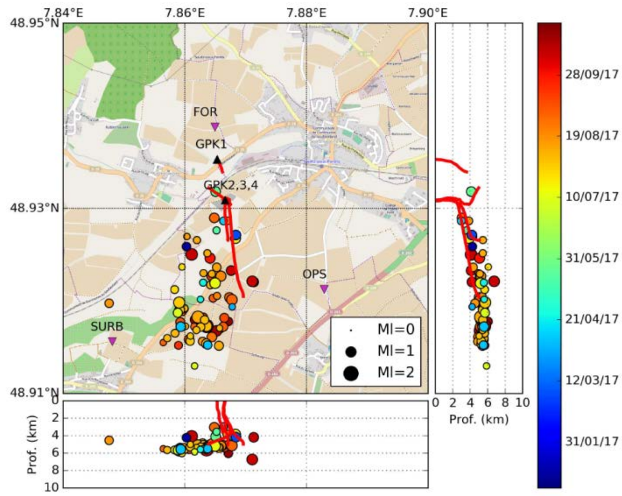

Figure 7: Induced seismicity located around GPK-4 in 2017.

Geochemical monitoring

The geothermal brine is produced from GPK2 well, at 150°C. This brine is a Na-Ca-Cl fluid, with a Total Dissolved Solids content of 100g/L, enriched in dissolved gases. The Gas Liquid Ratio of 1.03 Nm^3/m^3 in standard conditions (T= 273.15 K, P= 1.01325 hPa), containing 90% of CO_2. Within the aim to inject scaling inhibitors and apply a soft stimulation program into GPK4 well (DESTRESS Research program), a geochemical baseline acquisition and periodic monitoring are required to (i) detect any changes in terms of chemistry, (ii) assess the efficiency of these operations, and (iii) identify their consequences for the geothermal production loop. As key parameters, electrical conductivity, pH and chemical spectrum are then periodically monitored. Electrical conductivity and pH are measured by sensors directly on-field (Figure 8). Elementary chemistry is assessed by Inductive Coupled Plasma Spectrometry (ICP-MS), with the help of dedicated laboratory (SUBITO project).

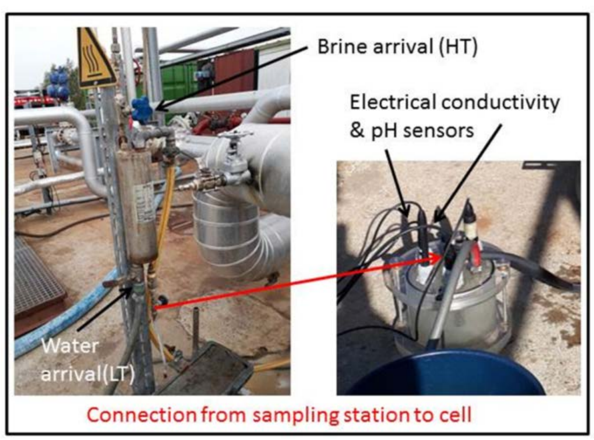

Figure 8: Sampling cell and sensors

Different analyses of elementary chemistry of the geothermal brine have been gathered in Figure 9 from Scheiber et al. (2012), Scheiber et al. (2013), Scheiber et al. (2014) and reports from SUBITO project.

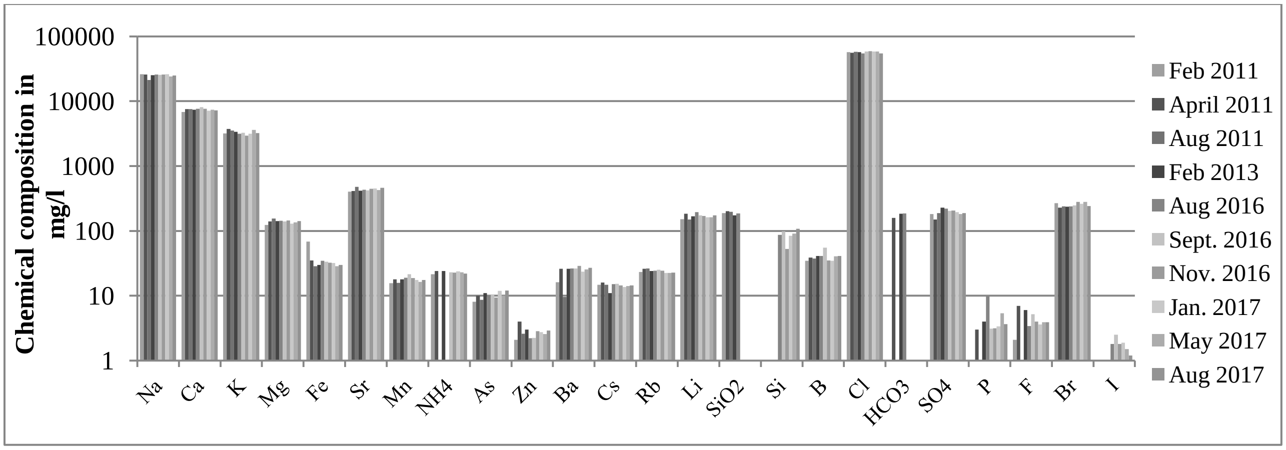

Figure 9: Elementary chemistry from geothermal brine - GPK2 (Mouchot et al., 2018)

Chemical element contents are quite stable with time, and especially under this first year of full exploitation started in summer 2016. The main elements, Na Ca Cl appear very stable. The behavior of minor elements, Fe, Zn, Ba, SO_4, Mn, P, and F is more variable, without any clear trend of increase or decrease. New set of chemical and gas analyses are planned within the following weeks giving the geothermal fluid characteristics after two years of industrial operation. Electrical conductivity and pH, parameters measured on-site are quite constant, sensitive to temperature variation. In average, at a geothermal fluid temperature of 60°C, pH is about 5.3 and electrical conductivity is more stable, about 120 mS/cm.

3.2 Rittershoffen heat plant

Heat plant operation

Rittershoffen heat plant started running in June 2016. During first 6 months of operation, the flowrate was progressively increased until December 2016. Since January 2017, the power plant has been run in commercial operation. The production flowrate is controlled by the client “Roquette” biorefinery located in Beinheim. Therefore, the production flowrate strictly follows the heat need of the biorefinery. Production temperature at the wellhead is approximately 168°C, but may change according to the production flowrate. The plant was running in 2017 93% of the time over the whole year.

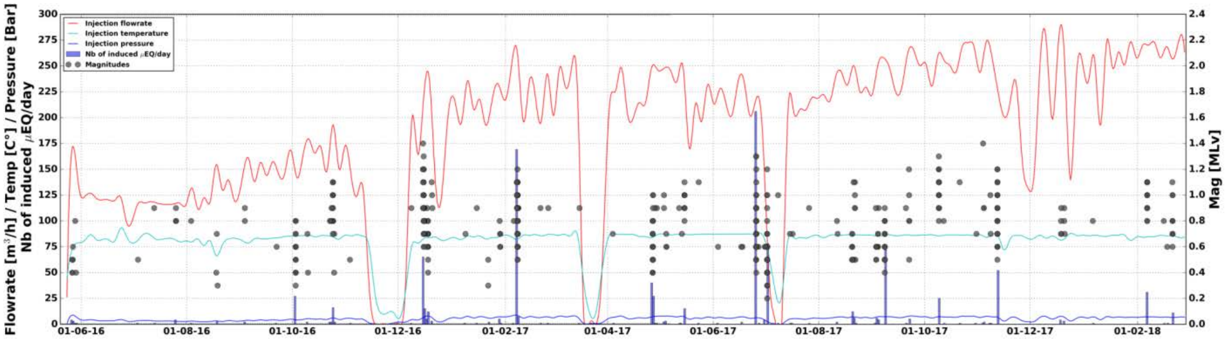

Figure 10: Moving average of injection flowrate values (red curve), injection temperature (light blue curve), injection pressure (dark blue curve) and associated microseismic events local magnitudes (points, right scale) in Ritterhsoffen heat plant between June 2016 and March 2018.

Seismic monitoring

During 2017, a total of 734 seismic events were detected in the direct vicinity of the project by the local seismic network. Most events are located within a 600m radius around the open section of the injection well GRT-1. The maximum local magnitude Mlv is 1.3. The maximum PGV is 0,24 mm/s. No induced seismic event was felt by the local population around Rittershoffen since operation started. The PGV threshold values (1.5 mm/s) was never reached. The generated microseismic activity is showed in Figure 11.

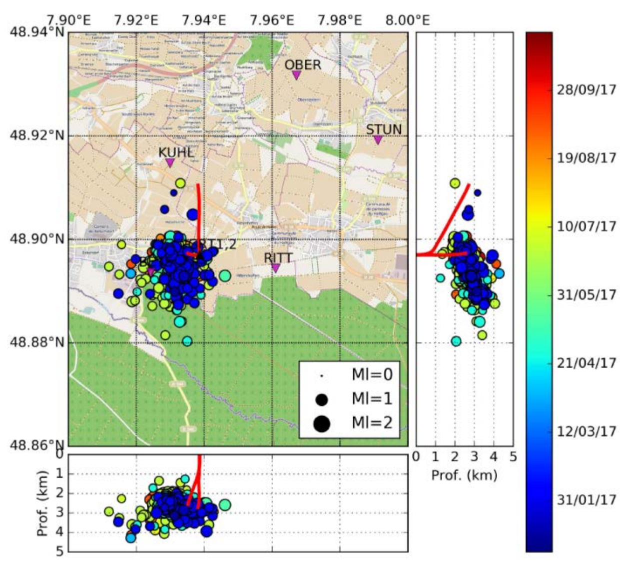

Figure 11: Induced seismicity located around GRT-1 in 2017.

4. Discussion and conclusion

Both Soultz-sous-Forêts power plant and Rittershoffen heat plant have been operated since spring 2016. Availability of both plants is higher than 90% during the first year of operation. Interestingly, injectivity of GRT-1 continued increasing after the stimulation and is today estimated to be higher than 5 L/s/bar. This phenomenon required the installation of an injection liner in GRT-1 in order to add pressure losses in the well to keep the injection pressure above the CO2 degasing pressure, estimated to be between 15 and 20 bar. This injectivity increase could be linked to fracture aperture increase because of the thermal cooling of the rock mass because of the forced circulation.

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