Using gravity in geothermal exploration: the case study of Wissembourg area, northern Alsace (France)

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ABSTRACT

We applied the concept of gravity pseudo-tomography on the existing data to the northern part of Alsace (France). The approach consists of applying a filtering of the Bouguer anomaly using different wavelengths. Each pseudo-tomography provides complementary information to the others. The obtained results revealed the presence of three important negative anomalies, two of them seem local around Rittershoffen and Seebach and the third one seems elongated from the west side of Soultz and Surbourg northward. The obtained residual anomalies were compared with new magnetotellurics results along an E-W profile crossing the Rittershoffen EGS project. Good correlation was obtained between both results. The negative gravity anomaly beneath GRT1-2, the two geothermal boreholes, corresponds well to the very conductive zone revealed by magnetotelluric.

1. INTRODUCTION

Gravity is usually used to investigate underground mass distribution according to density contrasts. It can be used at different steps for any project: i) alone: mainly qualitative approach to delineate possible negative anomalies which may be caused by fracture occurrences and/or water saturated rock, for instance ii) in conjunction with other geophysical methods (e.g. seismic, magnetotelluric, magnetic, etc) to achieve quantitative interpretation.

Gravity has been early used in geophysical exploration mainly for structural imaging problem (e.g. Guglielmetti et al., 2013) either in the area where seismics do not success, caused by basaltic or salt screen for instance, or for improving the pseudo-final geological model build using other techniques as seismic (e.g. Abdelfettah et al., 2014) or magnetolluric (e.g. Abdelfettah et al., 2016b) methods. It is also used in oil and gas exploration (Cevallos. et al., 2013) to get 3 or 4D images of reservoir modifications (e.g. Hare et al., 1999).

In geothermal application, gravity was also used for many objectives such as to delineate deep basins for instance where thermal conditions (permeability, water flow, etc…) are higher. It was also used to assess the fracture porosity in the weakness zones (Altwegg et al., 2015), where heated water flow should move. Gravity method has also been used in geothermal monitoring (e.g. Hinderer et al., 2015).

Our studied area is located at the Upper Rhine Graben (URG), in northern Alsace (France). Geologically speaking, the URG is mainly formed by a thick sediments materials (Cenozoic and Mesozoic) deposited in Triassic (mainly the Buntsandstein, Muschelkalk and Keuper) and Jurassic (named Lias and Dogger), below the Tertiary sediments. In some place, Permocarboniferious (Carboniferous and Permian) could be also crossed but not continuously and not everywhere (see e.g. Abdelfettah et al., 2014). The thickness of these sediments "package" vary and increase from west to east (Baillieux et al., 2011 and references therein). Below these sediments is the Palaeozoic basement. Its depth increases eastward according to the sediments increasing thickness.

In this study, we apply the developed pseudo-tomography concept (Abdelfettah et al., 2014) for the existing gravity data in order to delimit small zones where geothermal conditions could be favourable. As the whole area is about 240 km^2, it is obvious that smaller zones should be delimited to perform more detailed underground investigations. The existing gravity data is provided by BRGM database (Fig. 1).

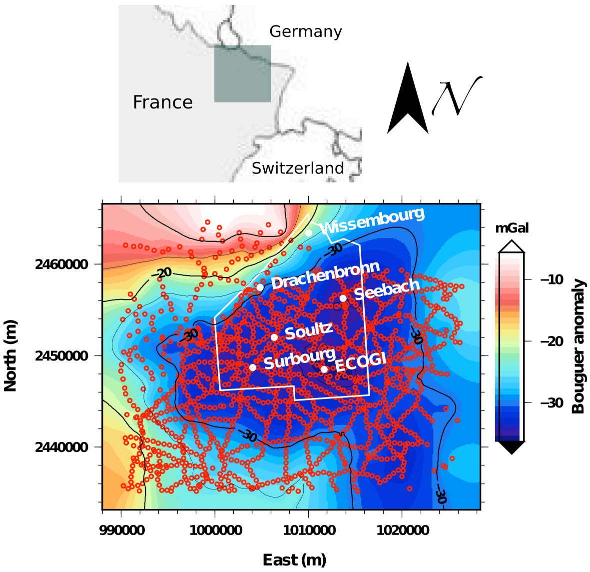

Figure 1: Location of studied area (top) and the whole gravity data used (red circle in bottom panel) to achieve this study. A total of 1312 gravity points have been used. The X- and Y-coordinates are in Lambert II Etendue system.

2. THE PSEUDO-TOMOGRAPHY CONCEPT

The idea behind is to avoid using only one residual anomaly where all gravity effects are there. It means that several residual anomalies will be provided by the pseudo-tomography (PT) approach. Using such concept, we can follow the progression of anomalies and delineate them according to horizontal extension but also with depth, throughout series of images built with continuously increment of the wavelength.

Several synthetic studies have been done to better understand the behaviour or the response of such a filter (see e.g. Abdelfettah et al., 2014, and references therein). Successful applications on real data have been also conducted to delineate deep Permo-carboniferious basins Swiss Molasse (Abdelfettah et al., 2014). In the URG area, the PT concept has been used to understand the distribution of the thermal anomalies where a correlation between gravity residuals and thermal anomalies has been established (Baillieux et al., 2014).

The principle of the PT technique is to use high- and band-pass Butterworth filters with progressively increasing wavelength. Basically, we construct two different but complementary PT images. The objective of the 1st one is to highlight the shallower gravity effects which may arise from filling sediments in the shallower part. The 2nd one is more focused on deep structures and anomalies, which are interesting for geothermal purposes. For instance, the high pass filter using wavelength < 15 km (i.e. 5, 10 and 15 km) will reveal more the sedimentary filling, whereas the band-pass filter of 10-30, 10-60 and so on will reveal more the deeper part.

3. RESULTS AND DISCUSSION

From the 1312 available gravity measurements (Fig. 1), only 453 points are inside the studied area delimited by the white polygon of Fig. 1. It means that the reminder measurements, i.e. 859 points, are used only to constraint the regional variation and therefore constraint our PT. In figure 2a, we showed a complete Bouguer anomaly of the studied area. We can notice however the lack of gravity data at the northern part of the area. This Bouguer anomaly is dominated by NW-SE trend which should be removed before interpretation. In Fig. 2b, we show the 1st residual anomaly obtained with high pass filter using wavelength cut of 5 km. Although the low-density distribution of the gravity measurements (i.e. great interstation), we can mainly observe the orientation of the filling basins which is in the northwest.

In fig. 3, we showed the 1st pseudo-tomography results. It was obtained using a successive high-pass filter using following wavelength: 10, 15, 20, 30, 40 and 50 km. With this methodology, we emphasis the structures/anomalies according to depth, for instance the negative anomaly at the western part (immediately West of the villages of Soultz-sous-Forêts and Surbourg) and eastern part of the studied area (beneath the village of Seebach). A negative anomaly is also observed at Rittershoffen, beneath the EGS project (Figs. 3c-f). These residuals (Fig. 3) contain all gravity effects from surface to much deeper structures. The 2nd pseudo-tomography (Fig. 4) shows only the deep anomalies, because the very shallower effect has been removed, or strongly reduced.

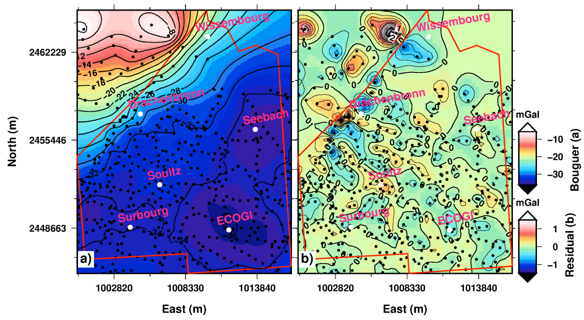

Figure 2: a) Complete Bouguer anomaly inside the studied area. b) Residual anomaly obtained by high-pass filter using wavelength cut of 5 km.

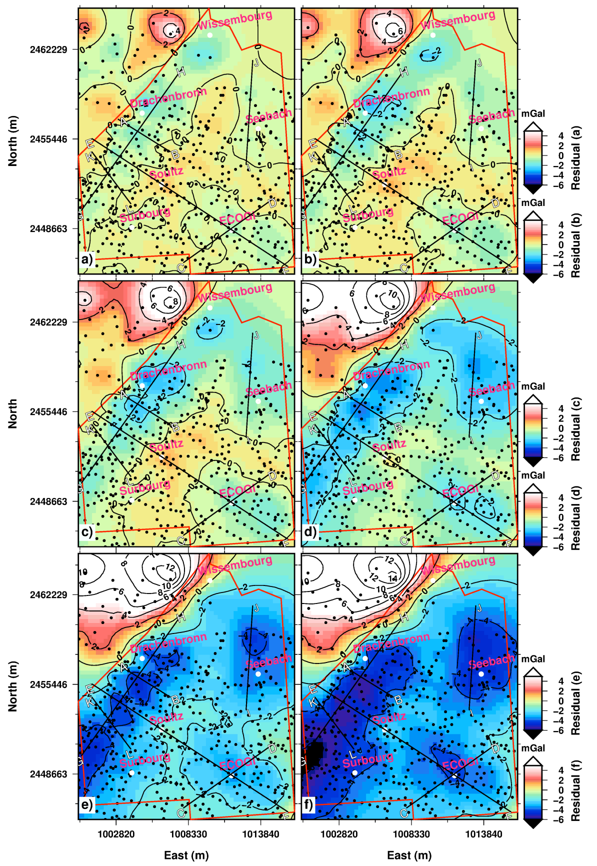

Figure 3: First pseudo-tomography obtained using high-pass filter having wavelength cut-off of a) 10, b) 15, c) 20, d) 30, e) 40 and f) 50 km.

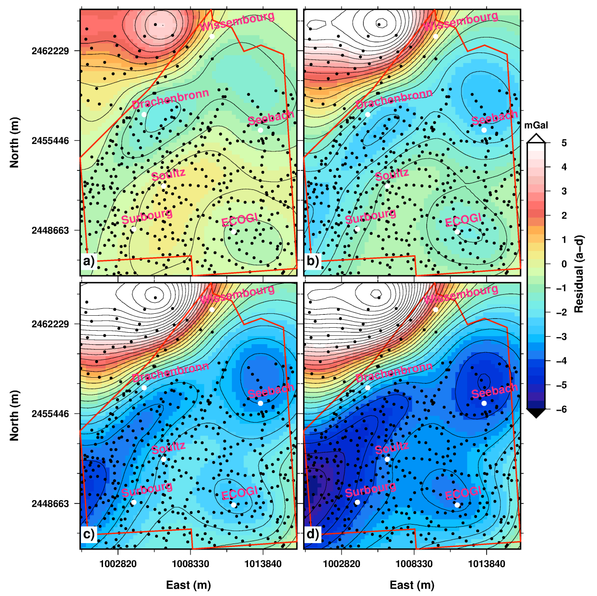

Figure 4: Second pseudo-tomography obtained using band-pass filter of a) 10-20, b) 10-30, c) 10-40 and d) 10-50 km.

Figure 4 shows the deeper negative anomalies, which are mainly at three locations; i) centred at Seebach, ii) elongated SW-NE anomaly limited from east by Surbourg and Soultz, and from west by Drachenbronn, and iii) centred at the Rittershoffen EGS project. This 3rd anomaly seems smaller in terms of amplitude compared to the two previous ones.

A very interesting feature can be observed when comparing the gravity PT response between Soultz-sous-Forêts and Rittershoffen, both being successful geothermal projects. At Soultz-sous-Forêts, the PT revealed positive anomaly whereas at Rittershoffen it revealed negative anomaly (Figs. 3-4). This negative anomaly is observed at many residuals and from rather small wavelength for instance from 20 and 30 km high passes (Figs. 3c-f). It means that its origin is rather shallow (i.e. in the sedimentary layers). Nevertheless, this anomaly remains in different other residuals especially at great wavelength, for instance those obtained in the second PT (Fig. 4). It suggests that this negative anomaly beneath Rittershoffen could be the superposition of two effects; one shallower (Figs. 3a-c) and one deeper (Figs. 3d-f and Figs. 4a-d). At Soultz, the positive anomaly persists from surface (Fig. 2b and Figs.3a-c) to deeper (Figs. 3d-f and Figs. 4a-b).

In some situation, profile representation can help to better understand anomaly variations than maps. To do that, we extracted 2D profiles from 3D pseudo-tomography results discussed previously and partly showed in Figs. 3-4.

Figure 5 shows the extracted 2D profiles. Many information are highlighted by these curves, mainly the locations of supposed deep border faults and the gravity effects arose from different depth.

Qualitatively speaking, Soultz and Rittershoffen (Fig. 5) seem to belong to different geological system especially at mid-depth level, i.e. from surface down up to ~2 – 3 km. Nevertheless and to be certain, quantitative study should be done on the basis of a geological model.

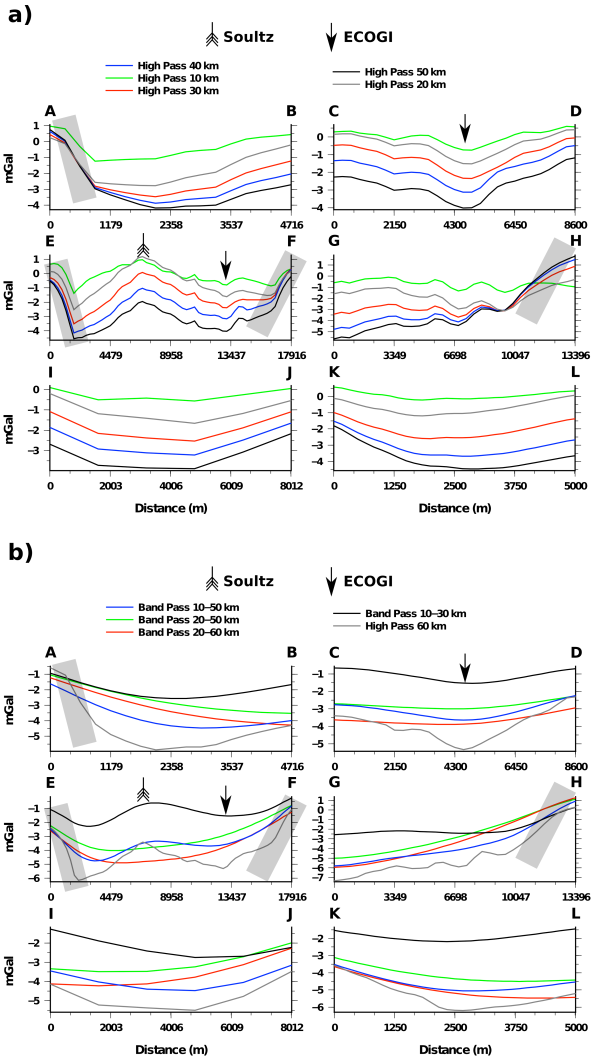

Figure 5: 2D profiles extracted from the 1st pseudo-tomography (a) and 2nd PT (b) showed in Figs. 3-4. Locations of these profiles are showed in Fig. 3. The grey areas showed the supposed location of border faults where important horizontal density contrast could be find.

In the south of the studied area, and crossing ECOGI geothermal project, we had the chance to acquire new magnetotelluric (MT) data along an E-W profile (Abdelfettah, et al., 2016a). The objective of MT study is to try to delineate vertical and lateral extension of the geothermal reservoir beneath GRT1-2, the two geothermal boreholes. As the electrical conductivity of a geothermal reservoir is always higher than the background, MT technique could provide a clear underground image under ECOGI project. As we can see on Fig. 6c, MT data show at depth a limited area where electrical resistivity is very low (< 1 Ω.m). The top of this conductivity anomaly is assessed at 2.2 km deep (Abdelfettah et al., 2016a). It means that the geothermal reservoir beneath ECOGI may be located at this depth.

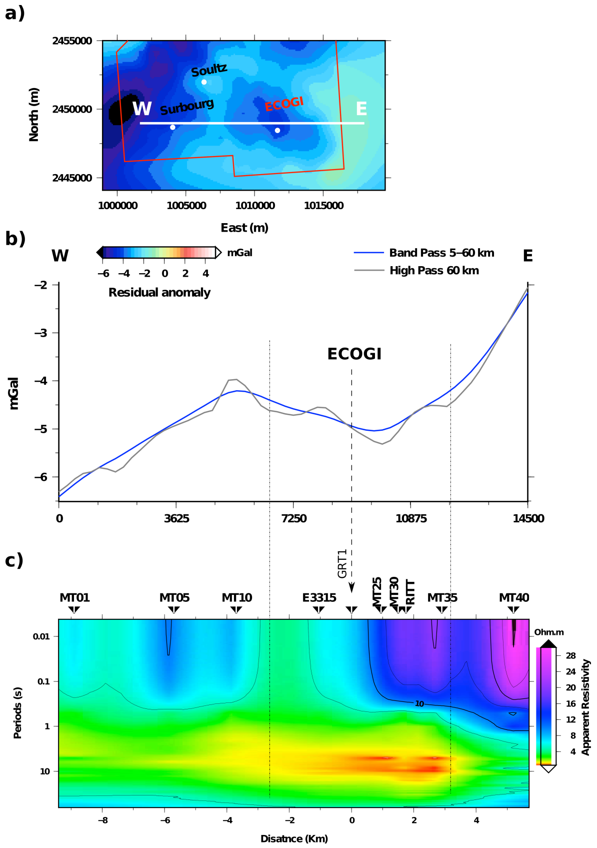

Figure 6: a) Residual anomaly around ECOGI geothermal project extracted from PT showed in Figs. 3-4. b) 2D cross-section extracted from 3D residual anomaly showed in party in (a). c) Magnetotelluric pseudo-section obtained in the same profile crossing GRT1. The location of MT and gravity profiles is showed by white line in (a).

The residual anomalies showed in Fig. 6b reveal also a negative anomaly beneath GRT1-2. It is furthermore well correlated with the same conductivity anomaly (Fig. 6c). As the hydrothermal reservoir is frequently full of faults and fractures, which are in turn filled with geothermal water, its bulk density decreases in comparison with the background. Consequently, the expected gravity anomaly above the geothermal reservoir is rather negative. It means that the origin of this negative anomaly therefore could be the same than that observed by MT data.

The comparison between the MT and gravity response on the same profile as done on ECOGI area, showed us that there could be a better geothermal potential on the negative anomalies rather than on the positive ones. Consequently, the three major negative anomalies revealed by the PT analysis (Figs. 3-5) could be interesting zones for forward geothermal projects. However, a more detailed study should be achieved to better understand the origin of the observed negative anomalies.

As said above, quantitative study should be conducted on the basis of the existing geological model or by constrained the forward modelling, to be certain about the origin of the observed anomalies. Additionally, the gravity measures are quite widely spread and especially in the North. Indeed the northern part of the studied area was not constrained by data because of the lack of data. In this way, a new gravity fieldwork is planned to acquire new measurements. The objective is to get accurate data, because the used one are old and their uncertainty could reach in some point one mGal. The northern part will be also covered by new data until the German border. Furthermore, it is planned to densify the measurements and therefore reduce the interstation to an average distance of 500 m.

3. CONCLUSIONS

Reinterpretation of existing gravity data in the northern Alsace has been achieved using the concept of pseudo-tomography. The obtained results revealed the existing of three negative anomalies; one is centred at Rittershoffen and the second one at Seebach, the third one seem rather elongated from SW to NE, and located between Surbourg and Soultz to the east and Drachenbronn to the west. These anomalies could be a potential target for future deep geothermal projects. The comparison of magnetotellurics and gravity data reveals that the origin of these negative gravity anomalies could be deep; the top could be located around 2 – 2.5 km. Quantitative study on the basis of an existing geological model is planned in the near future to study in details the origin of the observed negative anomalies.

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