European Geothermal Congress 2016
Strasbourg, France, 19-24 Sept 2016

Towards targeting geothermal reservoir: exploration program for a new EGS project in urban context in Alsace

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Keywords: Geothermal, EGS, exploration, geophysics, vibroseismic, gravity, aeromagnetic, Alsace.

ABSTRACT

As part of a geothermal project lead by 'Électricité de Strasbourg', a preliminary survey of seismic reflection was acquired during summer 2015 in the suburbs of Strasbourg area (Alsace, France). In addition, several other geophysical methods have been applied recently. A gravimetric survey was achieved in 2013 with the acquisition of 250 new measure points and during summer 2015, an aeromagnetic campaign, using a helicopter equipped with a magnetometer, was carried out over the same area.

All the collected data were initially independently processed to determine sub-soil characteristics and to locate the optimal target for a new geothermal project. The future joint interpretation of these data will lead to an exploration guidance using all these geophysical measurements.

1. INTRODUCTION

Based on the geothermal expertise gathered from the Soultz-sous-Forêts project, which was successfully demonstrated with the recent industrial geothermal doublet of Rittershoffen, new targets in the French part of the Upper Rhine Graben (URG) are under development by Electricity of Strasbourg (ES). More recently, the ES company aims at developing a new deep geothermal project in the southern part of the city of Strasbourg, in the county of Illkirch-Graffenstaden (Richard et al 2015; Baujard, 2016). The two wells of this new doublet will be drilled end of 2016 to reach a deep geothermal target at ~2700 m depth, consisting in a fractured/faulted zone at the interface between the clastic Triassic sandstone sediments (Buntsandstein) and the crystalline basement. With an expected temperature of ~150°C and a nominal flow rate of 70 l/s, the main objective of this deep geothermal project is to produce about 20 MWth and to deliver heat to a future district heating network and potentially to produce electricity in the summer time. The geothermal target is a normal fault, trending NS, with a significant vertical off-set which will be exploited via two deep inclined wells. Thus, a geophysical reconnaissance exploration program was set-up for better constrain the geometry of the fault at depth and the occurrence of hard rocks with a crystalline composition.

We present in this paper, as part of a deep geothermal project in Alsace (France), a three-stage exploration campaign:

1. First, a preliminary survey of vibroseismic reflection was acquired during summer 2015 within the "Illkirch-Erstein" license owned by ES in the suburb of Strasbourg area. This seismic survey was designed in order to qualify a potential deep geothermal target for an EGS (« Enhanced Geothermal Systems ») exploitation of the resource (Genter et al 2015b). Obtaining a structural and hydrogeological model of this kind of deep fractured reservoir is a key point for a successful project (Dezayes et al 2010). So geometry design and acquisition parameters have been discussed to provide a suitable and valuable image of the sub-surface. Furthermore within a complex structural model, a seismic processing sequence dedicated to enhance fault direction and dip has been implemented.

2. In parallel to this new seismic acquisition campaign, a gravity data acquisition campaign was planned in order to refine the gravity map of the Rhine-Graben area in the studied area (Rotstein et al 2006). The main objective of this gravity data acquisition campaign was the lithological and the structural characterization of the ante-Triassic basement buried under the sedimentary cover of the Rhine Graben.

3. Finally, an aeromagnetic survey of the prospect zone has been sub-contracted. Previous investigations have shown that the basement is the eastward prolongation of the Paleozoic Northern Vosges (Edel and Fluck, 1989; Edel and Schulmann, 2009). In order to characterize the nature and structure of the deep basement in the zone of interest by comparing and calibrating the magnetic characteristics of both areas, the survey has been extended to the northern crystalline Vosges.

This exploration campaign, combining three different geophysical methods, should allow characterizing the lithological and the structural properties of the sedimentary covers, as well as the underlying basement. Thus, the litho-structural results will be helpful for targeting the geothermal resource and securing the geothermal project.

2. SEISMIC ACQUISITION CAMPAIGN

First, the planed strategy was to reprocess older seismic lines, set up for oil prospecting, in the vicinity of the license to obtain first order information at a quite low cost. The design of the new vibroseismic acquisition was focused on a specific area, in order to ensure trajectories of the future wells, previously identified as targets. In the case of the Illkirch project in Alsace, exploration area was reduced to approximately 30km². Acquiring 37 km of 2D seismic lines was sufficient to obtain enough information to characterize the targeted fault without any exploration drilling.

However, in order to take maximum advantage of the information coming from the previous seismic acquisition, the new survey design had to take into account the previous geometry of the lines and the previous parameters used to acquired data respectively in 1975, 1977 and in 1985. In order to densify the spatial coverage, to increase the seismic resolution and to keep a coherent global design, the decision was taken to add three East-West seismic lines, the targeted fault being NS oriented. As a consequence, the distance between lines of the 1985's acquisition was reduced by half.

To correctly image faults with a significant apparent dip, seismic lines have to be as perpendicular as possible to the fault plane direction (Lavergne 1986). But due to the large distances between old seismic lines, an important uncertainty was remaining on the fault geometry. So, to have a better azimuthal constrains and to get information all along the wells trajectories, two extra-lines respectively NW-SE and NE-SW were set up. The obliqueness of these seismic lines compared to the main fault plane direction remains low enough to ensure a right migration of the sloping reflectors (Yilmaz 1987, 2001) while allowing intersection of possible faults in between two seismic lines (Figure 1).

Ideally, accurate information about the target depth, the frequency content and propagation velocities in the different geological layers are necessary to define the key parameters of the seismic acquisition. Reprocessing and reinterpretation of old seismic lines provide access to the necessary information to define the optimal geometry that will properly image the deepest layers down to the top basement and the identified target.

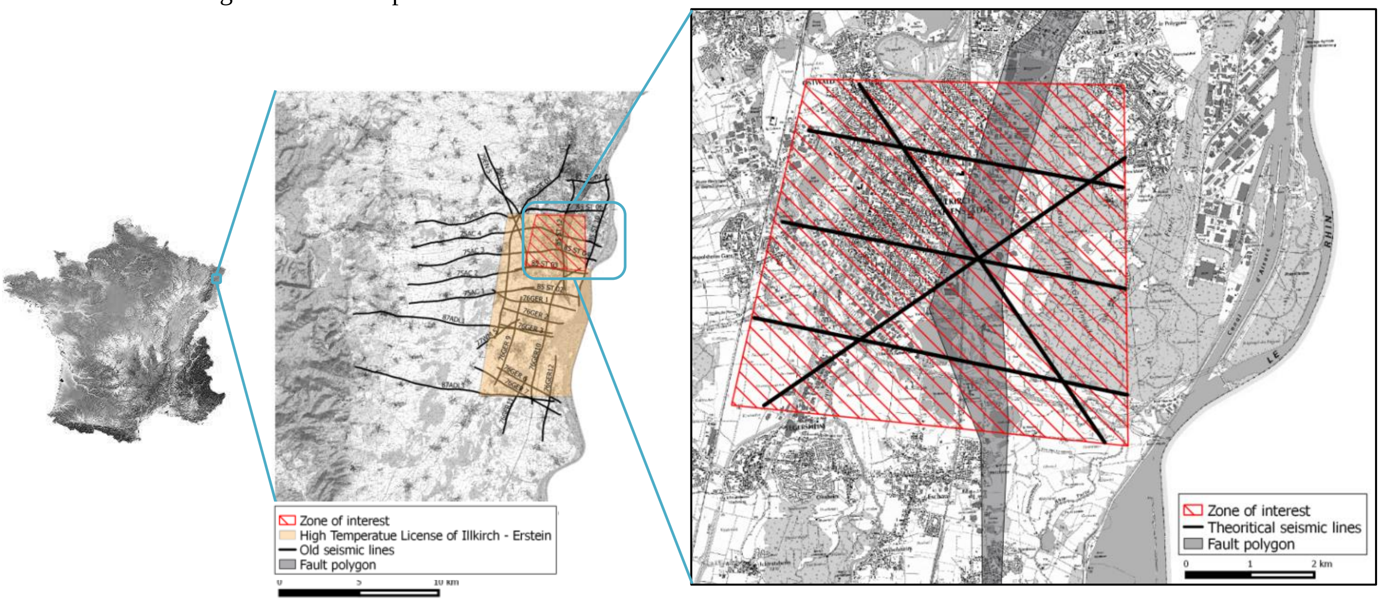

Figure 1: Refining the zone of interest for seismic acquisition within the high temperature license.

From a cost point of view, the total line length of the seismic acquisition (its processing and interpretation), is the overriding factors (Bouska 1997).

Therefore, it is necessary to precisely determine the extent of seismic recording device. As a first approximation the extension of the network, otherwise known as "offset", is commonly taken equal to the depth of the target. However, this first order estimate may be largely wrong if the seismic wave propagation velocities are not taken into account. So, for a more rigorous estimate of maximum offset, the equation [1] should be used (Talagapu 2005).

$$Offset_{max} = \frac{Z}{2}\left(\frac{V+V_s}{V-V_s}\right)^{\frac{1}{2}} \times \tan\theta \quad [1]$$

Z: target depth
V: average velocity of the target layer
V_s: velocity of the surface layer
θ: maximum dip of the target horizon

Equation 1 : Maximum offset estimation in function of velocities, target depth and maximum dip

The lack of offset could dramatically affect the data and even worse when the object is to image a fault scarp. As shown on Figure 2, shortened offset could not clearly image reflectors of the footwall. It would result in a complex tracking of laterally consistent seismic reflectors and finally to an inaccurate interpretation of the layer depth and of the position of the fault (Ourabah et al 2014).

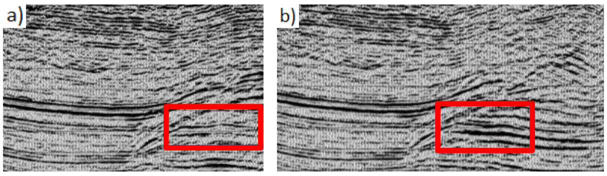

Figure 2: Effect of short offset acquisition on reflector identification. These migration sections have respectively a) 450m b) 1300m offset on the foot wall.

3. GRAVITY MEASUREMENTS CAMPAIGN

The main objective of this gravity data acquisition campaign was the lithological and the structural characterization of the ante-Triassic basement buried under the sedimentary cover of the Rhine Graben. The study area covers the "Illkirch-Erstein" license and its vicinity (1400 km²). The extension of the studied area outside of the permit aims to understand properly the problems of regional gravimetric and to calibrate interpretations by integrating geological information at the periphery of the basin and the existing deep drillings. The gravity data used are old detailed measurements carried out for the Mines de Potasse d'Alsace, numerized by Rotstein et al 2006 and archived by the BRGM in the Gravimetric French Bank, complemented by 250 new measurements acquired on the "Illkirch-Erstein" license. To achieve this integration, the old data have been reprocessed and had to be repositioned by statistical techniques. All data, old and new, were then validated, based on the examination of differences between the values of Bouguer measured at common stations and a prediction from the nearest stations. This allowed to remove the wrong stations and to estimate the accuracy of the gravity map. We notice that 93% of the restrained measures the Bouguer anomaly prediction was less than 0.5 mgal (see Figure 3).

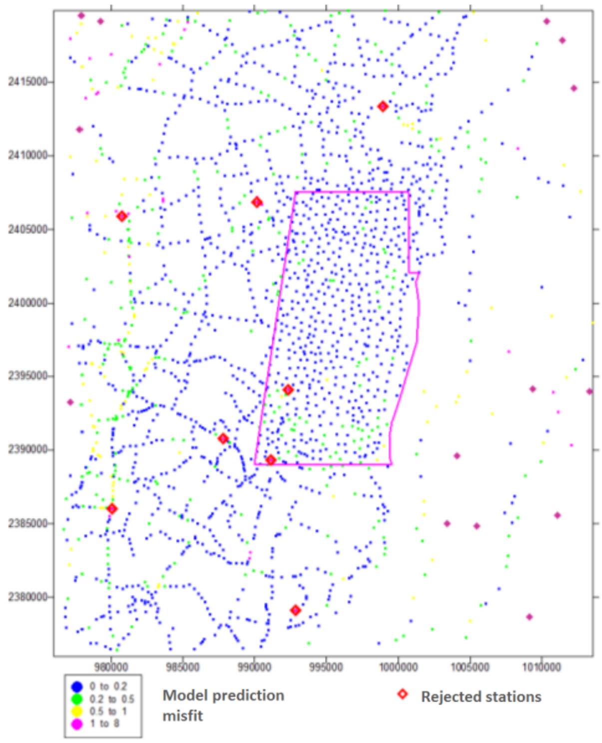

Figure 3: Map of the preexisting gravity measurements completed by 250 newly acquired gravity measurements with the "Illkirch-Erstein" license.

4. AEROMAGNETIC CAMPAIGN

The aeromagnetic acquisition consists in measuring the Earth's magnetic field a few hundred meters above the ground level from a plane or a helicopter. The prospected area is gridded accordingly to aerial constraints, but also based on the depth of the geological formations to be imaged. They can be accompanied by ground measurements in areas where flying is impossible. In comparison to ground data acquisition mode, this method has several advantages. It allows to cover an entire area (no access problem) in a very limited time with reduced staff. The aeromagnetic method is frequently used in the underground exploration to evaluate the thickness of a sedimentary basin and to locate and identify structures in the basement beneath the basin. This method also allows to detect faults and to delimit the boundaries of various geological structures having contrasted petrophysical properties. The processing and interpretation of data can be done in combination with seismic and gravity data (if available). As a matter of fact, this method is a good way to further constrain the litho-structural interpretation provided by seismic of gravity data acquisition.

A high-resolution aeromagnetic geophysical survey was conducted during the months of September and October 2015. Despite the area of interest was the "Illkirch-Erstein" license, -owned by ES, the acquisition area has been defined to connect the outcropping basement in the Vosges Mountains, where magnetic susceptibility values were measured on samples in order to calibrate the experimental values. Finally, the survey covers an area from the Vosges to the Rhine in the West-East direction, and an area of approximately 20 km to the North and to the South of the city of Strasbourg. Such an investigated area required a total of about 5000 km-of linear magnetic data. The East-West cross-lines were spaced by 400 meters, while control lines were spaced by 4000 meters and oriented North-South, perpendicular to the cross-lines (see Figure 4). Control lines are mainly used to t correct eventual drifts in altitude.

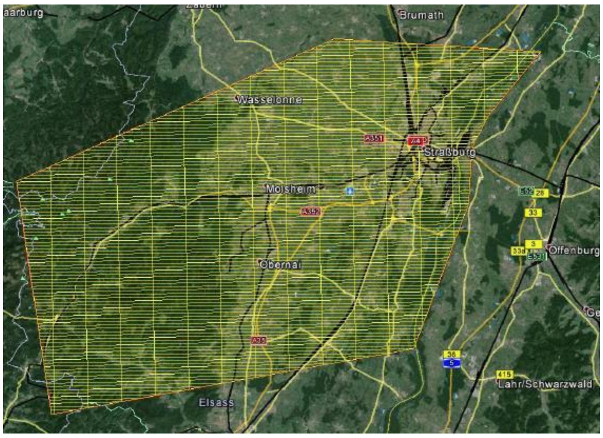

Figure 4: Location of the investigated area for aeromagnetic data based on East-West cross lines and North-South control lines.

A helicopter was mobilized for this project. The flight altitude was determined accordingly to the Europe SRTM 30m digital elevation model with a 25% slope. The nominal height of the survey was 300 meters. The equipment installed in the helicopter consists of a sting of 9 m holding a high resolution cesium vapor magnetometer, a GPS, an altimeter radar and a digital acquisition system coupled with a real time magnetic compensation system. The data was time-stamped with GPS time of the primary GPS receiver. To minimize the impact of helicopter maneuvers on the magnetic field, the magnetic signature of the helicopter was estimated by a series of tests and calibrations, performed before and after the survey.
Ground-based equipment complemented the onboard system and consisted of a magnetometer station equipped with a cesium vapor magnetometer and synchronized with an antenna and a GPS receiver to monitor the diurnal variation of the magnetic field.

5. RESULTS

At this state, it has to be mentioned that all the different data were processed and interpreted independently.

5.1. Seismic acquisition campaign

Regarding the processing sequence to properly migrate the data, the on-field preprocessing had shown good results when using the Pre Stack Time Migration (PSTM).

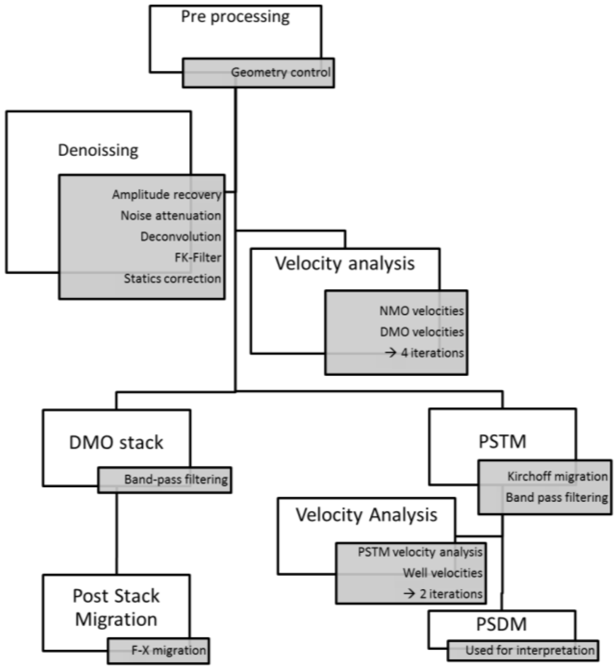

Figure 5: Processing flowchart for vibroseismic data.

PSTM is a migration technique for processing seismic data in areas where lateral velocity changes are not too severe, but structures are complex. Time migration has the effect of moving dipping events on a surface seismic line from apparent locations to their true locations in time. The resulting image is shown in terms of travel-time rather than depth, and must then be converted to depth with an accurate velocity model. The time to depth conversion was done using all valuable velocity data (sonic data from all available wells, processing velocities used for PSTM). Several iterations were done to refine the velocity model used for the Kirchoff migration. 4 iterations with residual statics correction were done at the NMO- DMO steps. Then PSTM velocities were refined twice to obtain the best PSDM section for both lines (Figure 5).
We finally obtain a 3D structural model in depth. This model was used to properly define the final target and wells trajectories. The Figure 6, south oriented, shows the main fault of the Illkirch-Graffenstaden (light brown) and the top and basement of the Buntsandstein layer (purple).

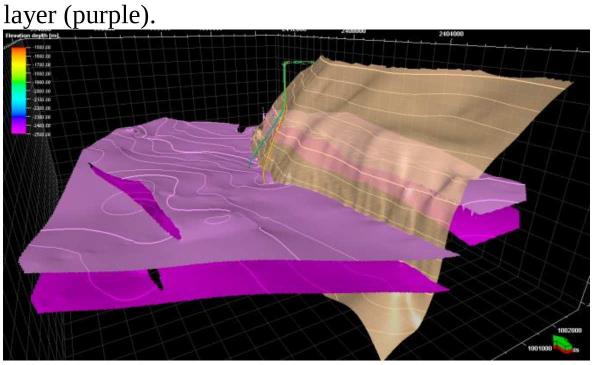

Figure 6: Structural model obtained using 2D seismic interpretation in depth. Top and bottom of the Buntsandstein horizons are in purple. The main fault (1km offset) is colored in brown.

5.3. Gravity measurements campaign

The modeling was performed on five profiles (taking into account the lateral extensions of the structures or 2.5D). The cuts to model were implanted near seismic lines.

Gravity modeling of the basement of the basin requires accurate information on its geometry and filling. On the “Illkirch-Erstein” license, seismic reprocessing has allowed to evaluate the depth of major sedimentary interfaces. Moreover, the interval speeds calculated at the deepest holes can be converted into density. This information, supplemented with data from surveys and outcropping basement geology at the edge of the basin, helped to build an initial gravity model. From this first model, the gravity effect of known structures were calculated and compared with the existing gravity anomalies. Most of the observed gravity anomalies are explained by the initial model. Gravimetry is generally influenced by the geometry of the basins. But in the Rhine-Graben due to a moderate contrast of the densities of sediments and basement rocks, the effect of density variations within the basement is relevant (Rotstein et al 2006; Edel et al 2007). For instance, positive residual anomalies with amplitudes from 3 to 5 mgal remain on the “Illkirch-Erstein” license area.

These anomalies are significant, their intensity being greater than the measurements accuracy. Before interpreting these anomalies by lithological or structural changes to the top of the basement, check as to be achieved that intra-sedimentary heterogeneities not taken into account by the initial model could explain these anomalies. The initial models were therefore supplemented by dense gravimetric bodies, into the basement, as shown in Rotstein et al 2006. The aero-magnetic data are showing the same tendency and seen to confirm this hypothesis.

The Figure 7 constitutes a structural synthesis of the basin which specifically highlights many major axes, known as the threshold of Erstein and the top of Eschau axis.

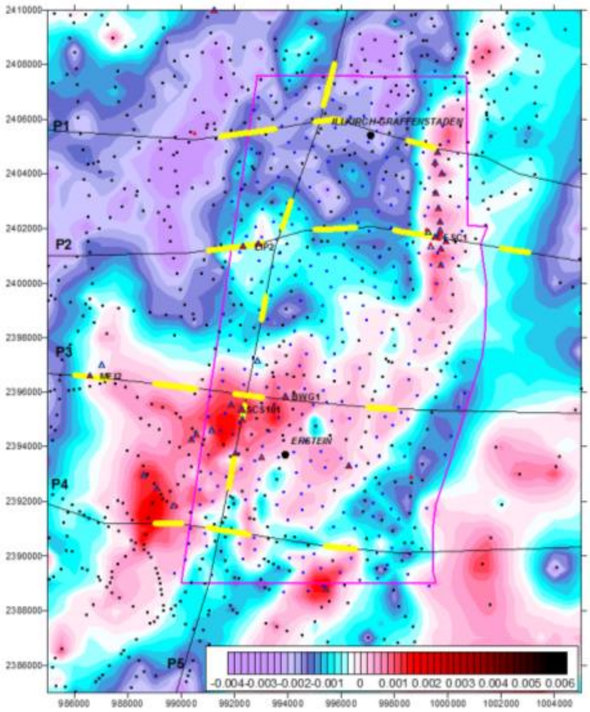

Figure 7: Map of the gravimetric discontinuities resulting from the vertical gradient of the Bouguer anomaly with the position of the interpreted profiles.

5.3. Aero-magnetic campaign

Following the acquisition, several corrections were done on the raw signal. The real-time compensation system has corrected the raw magnetic data using the magnetic attitude model of the helicopter. The positioning residual error of the acquisition generated by the time delay system (lag) and the shift in space (offset) between the magnetometer and GPS readings automatically lead to a shift in position that has been corrected. The spikes in the data, usually generated by radio from the helicopter were removed. Diurnal variations recorded at the station installed on the ground were corrected. The International Geomagnetic Reference Field was subtracted, and an altitude correction was performed by leveling cross-lines using control lines. The most important anthropogenic magnetic anomalies, caused by urban presence along the flight path, were removed carefully to keep as much as possible, the subsequent geological information. Finally, reduction to the pole and first vertical derivative was calculated.

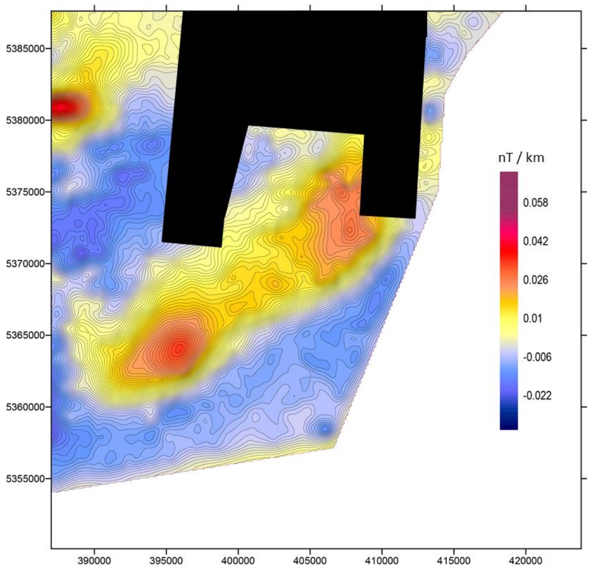

Figure 8: Preliminary results of the first vertical derivative of the magnetic field uplifted by 250 m of the Illkirch-Graffenstaden area.

Preliminary interpretation of the residual magnetic field showed in the western part a N80E oriented area with strong magnetism matching late hercynian granitoid intrusions (Figure 8). This anomaly corresponds to the Andlau granites, the Hohwald granodiorites, the Kreuzweg granite and the "Champ-du-Feu" granodiorites. Under the sector of the "Illkirch-Erstein" license, a wide NW-SE oriented area likely corresponds to the extension in the Rhine-Graben of these crystalline intrusions known in the Vosges Mountains which are outcropping. The presence of crystalline rocks below the sedimentary cover in Illkirch sector is a favorable factor for the project. These hard rocks are generally naturally fractured and have promising fracture permeability.

6. CONCLUSIONS

One of the most valuable geophysical methods to image fractured/faulted geothermal targets at great depth remains vibroseismic reflection. However, the success of such exploration depends strongly on the horizontal and vertical resolution obtained with the selected acquisition parameters.

The seismic reflection newly acquired would provide all necessary information in term of geometry design, acquisition parameters, source power and processing sequence to correctly model fractured reservoir for future EGS high temperature exploitation in Alsace. In particular, this campaign contributes to characterize the litho-structural framework of the Illkirch EGS project allowing to better locate the target and to define the trajectories of the wells.

On the "Illkirch-Erstein' license, the original goal, which was the lithological and structural characterization of the basement by gravimetry, can be achieved only partially. Indeed the effects of salt formations, hardly quantifiable, disturb the interpretation. However combined gravimetric and magnetic interpretation can contribute to the structural and lithologic knowledge of the basin. Gravity sections were thus finalized by slightly modifying the geometry of the initial seismic interfaces to improve the fit between theoretical and experimental anomaly. These gravity models show discontinuities that affect generally the whole sedimentary sequence down to the basement and can constitute an indirect contribution to the knowledge of the accidents affecting the basement. These discontinuities were postponed on gravity maps.

The purpose of the aeromagnetic acquisition campaign was to understand how the outcropping geological structures, identified on outcrops in the Vosges Mountains, extend in depth in the Rhine Valley and refine the general location of faults in correlation with the interpretations made by seismic and gravimetric acquisitions. The lack of well-documented deep wells is a major handicap to clearly evaluate the nature of the basement in terms of crystalline rocks in particular. Indeed, all geothermal projects in North Alsace showed that the geothermal resource was related to the presence of fractured zones that affect the basement. This relationship between the potential permeability and nature of the basement is crucial. This geophysical survey on the basis of aeromagnetic data should help define areas with specific petrophysical properties and to understand their compartmentalization by faults. The results combined with the interpretation of 2D seismic Illkirch should allow to better constrain the brittle nature of the base of the roof and thus to secure the terms of target projects.

The three geophysical data acquisition campaigns have essentially two direct impacts on deep geothermal projects:

- Firstly, for the geothermal project of Illkirch, it will provide a better knowledge of the litho-stratigraphic model in the sedimentary cover and of nature of the basement, which will allow better identification of targets and well trajectories.
- Secondly, this project will determine the best strategy for acquiring geophysical data for other geothermal projects exploration in a graben-like context. Indeed, if the results are positive this approach could be applied to other sectors of the Rhine graben which are currently in early phase of development.

Finally, a combined interpretation will be done after the drilling of the Illkirch-Graffenstaden doublet planed for end of 2016. Indeed, major information will be gathered after the drilling thanks to thorough geophysical investigation (VSP, sonic log, geological interpretation…).

This joint analysis will define exploration guidelines deciphering precisely the contribution of each geophysical measurement in order to even more secure the next deep geothermal projects led by Electricité de Strasbourg.

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ACKNOWLEDGMENTS

The authors would like to thank the ES for sharing scientific results about an ongoing geothermal project under development. A part of this work was conducted in the framework of EGS Alsace research project, which is co-funded by ADEME 'Agence de l'Environnement et de la Maitrise de l'Énergie', a cross-border collaboration between industrial companies ES, and ES-Géothermie, and Strasbourg University (EOST).