RESISTIVITY IMAGE UNDER GRT1-2 GEOTHERMAL DOUBLET OF THE RITTERSHOFFEN EGS PROJECT AS REVEALED BY MAGNETOTELLURIC

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ABSTRACT

We present the underground resistivity under Rittershoffen geothermal project (Alsace, France) as recovered by magnetotelluric data inversion. In the total, 10 MT acquisitions were recorded according to E-W profile crossing GRT1-2, the doublet of the Rittershoffen geothermal project. The recovered underground conductivity distribution by 2D inversion showed high conductivity anomaly beneath GRT-1 borehole, corresponding to the geothermal reservoir. The electrical conductivity variation doesn't follow the main geological units and particularly the basement-sediment interfaces. A good correlation is also obtained between conductivity anomaly located at Rittershoffen and the thermal anomaly obtained from borehole measurements. These two results are also correlated with gravity anomaly and specifically with the horizontal gravity gradient analysed from south.

1. INTRODUCTION

Magnetotelluric (MT) is becoming more and more used as a geophysical imaging technique, and more specifically in the field of geothermal exploration. Because it provides an electrical conductivity which is linked to rocks and pore water properties, but also with temperature. As the conductivity contrast between geothermal reservoir and background is generally important (easily more than five times), the efficiency of the MT method increases substantially.

Several MT works were achieved in order to get underground imaging in different geological context (e.g. Abdelfettah et al., 2016a and references therein), applied to different geothermal areas (e.g. Wannamaker et al 2004; Harinarayana et al 2006), in geothermal field of the Rhine Graben area around Soultz-sous-Forêts (e.g. Geiermann and Schill 2010; Abdelfettah et al., 2016b) and in monitoring of geothermal reservoirs (e.g. Peacock et al., 2012; Abdelfettah et al., 2018).

Our study is conducted in the Upper Rhine Graben (URG) around Rittershoffen village and crosses GRT1-2 geothermal boreholes, which constitute the geothermal doublet of the EGS Rittershoffen geothermal project (Baujard et al., 2017). The objective of this study is to delineate the geothermal reservoir using MT method and mainly characterize the fractured zone where electrical conductivity increases, for instance the sediment-basement interface. Furthermore, we have the possibly to compare with other results, mainly gravity study (e.g. Abdelfettah et al., 2016c) and thermal (Baillieux et al., 2014) results. Besides, one major challenge using MT method in this area, is to deal with the high level of the anthropogenic noise which affects considerably the electromagnetic data.

Geologically speaking, this part of the URG is formed by a thick layers of sediments (Cenozoic & Mesozoic) deposited from Permo-Triassic (mainly the Buntsandstein, Muschelkalk and Keuper) and Jurassic (named Lias and Dogger). In some places, Permo-Carbonifereous units are found but not continuously and not everywhere (see e.g. Abdelfettah et al., 2014). The thickness of these sediments varies and increases from West to East (Baillieux et al., 2011 and references therein). Below the sediments, we reach the Paleozoic basement, which shown eastward depth increases according to the sediments increasing thickness.

2. MT DATA ACQUISITION AND PROCESSING

The data were acquired around Rittershoffen area crossing geothermal project (Fig. 1). The theoretical MT sites were in the E-W profile passing through GRT-1 borehole. Nevertheless, as the profile cross several villages (e.g. Betschdorf, Surbourg, and so on), it was not possible to keet all the sites on a perfectly linear E-W profile. Consequently, somesite locations were slightly shifted to the north and to the south to avoid these villages, and the associated anthropogenic noise.

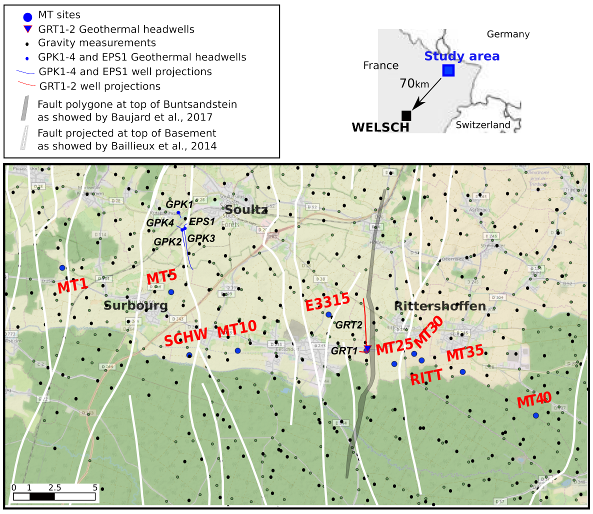

Figure 1: Geographical map showing MT sites location. For indication, deep geothermal wells of Soultz-sous-Forêts and Rittershoffen are shown, as well as the fault target of Rittershoffen project.

Doing MT measurement in such semi-urban environment is more challenging because a presence of a lot of anthropogenic electromagnetic noise. Because MT is a passive electromagnetic method which relies on natural non-stationary unpredictable events, it was decided to acquire time series continuously during at least three days in each site; this ensures to record usable long periods events and identify potential geothermal activity at 2-3 km depth close to GRT-1 borehole. We decide to record continuously the time series using 512 Hz of sample frequency and record, at least, three continuous days of each site. Remote reference site was also used located at Welschbrug Geophysical Station at ~70 km southwest of the studied area (Fig. 1). Same frequency sampling was used as local site and the stations were synced.

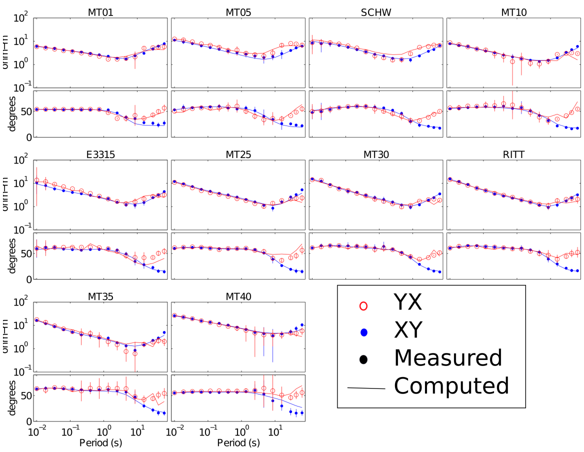

Figure 2: Observed and computed apparent resistivity and phase according to periods.

After data filtering, mainly railway noise at 50/3 Hz, power line at 50 Hz and their harmonics, after data checking we used Chave's code (Chave and Thomson 2004) computing the MT-impedance tensor, which is based on robust statistics and bounded influence to assess the impedance tensor. We recovered an impedance tensor with reasonable data uncertainty from what the reliable apparent resistivity and phase were estimated (Fig. 2).

We can also represent the apparent resistivity and phase variations by a pseudo-sections plot, where MT sites are plotted in the X-axis and the frequencies or periods plotted in Y-axis. As the frequency is directly related to the investigated depth, this plot showed the apparent resistivity variation according to apparent depth (Fig. 3). Such a pseudo-section is comparable to the seismic section before migration where the velocities are showed according to the well-known TWTT parameter (Two Way Travel Time) instead of depth.

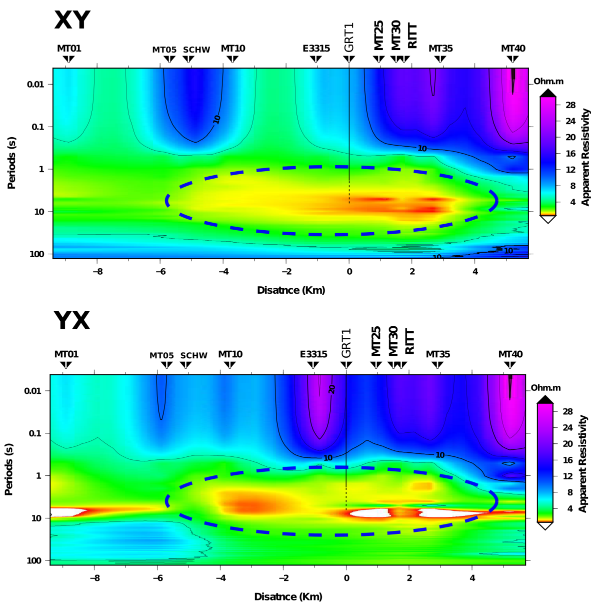

Figure 3: Pseudosection of the apparent resistivity for both TE and TM modes. Qualitative depth of GRT-1 is also showed.

Different features have been revealed by these pseudo-sections representation (Fig. 3). From surface, i.e. from 250 Hz down up to 0.1 – 1 s (1 s at the eastern part), the model shows for the two modes relatively resistive area, having mean values around 20 Ω.m. Downward to 50 s, we obtained fairly conductive area with mean values of ~3 – 4 Ω.m. This is mainly true for XY mode, but down to 10 s periods only for YX component especially at the eastern part of the model, for instance below the sites MT1 and MT5 (Fig. 3b), where resistivity is much higher compared to those observed at the shallower part.

The very interesting feature nevertheless is the very conductive (< 1 Ω.m) area observed directly under GRT-1 borehole (see dashed circle on Fig. 3). This conductive anomaly is more homogeneous in XY component whereas in the YX component it showed more heterogeneous values. Note that this anomaly seems confined and horizontally limited from MT10 site at the west to mid-distance between MT35 and MT40 from east.

3. UNDERGROUND CONDUCTIVITY RECONSTRUCTION

Once the apparent resistivity and phase values have been estimated, they can be used to compute the underground electrical conductivity variations under the sites. We can use both forward modelling and inversion to reach our objective. Both of them shows advantages and disadvantages: for instance to achieve forward modelling we need to know a priori geological model and the resistivity values of its geological units, and the advantage is that we don't care about a geology and its resistivities by the study will focus on its magnetotelluric response and a probable additional model effects. The inversion however provides non-unique solution, which is directly related to a dimensionality assumption, but can provide a resistivity model where no geological information is available. Our survey was performed along an ~E-W profile, so a 3D inversion is not suitable, but the profile being almost perpendicular to the main faults and 2D approach seems reasonable. The best approach depends on the objective of the study and surely their combination with the geological information could provide additional information.

In our 2D inversion, we used MARE2DEM code (Key, 2012), which use finite element approach in model meshing. This approach is allowing fine mesh in the area of high topography gradient, either at the surface (i.e. real topography) or in the underground (to describe the real geology which can be use) mainly in the forward modelling. In our inversion layout, we used the real topography of the studied area, which was also extended outside this area by 100 km to the east and to the west. This extension is important to take into account the topography variation of the surrounding area, mainly the Vosges Mountains but also to preserve the limit conditions.

We performed three different 2D inversions as shown in Fig. 4. The idea behind these inversions is to do a sensitivity analysis of the initial model and quantifying the footprint of the priori information given to the inversion. In the 1st inversion, we invert only the MT data for joint TE and TM modes. This inversion was done without priori geological information and the start model is a homogeneous model of 100 Ω.m. The 2nd inversion performed started with predefined geological model as a priori information. This initial model provided from vibroseismics data interpretation. In the inversion, we added a geometrical penalty, which means that the inversion is allowed only to change resistivity values inside the same geological unit but not crossing them. The resistivity values for this priori model were set arbitrary decreasing from surface downward until the sediment-basement limit and set to 100 Ω.m for the basement (Fig. 4b). The 3rd inversion performed started from priori model having only the topography of the basement. The idea is to take into account sediments cover with homogeneous resistivity of 10 Ω.m and homogeneous resistivity of 100 Ω.m for the basement. Note that this inversion was run without geometrical penalty. It means that the sensitivity of the prior model is only the meshing located in the sediments-basement limit.

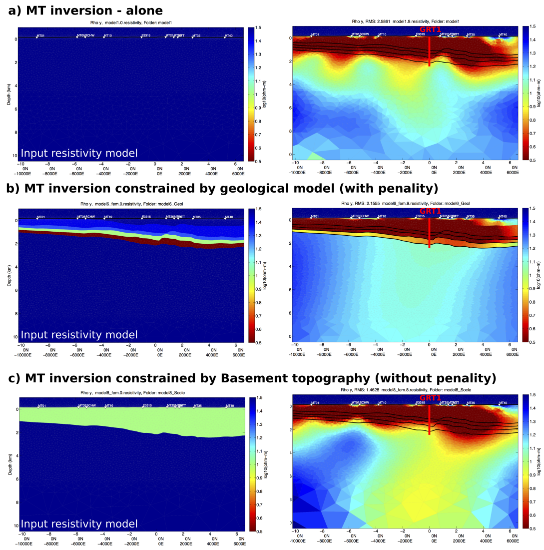

Figure 4: 2D inversion results using both TE and TM modes shown in right and starting resistivity models shown in left; a) MT data inversion alone. b) inversion constrained by geological model with geometrical penalty. c) inversion constrained by basement topography without a penalty.

4. RESULTS DISCUSSION

The recovered resistivity models from the performed inversions explain accurately the observed data (Fig. 2). The final misfits of these models are 2.58, 2.15 and 1.46 resulted from the 1st, 2nd and the 3rd inversion, respectively.

Several features can be observed from these resulted resistivity models, some of them are correlated and some of them are different. These three resistivity models: 1) agree that an important conductivity anomaly should be located beneath GRT-1 borehole to explain the data. This thick conductivity anomaly could start from the Buntsandstein reaching the depth of > 8 km in the basement and shows conductivity > 0.1 s.m^{-1}. 2) They agree also that the basement shows more resistive value around 100-150 Ω.m outside of this conductive anomaly. 3) The models agree also that the sediments cover, i.e. from surface until the bottom of the Buntsandstein (top of Buntsandstein in inversion 3) are very conductive showing resistivity < 1 Ω.m. 4) They also agree that some horizontal fluctuations could be there, mainly between MT1 and MT5, and under site MT10 eastward. Either in inversion 2, resistivity variation can be observed inside the Buntsandstein formation. 5) These results agree also that eastward of site

MT40, could be find a resistivity anomaly either within the sediments. But as there was no MT site east of MT40, it is not possible to accurately interpret this feature.

In parallel, these resistivity models showed different features mainly 1) the maximum depth of the conductive anomaly located beneath GRT-1. For inversion 1, it could be located at 8 km, and for inversion 2 and 3 stipulate maximum depth > 10 km. 2) The conductivity fluctuations located at the bottom the sediments continuous ~2 km in the basement in the case of inversion 1 and less than 1 km in the case of inversion 3. 3) The inversion 1 showed a resistive basement in the eastern part of the model located at depth of 4-5 km, whereas in the inversion 3, it is located only at 2 km depth under sites MT5 and SCHW. For this point, inversions 2 and 3 are agreeing on that resistive feature.

Correlation with gravity and thermal data

In the same studied area, several other works have been done using other kind of data. Very interesting correlation can be observed between resistivity model and gravity anomaly acquired on the same profile (Fig. 5). The conductivity anomaly beneath GRT-1 matches with the negative anomaly whereas the positive anomaly matches with the resistive anomaly located in the basement.

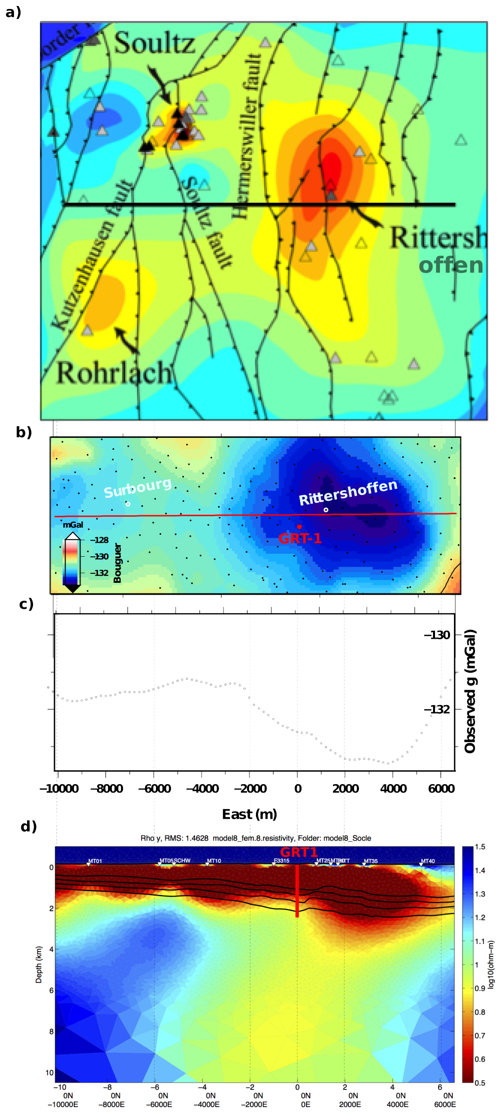

Figure 5: Correlation between thermal anomaly (a) located at the top of the basement (from Baillieux et al., 2014), gravity anomaly (b-c) and resistivity model (d). The location of the resistivity model is shown by continuous line on the map (a) and (b).

Very interesting correlation can be also observed between the resistivity model and the thermal anomaly computed at the top of the basement (Fig. 5). The high thermal anomaly located at Rittershoffen corresponds to the location of the conductivity anomaly observed beneath GRT-1, which correspond in the same time to the negative gravity anomaly. Against, in the western part where no thermal anomaly found, this area corresponds to resistive part located in the basement. Under site MT40 where a basement is recovered with high resistivity corresponds to the area without thermal anomaly, located immediately east of the main thermal anomaly of Rittershoffen.

The analysis of the multiangle horizontal gravity anomaly from 180°, i.e. from south, showed that sites located above the conductive anomaly mainly sites E3315, MT25, RITT and MT35 are located in negative gravity gradient, whereas other sites are located in the positive gradient anomaly (Fig. 6a). The site named MT40 however is located at the eastern end of the conductive anomaly, but located in negative gravity gradient but with much higher amplitude arouse from the sallower effect, which is an agreement with the resistive area observed in the shallower part under this site.

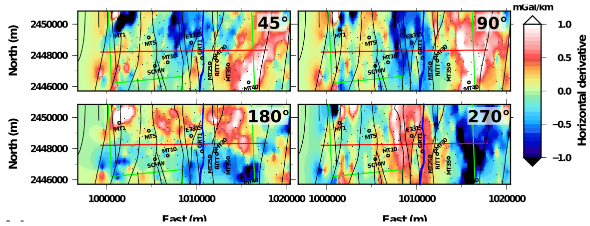

Figure 6: Multiangle horizontal gradient analysis where MT site are superimposed. The continuous line showed the location of the MT sites.

5. CONCLUSIONS

Magnetotelluric experiment have been done successfully in urban area which show several challenges in data acquisition and processing because it present a huge anthropogenic noise and very narrow space. We success in the data processing and we recovered accurate and reliable impedance tensor. Three different inversions have been performed to assess the underground electrical conductivity of geothermal project of Rittershoffen. All of them suggested the presence of high conductive anomaly beneath GRT-1, which reach at least a maximum depth of 7-8 km. In parallel, in the west part of the profile, under sites MT1, MT5 and SCHW, we recovered a resistive anomaly.

Very interesting correlations are also observed between the recovered resistivity model, the gravity anomaly and the thermal anomaly. The conductivity anomaly under GRT-1 corresponds well with the thermal anomaly and to the negative gravity anomaly. The behaviour is expected because the conductivity is strongly affected by thermal water and temperature and the hydrothermals alteration affect strongly the density and generate negative gravity anomaly. The results obtained in this study show the real potential of the magnetotelluric and the gravity methods in the derisking of the geothermal project and ensure the exploration of the best geothermal reservoirs.

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