Resistivity imaging of an analogue of the transition zone between the sedimentary cover and the basement of deep sedimentary basin for geothermal exploitation

J. Porté\textsuperscript{1,2}, M. Darnet\textsuperscript{2}, J-F Girard\textsuperscript{1}, N. Coppo\textsuperscript{2}, J-M Baltassat\textsuperscript{2}, F. Bretaudeau\textsuperscript{2} and P. Wawrzyniak\textsuperscript{2}
\textsuperscript{1} IPGS (UMR 7516 CNRS / University of Strasbourg), j.porte@brgm.fr, jf.girard@unistra.fr
\textsuperscript{2} BRGM (French Geological Survey), m.darnet@brgm.fr, n.coppo@brgm.fr, jm.baltassat@brgm.fr, f.bretaudeau@brgm.fr, p.wawrzyniak@brgm.fr

SUMMARY

The transition zone between the basement and the sedimentary cover is becoming an increasingly attractive target for the development of geothermal energy in deep sedimentary basin as encountered in the Upper Rhine Graben. Several geothermal power plants already exploit this target but the transition zone is however still poorly known with the presence of large permeability heterogeneities. Studies are currently ongoing in order to develop conceptual models on how it is formed and how heat can be exploited. In this study, we evaluate the ability of resistivity imaging by Controlled-Source Electromagnetic (CSEM) method in frequency domain, to identify favorable areas for the development of Enhanced Geothermal System (EGS). We performed a land-CSEM survey on an analogue of the transition zone in a well-known catchment basin at Ringelbach (Vosges mountains in France), to assess the relevance of such data. Gathered data consist in a 3D-grid of 48 reception sites uniformly distributed over the whole basin and using a single transmitter.

We performed 2.5D inversions of a data subset with the parallel adaptive finite-element code MARE2DEM to image the resistivity structure through a profile of interest and compared the result to a former Electrical Resistivity Tomography (ERT) inversion. CSEM inversion extended the shallow ERT image in depth and allowed to obtain a resistivity image of the transition zone. The integration of these results with existing geological and geophysical knowledge allowed identifying and mapping a fault zone as well as the fractured zone at the top of the unaltered granite basement. Results of this study demonstrate the importance of acquiring resistivity data at the target depth before drilling to maximize the success rate of a deep EGS project and point out the interest of pursuing the study with the 3D inversion of the whole set of data.

Keywords: Geothermal energy, Land-CSEM, 2.5-D inversion

Introduction

Following the success of the geothermal pilot site of Soultz-Sous-Forêts (Alsace) for the production of heat and electricity, several new projects are currently in development or are already in production, as the new geothermal power plant of Rittershoffen (Alsace, France). In order to better understand the geothermal target in Alsace, the CANTARE-Alsace project aims to characterize the transition zone between the basement and the sedimentary cover of the deep sedimentary basin of the Rhine Graben. Controlled-Source Electromagnetic (CSEM) investigation was undertaken on a shallow analogue of the transition zone, the catchment basin of Ringelbach (Vosges), to develop resistivity imaging in these contexts. Many information are available on its shallow structure due to the presence of two wells and several geophysical surveys (Well-logging, ERT, NMR) carried out between 1999 and 2007. Available geophysical data are summarized by Baltassat (2017). We expect the CSEM data to extend the maximum depth of investigation of former resistivity images (limited to 50 meters). In this paper, we present the first results of a 3D CSEM survey performed in 2017 and compared these against legacy data.

Study site

Studied since 1975, the catchment basin of Ringelbach is a well-known hydrogeological site, analo-
porté, J. et al., 2018, Resistivity imaging of the transition zone of deep sedimentary basin. According to previous studies, the site is composed of resistive sandstone (1000-3000 $\Omega \cdot m$) superposed over two granitic facies with a NE-SW fault separating the site in two blocks (Figure 1). The first one is identified as a weathered granite being conductive (250-1000 $\Omega \cdot m$), whereas the second one as a fresh granite with a strong resistive signature (>3000 $\Omega \cdot m$). Laboratory measurements (Belghoul, 2007) showed that the high conductivity of the Ringelbach weathered granite is related to its increased porosity but also as result of former hydrothermal alteration succeeding the granite burial (Wyns, 2012). The fault zone identified on the geological map and near the center of the P1 profile (Figure 1 and projected ERT result on Figure 2) displays a shallow conductive anomaly around 200 $\Omega \cdot m$. The two 150m deep wells are located on the sedimentary cover over the Heidenkopf (HEI) and the Hurlin (HUR) (Figure 1) and found a thin sandstone layer (70 meters thick in HEI and 30 meters in HUR) lying over a thin layer of granitic sand (around 20 meters thick) and finally over weathered granite. Unaltered granite has neither been seen in the wells nor imaged by the ERT method due to its limited depth of investigation (50m).

CSEM survey

The 3D Land-CSEM survey was carried out the first week of July 2017, over a 750×800 m² area with 48 reception sites gathered over a quasi uniform 3D-grid (Figure 1). Acquisition used Metronix ADU-07 acquisition systems, whereas the source was a Metronix TXM-22 and its control unit TXB-07. The source position was located at 1500 meters North from the Ringelbach basin on the sedimentary cover. The survey design originally planned two orthogonal electric transmitters, but the high resistivity from very dry sandstones at the source location drastically limited the injected current. It restrained our data set to a unique current polarisation by the use of an inductive transmitter. The horizontal loop used was 1184 meters long, covering an area of 93 720 m². Twelve frequencies were gathered varying from 0.25 Hz to 8192 Hz using square-wave signals. Audio-Magnetotelluric (AMT) sequences were also recorded in each site but are not presented.

Figure 1: Geological map of the Ringelbach Basin with the reception grid and the P1 profile from former ERT survey (yellow dashed line). Blue crosses show well locations; the Heidenkopf (HEI) and the Hurlin (HUR). The center of the loop (Tx) is located around 1500 meters North from the nearest point of the grid ©IGN 2017

Methods

Data were processed in the frequency domain using BRGM software PROCATS, allowing us to estimate transfer functions for all harmonics of the square wave signal using robust processing (Streich et al (2013) and Smai and Wawrzyniak (2018)). Quality control was performed sorting data with poor signal to noise ratio and looking manually for the smoothness of the amplitude and phase curves with frequency. Data are highly contaminated by noise below 8 Hz and above 4096Hz. Some harmonics of the fundamental frequencies were kept within this range for the amplitudes of the electric fields but no harmonics were kept for the phases as they were too noisy. In this study, we focus on 2.5D resistivity imaging for calibration purposes and to prepare for future 3D inversions. We selected 9 stations through the grid to form a profile similar to the one of interest P1 (Figure 1) imaged by former ERT surveys (Baltassat, 2017) and providing us a direct way to compare our results. Figure 2 displays ERT inversion result superposed on our CSEM inversion results and shows the main resistivity structures from the Ringelbach basin. On the ERT results, we can observe a thin resistive sedimentary cover lying over a more conductive weathered granite to the North-
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West, a fault zone with conductive anomalies in the center of the profile and to the South-East a block of fresh granite with a transition around receiver RX34. Inversions of the CSEM data were performed using the open-source parallel adaptive finite-element 2.5D code MARE2DEM (Key and Ovall, 2011) which use a modified OCCAM inversion approach (Key, 2016) looking for the smoothest model explaining the data. The code uses an unstructured triangular grid allowing to include topography in our model.

Results

First inversions used amplitude and phase data from the electric field oriented to the East as this component is the strongest for a horizontal transmitting loop located to the North. However, data suffer from strong static shift effects affecting our images. It resulted in structures totally incoherent with a priori geological information. Hence, as phase are not affected by static shifts (Zonge and Hughes, 1991), we chose to invert only phase data from the East-West electric field at the fundamental frequencies in the range of 8 Hz to 4096 Hz, resulting in 9 frequencies per site and giving us the best result according to a priori information. Figure 2 shows the result of the CSEM data 2.5D inversion. Shallow structures are in good agreement with the resistivity image obtained previously by ERT on profile P1. Indeed, the resistive block of fresh granite appears clearly in the South of the profile and vanishing at the conductive fault area. Resistivity values are over 2000 $\Omega\cdot m$ for the fresh granite and around 250 and 500 $\Omega\cdot m$ in the fault zone. We can see that the conductive anomaly from the fault area extends in depth compared to ERT result. The sedimentary cover (1000 $\Omega\cdot m$) is less well imaged with a thicker resistive layer than expected (around 200 meters instead of 80 meters according to well data). This is likely to be related to the lack of high frequency data (>4096 Hz) and hence of shallow depth of investigation (<100m). We also identify a conducting layer dipping to the North from the fault area and lying over a resistive body with similar resistivity as fresh granite.

Discussion and perspective

First results of this study gave us a deeper resistivity image of the Ringelbach basin, an analogue of the transition zone between the basement and sedimentary cover of deep sedimentary basin. The choice to keep the inversion using only phase data with limited number of parameters questions the relevance of our result. Nevertheless, synthetic cases were modelled and successfully inverted, supporting the consistency of our first images. Furthermore, our result is in good agreement with former resistivity information. Another point of discussion is the ability to image the conductive layer deeply under the sedimentary cover. Indeed, the limit between sedimentary cover and conductive weathered granite is too deep compared to well data. Transmitter imprint or 3D effects may degrade the resolution of the image to the North of the profile and explain the discrepancy. In future work, we will include AMT data in a joint inversion scheme to refine resistivity image further and confirm our resistivity model. We will also perform a 3D inversion of all the receivers to remove any potential 3D effects.

Conclusion

This work show the benefits of using EM methods to discriminate between resistive fresh granite and conductive weathered granite on a shallow analogue of the transition zone at the top of a granitic basement. Resistivity imaging could therefore be an efficient way to identify weathered granite areas more likely permeable with the presence of pre-existing fractures and hence avoiding unaltered and impermeable granites less favourable for geothermal reservoir development. A remaining challenge is though how to upscale our method to make such measurements underneath a thick sedimentary cover (>3km).

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References


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Figure 2: CSEM data 2.5D inversion result over the P1 profile from Baltassat (2017). Former ERT inversion is displayed and its shadow is projected over our result with the fault crossing location represented by an arrow. Source location is around -1.5 km in the y-direction with a 0.4 km shift on the x-axis