GRAVITY VERSUS THERMAL GRADIENT: CAN WE USE GRAVITY TO DISCRIMINATE POTENTIAL HYDROGEOTHERMAL AREAS ?

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Keywords: Exploration, gravity, temperature, Rhine Graben, thermal gradient.

ABSTRACT

We present results obtained from new accurate gravity data showing average data uncertainties around 0.02 mGal. The data were acquired in 2013 and 2016 in the Upper Rhine Graben within the “Electricité de Strasbourg” geothermal exploration permits located in northern Alsace (France). We achieved a qualitative study as well as a quantitative interpretation based on existing 3D geological models built mainly from 2D seismic and borehole data. The interpretation of the mismatch between the observed and computed Bouguer anomalies reveals high correlation between the density of the known fractures/faults and the high and negative mismatch values. This discrepancy is also interpreted in terms of negative and positive anomalies that express lack and excess of density values. The stripping approach conducted in the whole area but more specifically applied onto seven thermal gradient boreholes reveals that the density contrasts are often overestimated from the Jurassic but more specifically for the Buntsandstein. This reveals high fracture related porosity effect on the densities. The stripping technique applied on the same location as those of the thermal gradient boreholes reveals that the boreholes F3 and F5 could present higher geothermal potential compared to the other boreholes. This innovative approach using high accurate gravity data, post-processing and 3D finite element gravity modelling as well as 3D geological modelling leads to the same conclusion as the one obtained from thermal gradient borehole data analysis.

1. INTRODUCTION

For a given geothermal project, the choice of the drilling area is very important for project success. This step is very crucial for a project especially with restricted financial support like in geothermal energy (compared to oil/gas industry). Consequently, it is important to undertake an adequate exploration program to increase the likelihood for project success by delineating more accurately promising geothermal areas. This could be considered as one derisking step. Classically, the geophysical methods used in deep geothermal exploration are active-seismic and non-seismic methods, for instance electromagnetics, gravity and magnetics. Each of them present advantages and disadvantages. The choice of the used geophysical exploration methods depends on the scientific and technical challenges related to the targeted geothermal reservoirs but also usually on the allowed financial support.

Recent geothermal projects developed in the Upper Rhine Graben (URG) tend to target fault zones at the sediment – basement interface. Whereas seismic methods provide a useful and suitable underground image in the sediments, non-seismic methods give insights on nature and structure of basement rocks. As permeable fractured zones in basement – targeted by geothermal projects – present significant petrophysical contrasts due to intense hydrothermal alteration, high fracture density and natural permeability with their background (Genter et al., 2000), their geophysical characterization should be refined by non-seismic methods especially using gravity.

In this paper, we present recent results obtained from new gravity data analysis combined with 3D geological modelling. These results are the continuity of those discussed in Abdelfettah et al., (2016). The results obtained from gravity analysis will be compared to the results obtained from borehole data in seven subareas located in the northern part.

The studied area is located in the northern of Alsace, from Haguenau to the French-German boundary in the north and east including Soultz-sous-Forêts and Rittershoffen geothermal plants. To the west, it is limited by the main border fault of the Rhine Graben basin (Fig. 1). In total, 1033 gravity measurements were used; among them 800 new measurements and 233 old ones, located mainly in the southern part of the study area (Fig. 1).

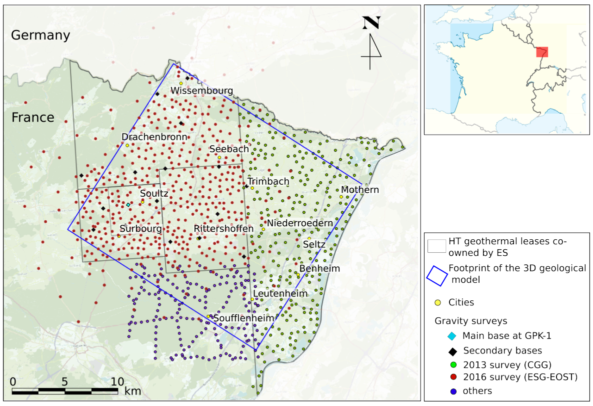


Figure 1: Study area showing gravity measurements and the lateral footprint of the geological model.

2. GEOLOGIAL MODELLING

During "EGS Alsace" and "ANR Cantare" French R&D programs, a 3D geological model covering approximately the same area than the gravity-studied area has been built based on reprocessed seismic data dating from the 80's (Maurer et al., 2016). Due to the parameters used at this time, with the objective highlighting tertiary layers potentially bearing oil, and scarce information of seismic velocities, this model had an average depth uncertainty of 30 m (reaching a maximum of 103 m) at the Jurassic - Trias interface, which was assessed by comparing the obtained depth after time-depth seismic conversion with the depth measured at boreholes. The first order faults as well as some major geological layers ("Schistes à poisson", Tertiary unconformity, top Trias, top Muschelkalk, and top Buntsandstein) have been mapped in 3D. The footprint of the geological model is shown in Figure 1 and its 3D views are shown in Figure 2. The 3D geological model was built by interpolating existing 2D seismic sections, constrained by borehole data located inside the study area.

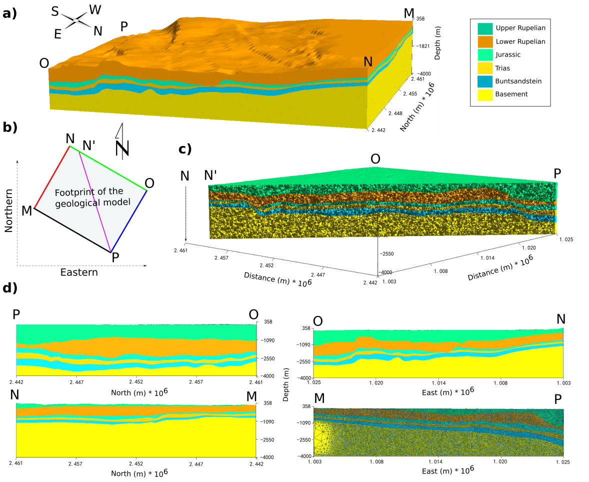


Figure 2: Geological model used in the quantitative and stripping studies. a) 3D view from NE, b) sketch of cross-sections shown in c and d. We show in (c) and the MP cross-section the used meshing.

3. OBSERVED AND COMPUTED BOUGUER ANOMALIES

A preprocessing step was performed on the observed data removing the bad measured data. It is the quality control step. Then, the data were processed and we get accurate Bouguer anomaly with average uncertainties of 0.02 mGal, which is an acceptable value for discussing about an "accurate" Bouguer anomaly (Fig. 3a).

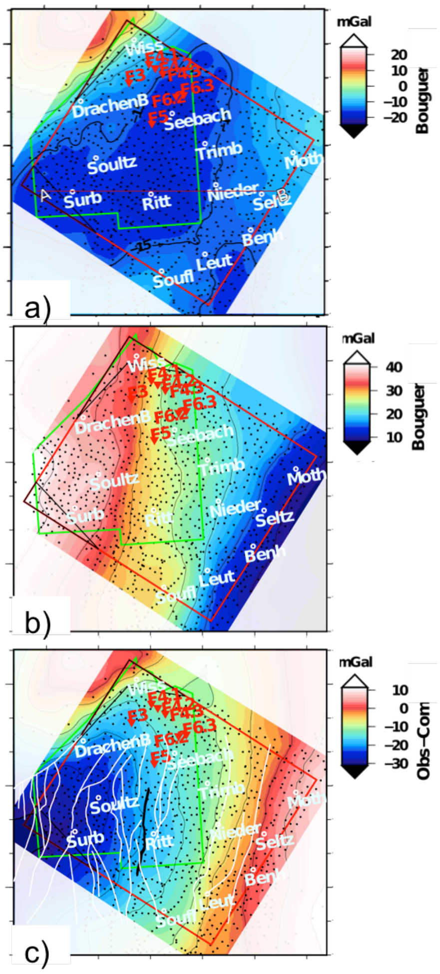


Figure 3: a) Observed Bouguer anomaly, b) computed Bouguer anomaly and c) discrepancy between observed and computed Bouguer anomalies. Note that the F3, F4.1, F4.2, F5, F6.1, F6.2 and F6.3 are thermal boreholes done by ESG (Maurer et al., 2018).

In order to compute the theoretical gravity effect of the modeled geological model, we took it and meshed it using finite element approach. We affected homogeneous density value for each geological unit and compute its gravity effect. The gravity measurements were located on the real topography and real coordinates (latitude, longitude) as observed points. The used density values are shown in Table 1, which represent the average values obtained from several sources. The computed Bouguer anomaly is shown in Fig. 3b.

In Figure 3c, we present the misfit or the discrepancy between the observed Bouguer anomaly and the computed one. It is computed by subtracting the theoretical value to the observed value for each measured point. It means that this misfit could be also interpreted in terms of negative and positive anomaly. The negative anomaly means that gravity attraction effect is overestimated and, on the contrary, for a positive anomaly this theoretical gravity effect should be increased. In this misfit (Fig. 3c), we can observe mainly that its dynamical range is greater than the dynamical range of both observed and computed Bouguer anomalies. Moreover, the entire area is not explained by the computation, where a maximum of misfit reaches -30 mGal in the western part of the area, which is a huge value. In the central part of the model, we reach also a huge misfit value between -10 and -20 mGal. We can understand that the density values used in the forward modeling are very far from the real densities.

Table 1. Density values assigned to the geological model used in the forward modeling. The names in brackets indicate the simplified name related to local geology used in the body of the paper.

Geological unit	Density (kg.m^{-3})
Plio-Quaternary and Serie-Grise (Upper Rupelian)	2100
Pechelbronn formation and Dolomitic Complex comprises Lower Rupelien, Priabonien and Bartonien (Lower Rupelian)	2250
Jurassic mainly Lias (Jurassic)	2470
Keuper and Muschelkalk (Trias)	2500
Buntsandstein (Buntsandstein)	2600
Basement (Basement)	2600

4. STRIPPING

In order to quantitatively understand the origin of the observed and computed anomalies, to better understand the misfit, but also to quantify the gravity effect of each geological unit and to understand the footprint of each of them on the total Bouguer anomaly, a stripping procedure was conducted. The idea behind the stripping is to compute the theoretical gravity effect from the geological model, and to subtract this effect from the observed Bouguer anomaly. We can do this for the whole model and we get the same results as the misfit shown in Figure 3c, but we can also achieve this for a specific geological unit (e.g. only for Jurassic), or several geological units as needed. Note that before this stripping, a qualitative study has been done by Abdelfettah et al., (2016) helping to understand the origin on each negative anomaly.

Additionally, sequential and cumulative stripping according to depth is very important to understand quantitatively the evolution of the anomalies according to depth. The principle of the sequential stripping is to strip geological units sequentially starting from the first layer, and then cumulate with the second one, and so on; for instance strip the Upper Rupelian firstly, then the Upper and the Lower Rupelian together until stripping the whole units of the model. The results obtained from the sequential stripping are shown in Figure 4.

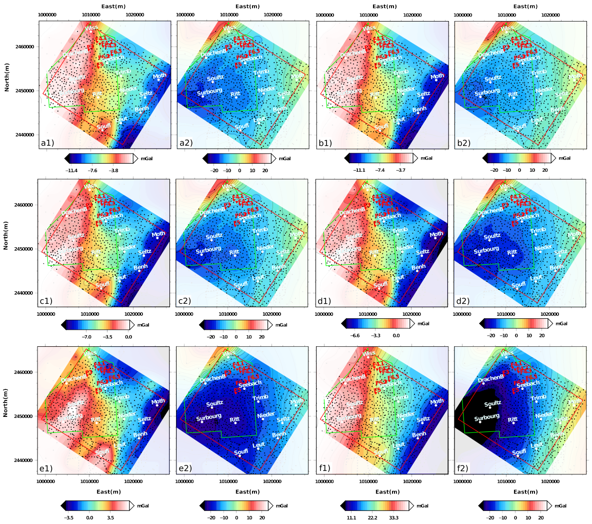


Figure 4: Cumulative stripping results. a1) shows the Upper Rupelian gravity effect and a2) shows the stripped Bouguer anomaly. b1) showed the cumulative gravity effect of the Upper and Lower Rupelian units and b2) shows the corresponding stripped Bouguer anomaly. c1) shows the cumulative gravity effect of the Upper and Lower Rupelian as well as the Jurassic units, and c2) shows the corresponding stripped Bouguer anomaly. d1) shows the cumulative gravity effect of Upper and Lower Rupelian, the Jurassic and the Triassic units, and d2) shows the corresponding stripped anomaly. e1) shows the stacked gravity effect of the Upper and Lower Rupelian, the Jurassic, the Triassic and the Buntsandstein units, and e2) shows the corresponding stripped anomaly. f1) shows the total gravity effect of the whole model and f2) shows the corresponding stripped Bouguer anomaly. The stripped anomalies shown in panels a2, b2, to f2 are directly compared to Bouguer anomaly shown in Figure 3a.

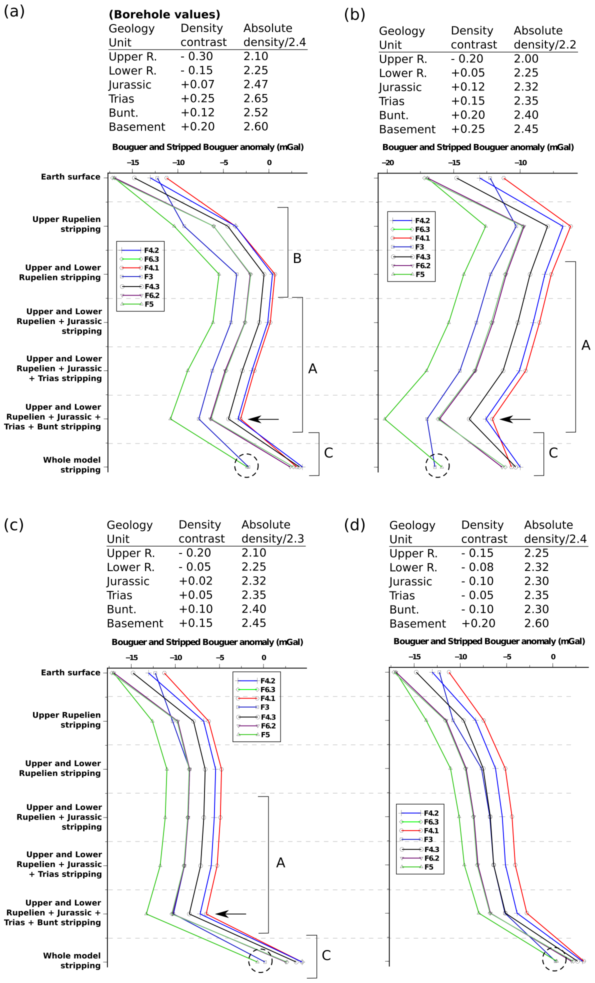
The stripped Bouguer anomaly after the Upper Rupelian stripping is significantly reduced by ~10 mGal, which means that both geometry and density of the geological model were well assessed (Fig. 4a2). The next step is the combination with the Lower Rupelian and the resulted stripped Bouguer anomaly is more reduced (Fig. 4b2). This is what we are expecting from the definition of the stripping itself.

From stripping of Jurassic, but mainly from Trias and Buntsandstein, the stripped Bouguer anomaly is not reduced and its negative amplitude increases (Figs. 4c2-e2). This behavior is also well observed in Figure 5a, which represents the same results as those shown in Figure 4 but we focus the analysis on the same location as the seven thermal boreholes located in the northern part of the studied area.

The stripping of gravity effect of the Upper and Lower Rupelian were done in the right (Fig. 5a), whereas the stripping of the effect of the Jurassic, but mainly the Triassic and the Buntsandstein were badly done. "Badly" means that the product of the thickness of the geological unit and its density value are not correctly chosen and consequently the resulted (stripped) anomalies do not reflect the observed data. As geometries of the geological structures modeled and used in the modeling are well constrained, our interrogation is then around the chosen density values. From that observation, we decide to change the density contrasts according to the reference density in order to improve the stripping results.

We performed the first density test using borehole values (Fig. 5a). These density values were measured in GRT-1 geothermal borehole done in 2012 at Rittershoffen, except for the Upper Rupelian and the upper part of the Lower Rupelian where average values were taken, because there are no available well logging data. What we can observe from the stripping curves is that the stripping evolution curves can be subdivided into three parts: 1) the part (B) where the stripped effect seems overestimated, because the stripped values reach 0 only after removing the Upper and the Lower Rupelian formation. 2) the part (A) where the obtained stripped values are smaller than those obtained before. This means that the used density contrast (here positive) should be reversed and then negative contrast should be used to take into account the gravity effect of the Jurassic, the Trias and the Buntsandstein units and 3) the last part (C) is the part where the obtained stripped values are relatively close to zero, and so the effect of the basement is well assessed.

Two other density tests were conducted and shown in Figs. 5b and 5c, which aimed to test the used reference density. We used the same density values; except for the Upper Rupelian where it was increased by 100 kg. m^{-3} in Fig. 5c to keep the density contrast to 200 kg. m^{-3}. We can observe that for both tests, the stripped values for the Upper and Lower Rupelian (only the Upper Rupelian in Fig. 5b) were indeed reduced compared to the Bouguer anomaly, which are represented in values at the earth's surface. The part (A) for both tests (Figs. 5b and 5c) shows that the density contrast should be inverted and then negative density contrasts should be considered. The part (C) shows that the stripped values obtained in Fig. 5c are correct whereas those obtained in Fig. 5b remain unsatisfied. This means that the used density contrast is correct in sign, i.e. it should be positive indeed, but it could be higher. We should before change the density of the upper structures (mainly Jurassic, Trias and Buntsandstein) and then for lower part (i.e. Basement). Doing this, we are sure that our approach will converge to reduce the observed Bouguer anomaly and the sense of gravity accumulation will be preserved.



(a) **(Borehole values)**

Geology Unit	Density contrast	Absolute density/2.4
Upper R.	- 0.30	2.10
Lower R.	- 0.15	2.25
Jurassic	+0.07	2.47
Trias	+0.25	2.65
Bunt.	+0.12	2.52
Basement	+0.20	2.60

(b)

Geology Unit	Density contrast	Absolute density/2.2
Upper R.	- 0.20	2.00
Lower R.	+0.05	2.25
Jurassic	+0.12	2.32
Trias	+0.15	2.35
Bunt.	+0.20	2.40
Basement	+0.25	2.45

(c)

Geology Unit	Density contrast	Absolute density/2.3
Upper R.	- 0.20	2.10
Lower R.	- 0.05	2.25
Jurassic	+0.02	2.32
Trias	+0.05	2.35
Bunt.	+0.10	2.40
Basement	+0.15	2.45

(d)

Geology Unit	Density contrast	Absolute density/2.4
Upper R.	- 0.15	2.25
Lower R.	- 0.08	2.32
Jurassic	- 0.10	2.30
Trias	- 0.05	2.35
Bunt.	- 0.10	2.30
Basement	+0.20	2.60

Figure 5: Stripped gravity anomalies according to depth/thickness extracted at the same location of the seven gradient boreholes (Maurer et al., 2018). These curves were obtained for several density values; a) using borehole values obtained in GRT-1 geothermal borehole, b) and c) using average density values according to different density reference and d) improved borehole density values aimed to reduce the stripped values to reach at the end a minimum value around zero.

The stripped curves recovered in Fig. 5d showed clearly that from surface up to the top of the Basement, the density contrast should be negative rather than positive. Three (relatively) important negative density contrasts were identified; 1) for the Upper Rupelian with its -150 kg.m^{-3}, this negative density contrast is well observed in all tests but also in sampling measurements and previous works (e.g. Baillieux et al., 2014 and references therein). This negative density contrast can be considered as realistic and then its gravity effect is well recovered. 2) The second observed negative density contrast of -100 kg.m^{-3} is recovered at the Jurassic formation. Negative density contrast is also observed in the borehole data between Jurassic and Trias, which is the inverse behavior observed here using stripping (Fig. 5a and 5d). 3) The third negative density contrast of -100 kg.m^{-3} is located at the Buntsandstein formation. This behavior is observed in the totality of the tests done (see arrows in Fig. 5), which stipulates negative density contrast to reduce the Bouguer anomaly, otherwise the resulted stripped anomaly becomes even more negative.

5. GRAVITY VERSUS THERMAL GRADIENT

The temperature profiles performed in the deep geothermal wells drilled in the Upper Rhine Graben (Fig. 6), and in particular in Northern Alsace, show a linear temperature curve in the sedimentary cover down to the top of the Muschelkalk formations, i.e. Trias. Below this depth, the gradient decreases sharply, indicating the transition from a conductive gradient in the upper part of the formation, to a convective reservoir below. The top of the Muschelkalk is defined as the Cap-Rock of the convection loop of the geothermal brine which induces an important geothermal gradient up to 10°C/100 m in this region. From this observation, a new exploration method emerged, which consists in drilling shallow wells in the sedimentary part of the graben to measure a temperature profile calculating the gradient in the sedimentary cover and extrapolating the temperature at the Cap Rock and in the geothermal reservoir. This method of exploration was found to be relevant because of its valuable contribution to the estimation of the temperatures at the geothermal target.

A comparative analysis of all investigated zones shows strong heterogeneities in the measured thermal gradients values from one zone to the other. The gradients range from 6.3 ° C / 100 m to 7.6 ° C / 100 m. The analysis of the thermal values obtained from the gradient boreholes shows mainly that the wells F3 and F5 exhibit an important gradient compared to the others (Maurer et al., 2018). Interestingly, the gravity values show, for the same wells, residual negative values even after stripping (see dashed circle in Figure 5). This interesting feature was obtained in the four examples shown in Figure 5 but also in other similar examples, which are not shown here. It means that independently to the used density values, these two wells show lower density in the lower part of the sediments, mainly at Triassic and Buntsandstein formations. The decrease in the density values could arise from rock heterogeneity, mainly in the Basement, as revealed by magnetic data analysis (Edel and Fluck, 1989) or by the presence of a highly fractured geothermal area with a water/rock ratio large enough to significantly decrease the bulk density, as shown in Figure 3c where a large mismatch between the observed and computed Bouguer anomalies is located mainly in the area of high fracture/fault density.

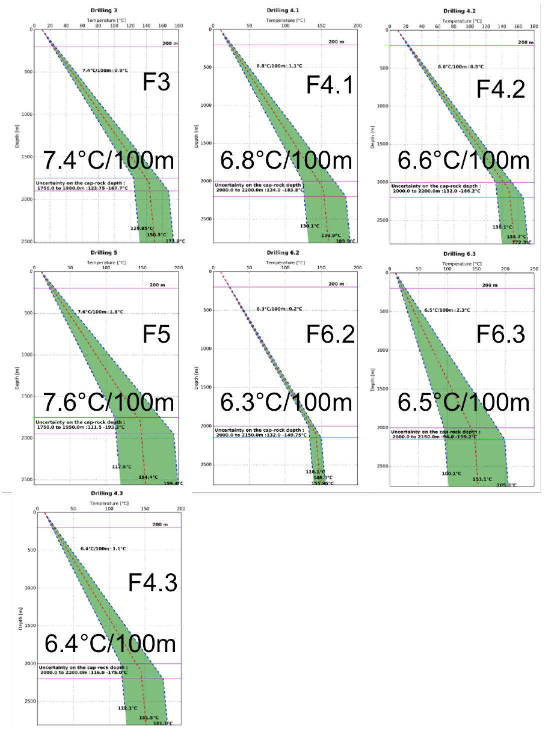


Figure 6: Results obtained from thermal gradient data analysis as discussed in Maurer et al., (2018). The red dashed lines are the median of the best and worst cases (blue dashed lines).

3. CONCLUSIONS

New gravity data acquired in northern Alsace were presented and the Bouguer anomaly was obtained using a new data processing approach which shows small data uncertainties (< 0.06 mGal) compared to the older Bouguer anomaly.

A quantitative study based on the high accurate 3D forward modeling using finite element approach, and a 3D geological model derived from vintage seismics was done and the results, namely the computed Bouguer anomaly, showed high discrepancy with the observed anomaly. The computed misfit between the observed Bouguer anomaly and the computed one reveals areas having low-density values. This density decreases could be explained either by variation of petrography within the basement and/or from highly fractured zones associated with geothermal fluid affecting the bulk density values around the known geothermal sites of Soultz and Rittershoffen.

The interpretation of the resulting stripped Bouguer anomaly showed that the density values of the Jurassic but especially the Triassic and Buntsandstein were overestimated using the density values measured in GRT-1 borehole. It means that the borehole density values do not reflect the density variations, which occur in large scale especially around geothermal zones having high fracture-related porosity effect.

The stripping approach revealed that the lower part of the sediment, mainly the Triassic and Buntsandstein, present a negative density contrast, which is not necessary expected mainly from borehole measurements. Interestingly, correlation is found between the gravity analyses and the gradient boreholes done in the same area. Under boreholes F3 and F5, gravity interpretation suggests huge density decreases in the Buntsandstein, probably also in the upper part of the Basement, which may arise from high density fracturing and important geothermal water affected significantly the bulk density. The analysis of the thermal borehole data suggests also that this two boreholes show a higher geothermal potential compared to the other boreholes.

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Acknowledgements

This work was done in the framework of the EGS Alsace project cofunded by ADEME, Electricité de Strasbourg and University of Strasbourg. This work was partly cofund by ANR under the grant agreement ANR-15- CE06-0014 (Project CANTARE-Alsace). This work, mainly interpretation and writing of the paper, is financed by Geophimage geophysical company. Thanks to Dr. Paul Baillieux for fruitful discussion and for providing us the fault locations.