On-going seismic monitoring of the Rittershoffen EGS project (Alsace, France)

Vincent Maurer[1], Marc Grunberg[2], Alexandre Richard[1], Cécile Doubre[2], Clément Baujard[1], Maximilien Lehujeur[2]

[1] ES-Géothermie, 3a chemin du gaz, F-67500 Haguenau, France

[2] EOST, 5, rue René Descartes, F-67084 Strasbourg cedex, France

vincent.maurer@es.fr

Keywords: seismic monitoring, induced seismicity, natural seismicity, enhanced geothermal system, Alsace.

ABSTRACT

The ECOGI joint venture (ES group, Roquette Frères and Caisse des Dépôts et de Consignation) is in charge of the development and the exploitation of the Rittershoffen enhanced geothermal system (EGS), located in Northern Alsace, in France. A seismic network has been deployed in order to monitor natural seismicity and to detect any rise of induced micro-seismic activity potentially triggered by geothermal operations. 1D velocity models were built both for P-velocity and for S-velocity from well logging measurements accordingly to the geology recognized in the wells. From the drilling phase of the first well to the end of the circulation test, after the drilling of the second well, more than 500 induced micro-earthquakes were automatically detected by the real-time automatic system set up to monitor the project. No induced event was felt by the local population. The deployed networks also allowed detecting natural seismicity not necessarily detected by the national seismic monitoring network. About 600 local and regional earthquakes were detected since the installation of the Rittershoffen permanent network in 2012. Among them, 50 natural earthquakes have been detected in a range of 30 km around the drilling platform. These earthquakes are related to the tectonic activity of the Rhine graben.

1. INTRODUCTION

Designed to produce 24 MWth (170 °C, 70 l/s) with a doublet, the Rittershoffen EGS project is located 6 km eastwards of well-known Soultz-sous-Forêts EGS project, in Northern Alsace, France. The first well, GRT-1, reached its final depth of 2580 m MD end of 2012 for targeting local normal-faults located at the interface between the clastic Triassic sandstones and the top crystalline basement. Numerous logs and hydraulic tests were performed beginning of 2013 and it has been decided to develop the permeability between the well and the reservoir. A reservoir development strategy has been performed and the results were positive, since the injectivity of the well was multiplied by a factor of five (Baujard et al 2015, Maurer et al 2015, Recalde Lummer et al 2014). The second well, GRT-2, was drilled from March to August 2014 using a HH300 drilling machine. This machine is able to hang 270 t and was used to drill a deviated well of 3200 m length down to 2707 m depth. After the drilling phase, production tests and circulations tests were performed. No reservoir development was required since production tests revealed that the initial productivity index was high enough for developing an industrial geothermal project (Baujard and al 2015).

Before, during and after drilling operations, induced seismicity was monitored by a series of sensors. Since 2012, the induced micro-seismicity of both Soultz-sous-Forêts and ECOGI geothermal projects has been monitored by two joined permanent seismic networks composed of 12 surface stations in total (see Figure 1).

As some induced seismic activity was expected during the reservoir development of the first Rittershoffen well, GRT-1, the permanent seismic monitoring network has been reinforced with a temporary short-period network:

- The Soultz seismic network is composed of short-period (1 Hz) seismometers, one or three components (L4C/L4C 3D), deployed at surface. Signals are digitized on site by 15-bit GEOSTAR data loggers and sampled at 150 Hz. The signals are then transmitted to a central site via a radio link where samples are synchronized with an external time receiver (DCF). At the central site, a SeisComp3 plugin fetches the GEOSTAR formatted data and makes it available through SeedLink to Strasbourg University (EOST), via an internet connection.

- The Rittershoffen seismic network is composed of short-period (1 Hz) three components seismometers (L4C 3D), deployed at the surface. Signals are digitized by Quanterra Q330S directly in miniSEED format at a sampling rate of 100 Hz, increased to 200 Hz by beginning of 2014, and are sent to a central site via a Wifi connexion. Here a SeisComp server makes data available to the Strasbourg University (EOST) via internet. Unlike the

Soultz network, this architecture prevents from data losses in case of transmission failures since the data are always available at the server installed in the field.

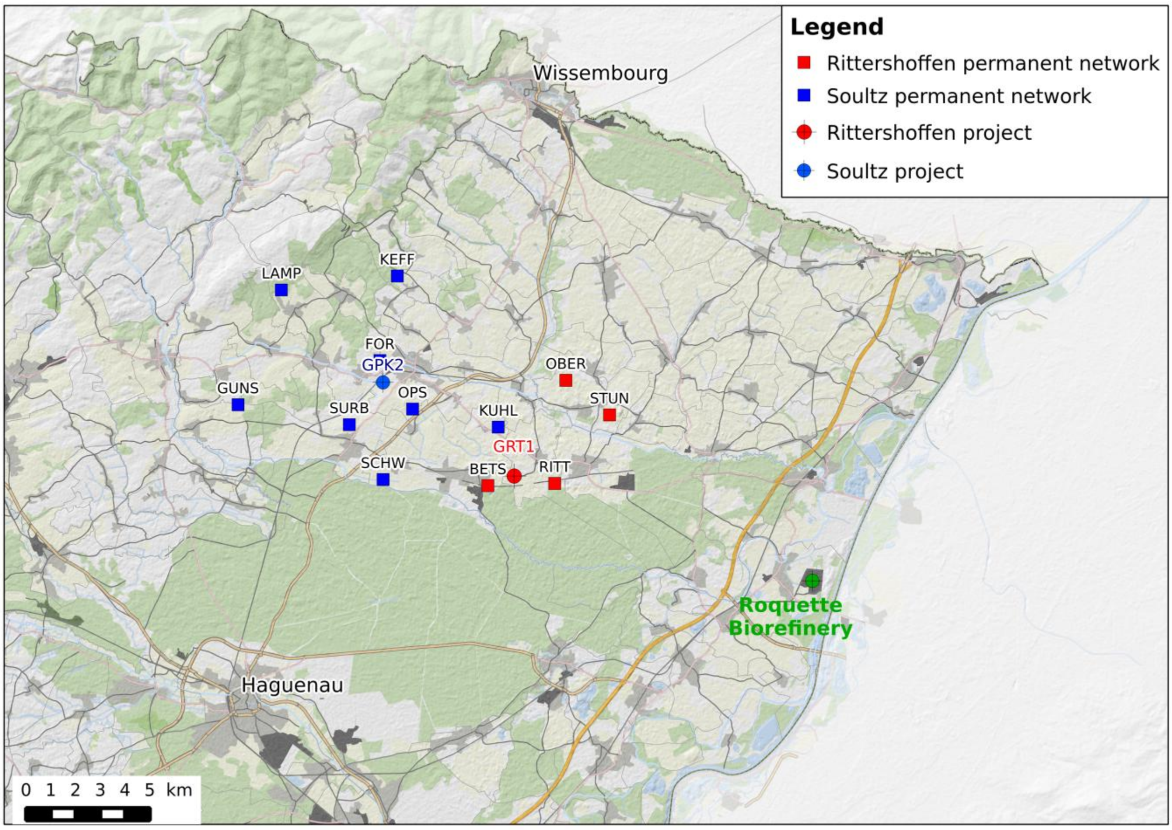

Figure 1: Location of the permanent seismological network designed to monitor the Rittershoffen and the Soultz EGS projects.

As some induced seismic activity was expected during the reservoir development of the first Rittershoffen well, GRT-1, the permanent seismic monitoring network has been reinforced with a temporary short-period network. In total, up to 300 short-period stations were installed in a range of 25 km around the drilling platform (Gaucher et al 2013, Le Chenadec et al 2015, Lehujeur et al., 2013, Lehujeur, 2015, Maurer et al 2013) varying in function of the operations performed (see Figure 2). This temporary network was finally dismantled end of November 2014. They remained deployed after the production tests, so five months after the end of the drilling phase of the second well of the project.

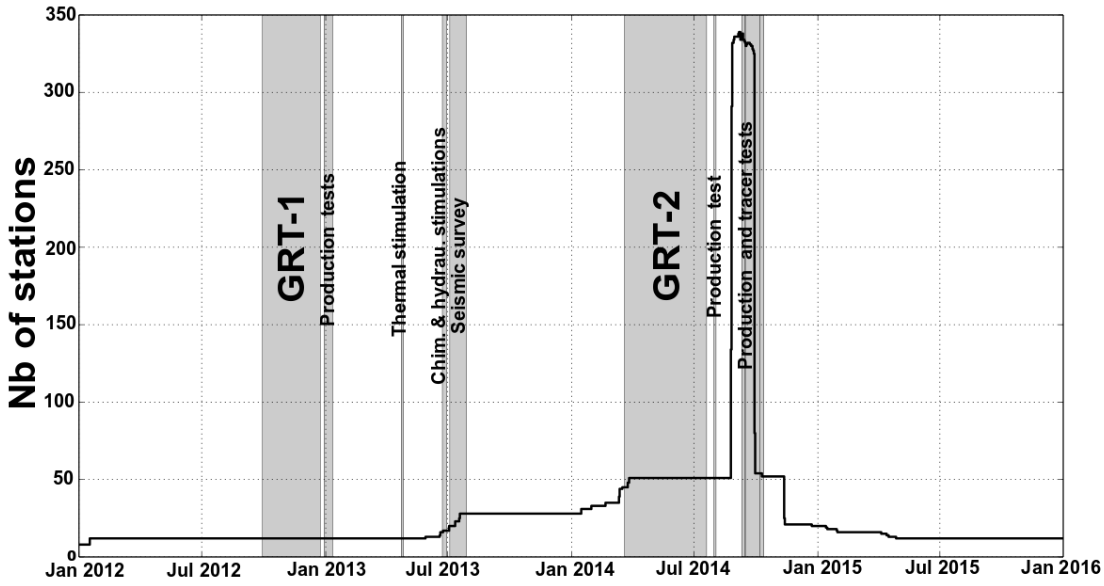

Figure 2: Number of stations installed in function of operations performed on the drilling platform.

Signals from all permanent stations and from 17 temporary stations were sent to the Strasbourg University in real-time, where they were processed and archived by an automatic detection system (SeisComp3). For the non-telemetered stations, waveforms were manually integrated to the system afterwards. To detect seismicity, this system is based on a STA/LTA method on the vertical components of each station.

2. VELOCITY MODEL

In order to locate the induced micro-seismic events, a 1D velocity model was built based on both sonic logs, VSP, and litho-stratigraphic logs performed in the two deep wells. In order to locate micro-seismic events, a first 1D velocity model was build according to previous local studies based on the Soultz-sous-Forêts project (Cuenot et al., 2008). Moreover, a second 1D velocity model was build based on sonic and stratigraphic logs performed in the GRT-1 well (Aichholzer et al 2015) and from a vertical seismic profile (VSP) performed in July 2013 after the hydraulic stimulation of GRT-1 (Figure 3).

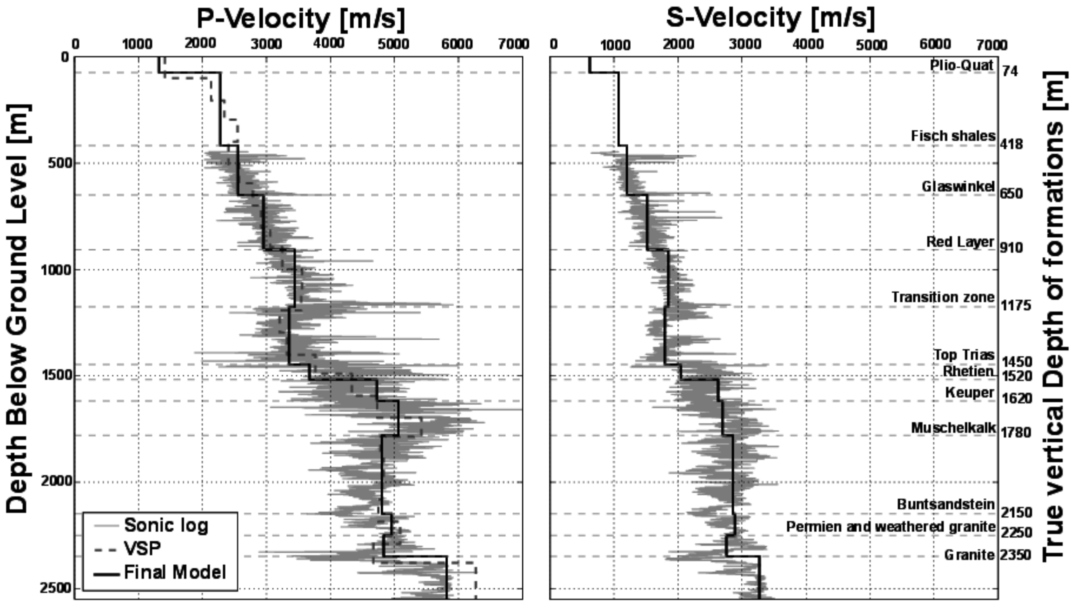

Figure 3: Velocity model of Rittershoffen used to locate the micro-seismic events

Sonic logging is a well logging tool that provides a formation's interval transit time, which is a measure of a formation's capacity to transmit seismic waves. Geologically, this capacity varies with lithology and rock textures, most notably decreasing with an increasing effective porosity. In the first well, GRT-1, the sonic log was a three-component instrument, measuring V_P, V_{Sh} and V_{Sv} taking a measure about every 20 cm. The VSP consisted in installing a seismic sensor at the bottom hole of the well and pulling it up regularly. At the surface a vibrator truck was used as seismic source. Since both the time of the sweep and the position of the sensor are known, the velocity is directly measured. A measure was taken every 100 m. VSP provided only information on V_P. Both VSP and sonic log provide regular measurements of velocity, but without taking into account the change of geology all along the well. For that reason, to build the 1D P-velocity model, the main geological formations identified by Aichholzer et al 2015 were considered and an average of both sonic log and VSP were used to determine the velocity of each formation. Since no V_S information was provided by the VSP, an averaged V_P/V_S ratio of the sonic log was used for each formation to determine the 1D S-velocity model.

3. SUM UP OF THE SEISMICITY PREVIOUSLY RECORDED

Between the installation of the Rittershoffen permanent network and the beginning of the drilling of the first well, GRT-1, no natural seismic event was detected. In the drilling phase, only one single event (0.8 Mlv) was detected in the vicinity of the well mainly due to significant drilling mud losses observed in a permeable fracture zone located in the Muschelkalk formation.

The first significant induced micro-seismicity occurred in April 2013, during thermal stimulations (Maurer et al 2015), i.e. four months after drilling operations. Thermal stimulation consists in injecting cooled geothermal brine into a hot well. This treatment creates thermal chocks, used to unseal large minerals from the open-hole section, thus enhancing the permeability. It consists in injecting reservoir fluids previously discharged from the well at an ambient temperature of 10°C into an open-hole section made of silicate rocks (sandstone, granite) lying at a down-hole temperature around 160°C. The beginning of induced micro-seismic activity occurred only one day and a half (32 hours) after the beginning of the injection. The injection generated 113 micro-earthquakes, with a maximum magnitude of 1.2 MLv.

In June 2013 two phases of stimulations were performed to enhance the connection between the well and the reservoir. First, chemical treaments were achieved between the 23rd and the 25th of June 2013 into three different packers-separated zones of the open hole section. In total 216 m^3 of biodegradable products were injected (Baujard et al, 2015, Recalde Lummer et al 2014). No micro-seismic activity was detected during these operations. Secondly, a hydraulic stimulation was performed between the 27th and the 28th of June 2013. In total, 217 induced events were automatically detected (Maurer et al 2015; Maurer et al 2016). The seismic activity started right after the flow rate exceeded 25 l/s, meaning that the injection flow rate had to overtake the maximum injection flow rate of the thermal stimulation to generate new micro-seismicity, also called Kaiser effect, which states that many materials behave elastically during reloading until the previous maximum load is reached (Kaiser 1959).

The location of the micro-seismic cloud is tightened around the bottom of the first well GRT-1. The cloud is spreading on a 1 by 3 km ellipse, slightly shifted to the south compared to the bottom hole. The mean depth is around 3500 m to be compared to the depth of the main structure that has been crossed at 2350 m, indicating that the 1D velocity model is probably slightly and globally too slow. The shifts observed both in depth and in latitude could also be explained by the geometry of the network. Indeed, at that time, no station was installed in the southern part of the well pad, leading to a North/South bias in the azimuthal coverage. Moreover the 1D approximation also creates mis-locations as shown by Kinnaert et al 2016.

About 85 hours after the last injection, while all activity was stopped on the platform, a sudden rise of seismic activity was observed. A small crisis of 37 induced micro-seismic events was detected between the 2nd and the 4th of July. The largest micro-seismic event of the stimulation sequence occurred during this crisis and reached a magnitude Mlv of 1.6. The main objective of ECOGI was to avoid inducing an event felt by the neighbourhood population. The maximum magnitude threshold set by ECOGI (Mlv=1.7) was never reached and no event was felt by the local population neither in April nor in June 2013. Compared to the previous locations, the seismic cloud associated to this crisis were relocated using is clearly located in the Northern part of the previous seismic cloud (Lengliné et al 2015), where no significant seismicity occurred before. This seismic activity which triggered several days after the last injection has been already described in other projects, and are definitively explained as late adjustments of accumulated mechanical stress (Dorbath and al 2009).

On May 2014, during drilling operations of GRT-2, some induced micro-seismic events have been observed. Because of the clayish composition of the Liassic sedimentary formation, some drilling instabilities took place with clay collapses when the drill bit reached around 1700 m depth in the Middle Triassic formation. Due to some mechanical instabilities related to the occurrence of a thick argillaceous and marl formations, some rock fragments fell onto the drill bit as well as on the bottom hole assembly and the deepest pipes. As the drill pipe and the drill bit were stuck in the well, the drilling operator decided to increase the mud overpressure to be able to improve the drilling mud circulation in the well and therefore, pull out the drill bit from the well. This operation triggered some micro-seismic activity which was detected and located by the 43 stations operating at this date. This activity was concentrated in two hours of time with a maximum seismic rate of about 100 events per hour.

In total 186 events were detected with a maximum magnitude to 1.2 Mlv.

Since the end of the drilling of the 2nd well on July 2014, no induced micro-seismic activity was detected, meaning that no induced seismicity was related to the production or the circulation tests, while a dense network composed of more than 300 stations was installed. The Figure 4 summarizes the induced seismicity detected in the drilling phases and during the different stimulation phases since the beginning of the project.

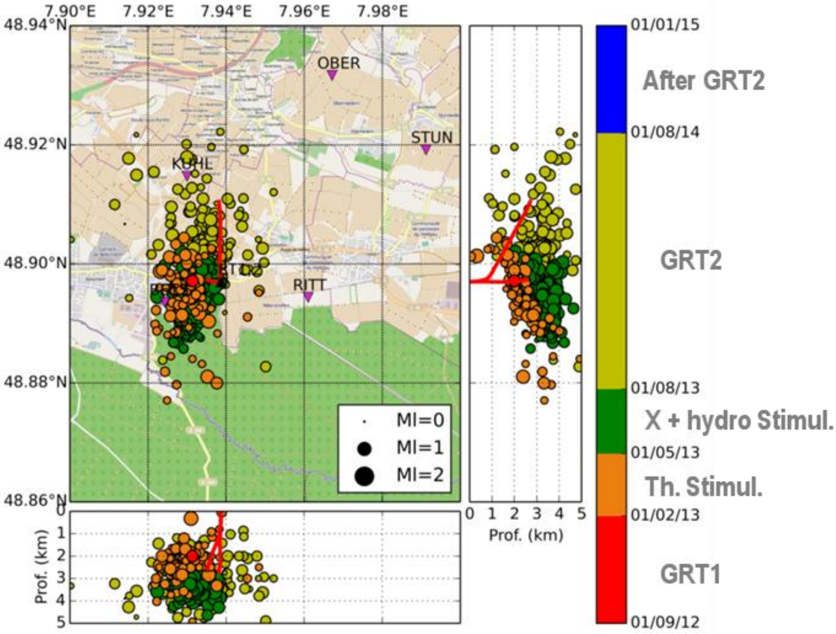

Figure 4: Induced seismicity detected and located during the drilling operations, the stimulations operations and the production and tracer tests between 01/09/2012 and 01/01/2015

In December 2015, the down-hole pump was installed at depth in the production well, and the production well was awake in order to increase the temperature of the pump to facilitate its lubrication (Ravier et al 2016). This operation did not trigger any seismicity. However, the beginning of the exploitation of the Rittershoffen is planned in spring 2016. As low magnitude seismic events are occasionally associated to deep circulations of such projects, the micro-seismic activity will be carefully monitored in real-time during starting operational tests of production of the plant as well as later, during its exploitation. Moreover a reinforcement of the permanent networks by eleven broadband surface stations composed of Trillium T120 seismometers and 24-bits Taurus data loggers, sampled at 250 Hz is planned before the starting of the production operations.

4. NATURAL SEISMICITY

Since the end of the drilling of the 2nd well on July 2014, no induced micro-seismic activity was detected. However, since the beginning of the project, natural seismicity is also detected and located all around the drilling platform.

The Rittershoffen project is implemented within the Rhine graben, which is one of the largest rift valley in France. The latter belongs to a set of rifts, alternating according to a submeridian axis from the North Sea to the Mediterranean, which is the "West-European rift" (Villemin 1986). This basic structure is partly due to the reactivation of paleo-accidents dated from late-Hercynian times of Northern European crust. The Rhine Graben extends 300 km between the cities of Basel in the South and the North of Mainz in a general direction N 20°E. The Rhine Graben is structuring the extensional tectonics dated Oligocene (35-30 Ma). As a rift, it represents a reference model. Indeed, its borders are formed by tectonic regional extension that dives into the core of the graben. The apparent normal off-set of these border faults (several hundred of meters) gives an indication of the order of magnitude needed to accommodate the vertical movement associated with extensive Tertiary phase (Genter 1989). These normal faults, dip of 55° to 75° on average (Sittler 1969). Further inside, the graben itself 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 600 regional or local natural earthquakes have been detected by permanent or temporary networks dedicated to the monitoring of geothermal activities. Among them, about 50 local earthquakes have been located in a range of 30 km of the drilling platform that was not detected by the national seismic monitoring network (see Figure 5). An important natural seismicity is observed southwards of the Rittershoffen project, in the Haguenau forest, as well as northwards and north-eastwards. Even if some small clusters of events could be seen, identifying structures remains rather speculative since the natural seismicity is scattered.

The installation of these seismological networks revealed a natural seismicity proving, if needed, that the Rhine graben is still tectonically active.

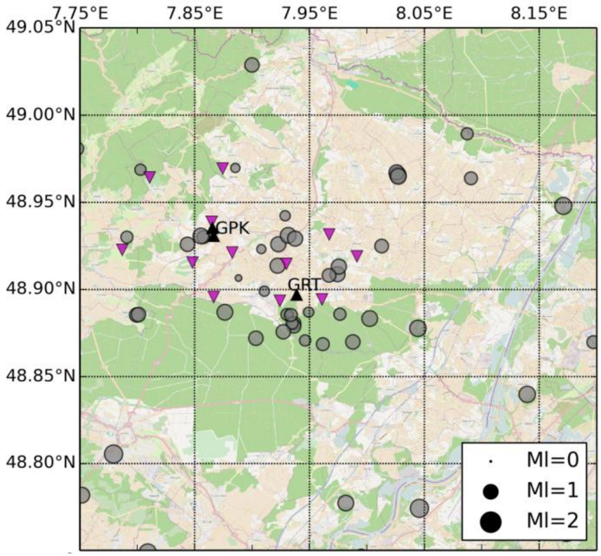

Figure 5: Natural seismicity detected in a range of 30 km around the platform since the installation of the Rittershoffen permanent network in 2012.

5. CONCLUSION

The permanent and temporary networks installed for the seismic monitoring of the Soultz and Rittershoffen projects led to detect both natural seismicity and micro-seismicity induced by geothermal activities. In total, more than 300 stations have been installed to monitor the Rittershoffen project during drilling of the two wells, during reservoir development phases and during production and circulation tests. A site-adapted 1D velocity models were built both for P-velocity and S-velocity that take into account the geology recognized during the drillings.

More than 500 induced micro-earthquakes were automatically detected by the real-time automatic system set up to monitor the project. The largest micro-seismic event triggered during the reservoir development phases of the first well GRT-1 occurred reached a magnitude of 1.6 (Mlv). The main objective of the project manager was to avoid inducing an event felt by the neighbourhood population. The maximum magnitude threshold set (Mlv=1.7) to stop operations was never reached and no induced event was felt by the local population. As micro-seismic events are occasionally associated to deep circulations of such projects, the micro-seismic activity will be carefully monitored in real-time and the seismic network will be reinforced during starting operational tests of production of the plant as well as later, during its exploitation.

Due to their local character, the permanent and temporary networks also allowed detecting natural seismicity not necessarily detected by the national seismic monitoring network. About 600 local and regional earthquakes were detected since the installation of the Rittershoffen permanent network in 2012. Among them, 50 natural earthquakes have been detected by these networks in a range of 30 km around the drilling platform. These earthquakes are related to the tectonic activity of the Rhine graben. However, if some small clusters of events could be seen, identifying structures remains rather speculative since the natural seismicity is scattered. The beginning of the exploitation of the Rittershoffen is planned in June 2016.

REFERENCES

Aichholzer, C., Duringer, Ph., Orciani, S., Genter, A.: New stratigraphic interpretation of the twenty-eight-year old GPK-1 geothermal well of Soultz-sous-Forêts (Upper Rhine Graben, France), *European Geothermal Workshop 2015*, Strasbourg, France, (2015)

Baujard, C., Genter, A., Graff, JJ., Maurer, V., Dalmais, E.: ECOGI, a new deep EGS project in Alsace, Rhine Graben, France. *World geothermal Congress 2015*, Melbourne, Australia (2015).

Cuenot, N., Dorbath, C., Dorbath, L.: 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, (2008), 797-828.

Dorbath, L., Cuenot, N., Genter, A., Frogneux, M.: Seismic response of the fractured and faulted granite to massive water injection at 5 km depth at Soultz-sous-Forêts (France), *Geophysical Journal International*, (2009).

Gaucher, E., Maurer, V., Wodling, H., Grunberg, M.: Towards a dense passive seismic network over Rittershoffen geothermal field, *2nd European Geothermal Workshop 2013*, Strasbourg, France, 24-25 Oct. (2013).

Genter, A.: Géothermie Roches Chaudes Sèche : Le granite de Soultz-sous-Forêts (Bas-Rhin, France), *Thèse Doctorat à l'Université d'Orléans*, 191p, (1989).

Kaiser, E. J.: A study of acoustic phenomena in tensile test, *Doctoral thesis*, Tech. Hochschule München, Munich, Germany, (1959)

Kinnaert, X., Gaucher, E., Kohl, T., Achauer, U.: Modelling earthquake location errors at a reservoir scale: a case study in the Upper Rhine Graben, *Geophysical Journal International*, submitted, (2016).

Le Chenadec A., Vergne J., Lehujeur M.: Ambient seismic noise tomography of the Outre-Forêt region (Alsace, France) from the EstOF dense temporary seismic array. *4th European Geothermal Workshop 2015*, Strasbourg, France, 19-20 Oct (2015).

Lengliné O., Boubacar M., Schmittbuhl J.: Seismicity related to the hydraulic stimulation of GRT1, Rittershoffen, Alsace, France, *4th European Geothermal Workshop 2015*, Strasbourg, France, 19-20 Oct (2015).

Lehujeur, M., Vergne J., Schmittbuhl J., Maggi, A.: Imaging a deep geothermal reservoir using ambient noise correlation, *European Geothermal Congress 2013*, Pisa, Italy (2013).

Lehujeur, M.: Imagerie d'un reservoir géothermique par correlation de bruit, Thèse de doctorat, l'Université de Strasbourg, France (2015)

Maurer, V., Baujard, C., Gaucher, E., Grunberg, M., Wodling, H., Lehujeur, M., Vergne, J., Lengliné, O., Schmittbuhl, J.: Seismic monitoring of the Rittershoffen EGS project (Alsace, France), *2nd European Geothermal Workshop 2013*, Strasbourg, France, 24-25 Oct. (2013).

Maurer, V., Cuenot. N., Gaucher. E., Grunberg, M., Vergne, J., Wodling, H., Lehujeur, M., Schmittbuhl, J.: Seismic monitoring of the Rittershoffen EGS project (Alsace, France), *World geothermal Congress 2015*, Melbourne, Australia (2015).

Maurer, V., Grunberg, M., Cuenot, N., Richard, A.: Towards calibrating an automatic detection system to monitor micro-seismic activity induced by geothermal projects in the Upper Rhine Graben, *European Geothermal Congress 2016*, Strasbourg, France, (2016).

Ravier, G., Baujard, C., Dalmais, E., Maurer, V., Cuenot, N.: Towards a comprehensive environmental monitoring of a geothermal power plant in the Rhine graben, *European Geothermal Congress 2016*, Strasbourg, France, (2016).

Recalde Lummer, N., Rauf, O., Gerdes, S., Genter, A., Scheiber, J., Villadangos, G.: New biodegradable stimulation system - First field trial in granite/Bunter sandstone formation for a geothermal application in the Upper Rhine Valley, *Proceedings of Deep Geothermal Days*. Paris, France, (2014).

Sittler, C.: Le Fossé Rhénan en Alsace. Aspect structural et histoire géologique. *Rev. Geogr. Phys. Géol. Dyn.* (2), 11, 5, 465-493, (1974).

Villemin, T.: Tectonique en extension, fracturation et subsidence : le Fossé Rhénan et le Bassin de Sarre-Nahe. *Doctorat de l'Université de Pierre et Marie-Curie*, Paris VI, 270 p., (1986).

Acknowledgements

The authors would like to thank ECOGI for funding part of the monitoring network and for sharing some geoscientific data. A part of this work was conducted in the framework of the Labex G-Eau-Thermie Profonde, which is co-funded by the French government under the program 'Investissements d'Avenir', a cross-border collaboration between industrial companies, ES, and ES-Géothermie, academics (KIT, EOST) and the EEIG "Heat Mining" of Soultz-sous-Forêts. We also thank the Geophysical Instrument Pool Potsdam from the GFZ German Research Centre for Geosciences (Germany) and the Fairfield Company for providing most of the temporary seismological units.