Advances on Electro-Magnetic Imaging for De-Risking Enhanced Geothermal System Prospects

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Proceedings World Geothermal Congress 2020
Reykjavik, Iceland, April 26 – May 2, 2020

Advances on Electro-Magnetic Imaging for De-Risking Enhanced Geothermal System Prospects

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Keywords: resistivity, electromagnetics, exploration, EGS, CSEM, MT

ABSTRACT

Exploiting geothermal resources at temperatures between 120 and 200°C in sedimentary and basement rocks, in rifts or in flexural basins, to produce electricity or heat is now possible because of the development of Enhanced Geothermal System (EGS) technology. Reaching such temperature range is a major challenge for mainland France and Europe as it usually requires drilling at more than 2km depth. Aside from temperature, two other conditions are required to allow the exploitation of the geothermal energy: the presence of fluid, which is the heat vector, and sufficient permeability to allow the production and re-injection of the natural fluid. This translates into the reservoir being located in the deep layers of sedimentary basins and the upper part of the Paleozoic basement, including the transition zone between the two.

The reality is however even more complex as the geothermal potential of this zone is also strongly influenced by large heterogeneities comprising lithology of the cover/basement, the internal architecture of the transition zone, the structural history of the batholith and the presence of natural faults and fracture networks. It is therefore clear that the characterization of the transition zone and its heterogeneity in the deeper part of sedimentary basins constitutes one of the most challenging problems for the development of geothermal resources.

Within the frame of several national and European research projects (e.g. FP7-funded IMAGE, ANR-funded CANTARE and ADEME-funded DEEP-EM projects), we have undertaken to develop geophysical techniques capable of imaging the electrical resistivity of the transition zone, as this physical parameter is highly sensitive to the presence of geothermal fluids and associated hydrothermal alterations. In this paper, we report out our analysis of core, well and field-scale resistivity measurements to establish the feasibility of electro-magnetic (EM) imaging for de-risking EGS prospects in the Upper Rhine Graben. Data comes from the Soultz-sous-Forêts and Rittershoffen producing geothermal plants, an EM field trail near the Strasbourg city but also from EM measurements performed on an analogue found on exhumed crystalline basement in the Vosges Mountains.

This work shows that the knowledge of the electrical properties of the transition zone can help assess its porosity/permeability and hence guide the exploration and development of deep geothermal resources. It also demonstrates that the main challenges for imaging with EM methods such a zone reside in the ability of imaging with high accuracy resistivity variations within the thick sedimentary cover but also in the ability of acquiring EM datasets with high signal to noise ratios despite the presence of strong anthropogenic noise. It also showed that the integration of the EM data with other datasets, especially structural constraints (e.g. horizons from seismic imaging), will be key to achieve sufficient resolution at target depth.

1. INTRODUCTION

Surface geophysical exploration techniques are important tools for geothermal resource assessment as they provide unique information on the resource geometry away from boreholes. For magmatic environments, passive EM techniques (e.g. magnetotellurics or MT) have been traditionally used for geothermal exploration to map the geometry of the geothermal reservoir through the mapping of the high temperature alteration zones (Munoz, 2014). For sedimentary environments, it is not clear whether such features exist and whether they can be used to map the potential geothermal reservoir to be developed with an Enhanced Geothermal Systems (EGS) concept.

In this paper, we report out our analysis of core, well and field-scale resistivity measurements to establish the feasibility of electro-magnetic imaging for de-risking such EGS prospects in the Upper Rhine Graben. Since this area is highly urbanized, an additional challenge is the presence of strong anthropogenic noise that can obfuscate natural MT signals. Focus has therefore been on active EM techniques, like the Controlled-Source Electro-Magnetic (CSEM) method.

2. CORE SCALE RESISTIVITY MEASUREMENTS

Electrical formation factor and surface conductivity measurements have been performed on granitic core samples taken from an analogue of the transition zone between deep layers of sedimentary basins and the upper part of the Paleozoic basement, exhumed in the Ringelbach's mountains (Belghoul, 2007). It shows that the higher porosity of the samples, the higher surface and pore fluid conductivity are (Figure 1). Since the amount of alteration clays controls the rock surface conductivity (Revil et al, 1998), we can conclude that the higher the degree of alteration of the granite is, the higher the conductivity is. In addition, the higher the porosity is, the higher the permeability of the samples is (figure 2). Porous and permeable altered granitic formations found within the transition zone are therefore likely to exhibit elevated electrical conductivity compared to unaltered and tight granite.

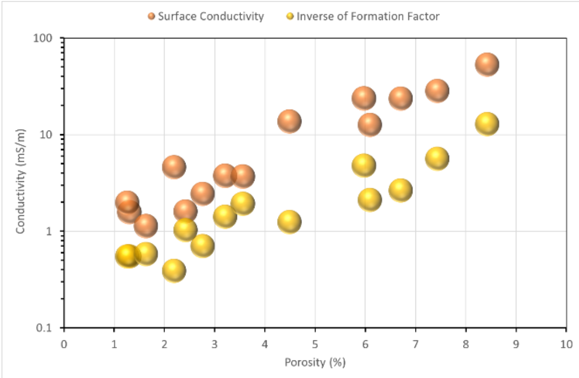

Figure 1: Surface (orange) and pore conductivity (yellow) of altered granite core samples extracted from the Ringelbach transition zone (Belghoul, 2007).

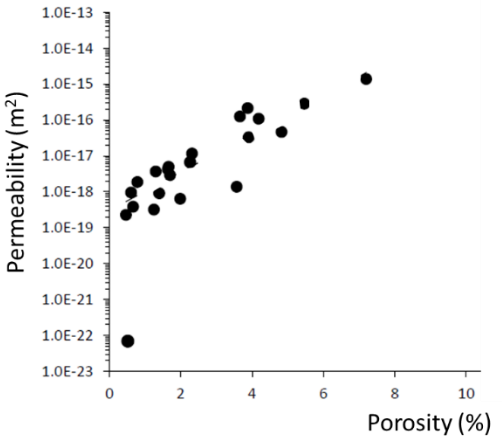

Figure 2: Permeability of Ringelbach's core samples as a function of the porosity of the samples (Belghoul, 2007).

2. WELL SCALE RESISTIVITY MEASUREMENTS

To extend the aforementioned electrical conductivity observations made on core samples to deep geothermal reservoirs, we present here electrical resistivity logs taken in the Soultz-sous-Forêts granitic basement (figure 3). As predicted, altered zones are electrically more conductive than unaltered granite, with a factor ranging from ten to thousand times. Similarly, in the Rittershoffen geothermal project, altered zones at the top of the granitic basement proved to be electrically conductive but notably, the main permeable fault zones coincide with the most electrically conductive zones (Glass et al., 2018). The electrical conductivity of the granitic basement is therefore a parameter of choice to explore for hydrothermally altered and fractured fault zones.

Extensive petrographical and mineralogical studies on core sections from the Soultz wells (Traineau et al., 1991, Ledésert et al., 1999, Genter et al., 2000) have shown that there are two kinds of crystalline medium penetrated by the geothermal drillholes. Such kind of observations about hydrothermal alteration of the basement has been confirmed in the geothermal Rittershoffen wells from cutting analysis (Vidal et al., 2018).

For high resistivity values, it corresponds to unaltered and poorly fractured granite where matrix permeability is rather low with orders of magnitude ranging between 10^{-18} and 10^{-21} m² (Hettkamp et al. , 1999).

For low resistivity values, it corresponds to hydrothermally altered and fractured zones. Such zones are rather complex in terms of geometry (high fracture density, damaged zone), cataclastic facies (breccia, cataclased granite), mineralogical composition (many secondary minerals like quartz, clays and carbonates) and they show strong variations in petrophysical properties like secondary porosity values due to partially clogging of the natural fractures. Generally the most permeable features are belonging to such hydrothermally altered zones. Permeability could range from 10^{-14} to 10^{-16} m². Some of the permeable naturally hydrothermally altered zones intersected by the Soultz boreholes had transmissibilities between 0.1 and 50 dm (darcy meter; 1 dm = 10^{-12} m²) demonstrating that much more than 90 % of the water in the granite is carried by a few highly permeable faults and not by the joint network (Jung, 2013). However, in such altered and fractured zones, the occurrence of clay minerals like illite is very common. Thus, low resistivity values could match with the occurrences of natural brine and/or to clay rich altered granite facies.

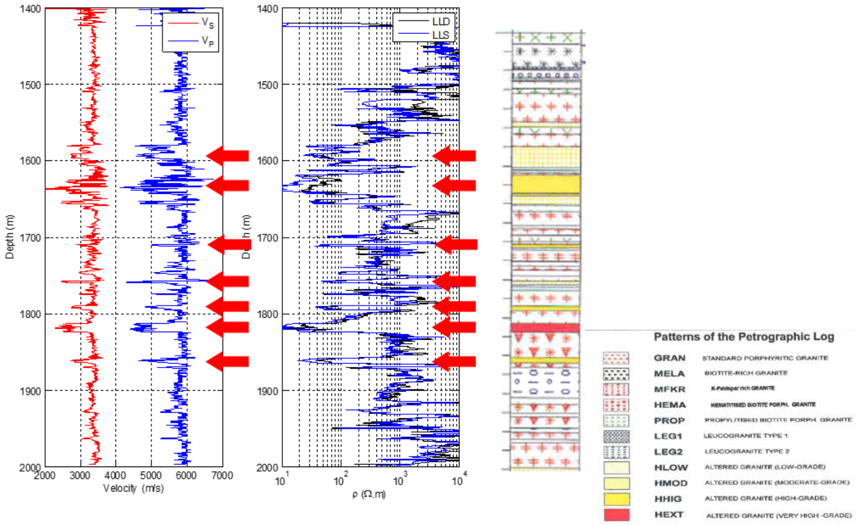

Figure 3: P-wave (blue) and S-wave (red) logs (left), shallow (blue) and deep (black) laterolog (middle) and petrographic log (right) in the Soultz-sous-Forêts GPK1 well (From Traineau et al., 1991). Most altered granitic facies are marked with red arrows.

3. FIELD-SCALE RESISTIVITY MEASUREMENTS

3.1 CSEM measurements on Ringelbach's analogue

Here, we have looked into the resistivity signature of transition zone outcropping in the Ringelbach area in the Vosges Mountains. To do so, we acquired a 3D Controlled Source Electro-Magnetic (CSEM) survey over a 1000m x 1000m area cutting through the transition zone (from the Triassic sedimentary cover deep down into the crystalline basement, figure 4). The 3D resistivity cube obtained from the inversion of such data shows that the fractured and altered granite found within the transition zone forms a thick conductive layer extending up to 200m into the basement (figure 4). Resistivity logs obtained on two shallow exploratory boreholes confirmed this observation. Interestingly, the conductive and altered transition zone is also laterally extensive. However, in some areas (e.g. Eastern part of the survey area), this conductive anomaly is interrupted by a more resistive and hence most likely less altered granitic body. This study shows that mapping the resistivity distribution within the transition zone can help identifying and mapping altered and fractured zones. The challenge remains now to deploy electromagnetic techniques capable of remotely detecting and imaging such anomalies, deeply buried underneath a thick sedimentary and hence conductive cover.

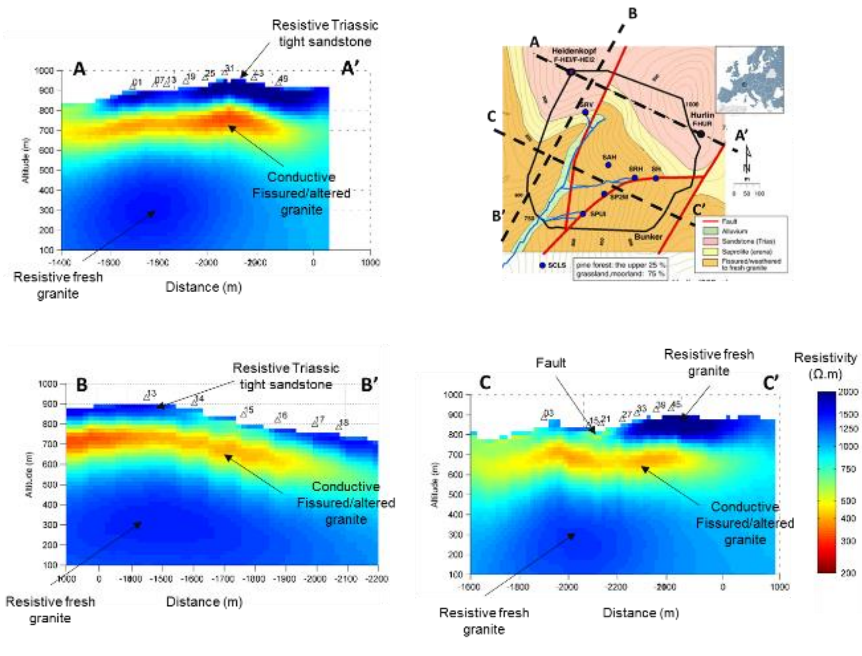

Figure 4: Left: 3D resistivity cubes (top: strike and bottom: dip lines) obtained from the inversion of 3D Controlled-Source Electro-Magnetic data acquired over the Ringelbach area. Right: Geological map (top) and cross-section (bottom) of the Ringelbach area.

3.2 CSEM synthetic study

In an attempt to quantify the magnitude of the CSEM signals generated by altered fault zones deeply buried underneath a thick sedimentary cover, we modelled four different geological scenarios representative of the Upper Rhine Graben (figure 5):

1. A five-layer earth model with a 800m thick sedimentary cover, typical of basement horsts found in the Rittershoffen area (model 1)
2. A five-layer earth model with a 1100m thick sedimentary cover, typical of down-thrown fault blocks found in the Rittershoffen area (model 2)
3. A fault model with a 300m-offset normal fault, typical of regional faults found in the Rittershoffen area (model 3)
4. A conductive fault model with a 300m-offset normal fault and 100m thick conductive fault core, as observed on the Rittershoffen resistivity logs (model 3)

We computed the CSEM response using the POLYEM3D code (Bretaudeau et al., 2017) for frequencies ranging from 0.01 Hz until 4Hz (figure 6). We modelled the transmitter as a 1km grounded electric dipole and the receiver as a horizontal electric sensor located 5km away from the transmitter (typical maximal usable offset range observed on CSEM data in the Upper Rhine Graben). We placed the normal fault at the mid-point between the transmitter and receiver to ensure maximal sensitivity. When comparing the CSEM response of models 1 and 2 to a homogeneous 2Ω.m half-space, it is clear that the main CSEM anomaly (ranging between 10 and 100%) is caused by the presence of the deeply buried Jurassic limestones/sandstones (from 5 to 100Ω.m) and unaltered granitic basement (5000Ω.m). When comparing the fault model (model 3) and model 1/2, it shows that the offset of the geological layers due to the normal fault generates a second order effect (CSEM anomaly between 1 and 10%). Finally, the addition of conductive fault zone to the fault model (model 4 versus model 3) generates a marginal CSEM anomaly (less than 1%). This study demonstrates that the challenge for imaging with the CSEM method deeply buried conductive fault zone resides first in the ability of imaging with high accuracy the resistivity variations of the thick sedimentary cover. This surely will require to integrate structural constraints (e.g. from seismic imaging) to compensate for the lack of vertical resolution of EM techniques.

A sensitivity study showed that the amplitude of the CSEM anomaly is strongly dependent on the thickness of the conductive fault zone. Since very few deep geothermal wells have crossed such fault systems, it is highly uncertain how extensive such faults area. Here, we assumed a 100m cumulative thickness (altered zone + fault core) from the Soultz-sous-Forêts resistivity logs but recent resistivity logging in the Rittershoffen geothermal system showed thicker alteration zones (Glass et al., 2018). In addition, MT soundings performed in this area suggests that much more extensive deeply buried conductive fault zones exist (Abdelfettah et al., 2019).

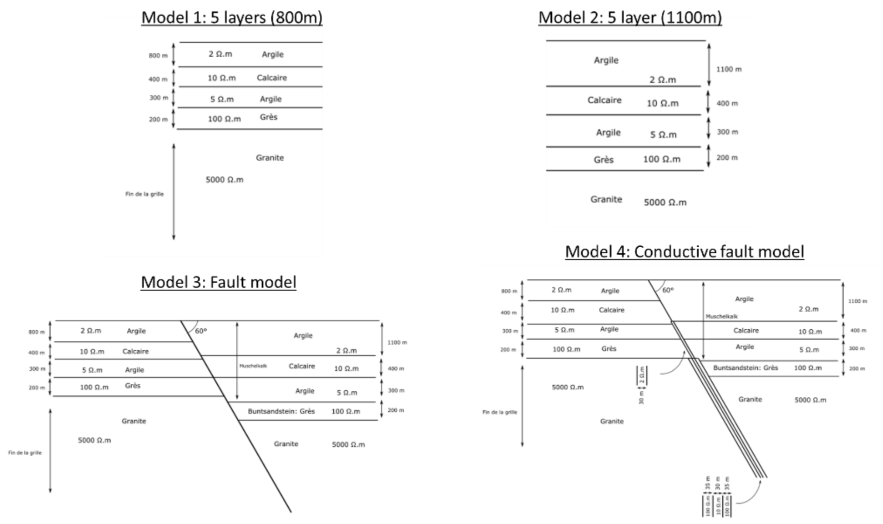

Figure 5: Geometry of the four different geological scenarios tested to assess the magnitude of the CSEM signal associated to altered fault zones deeply buried underneath a thick sedimentary cover

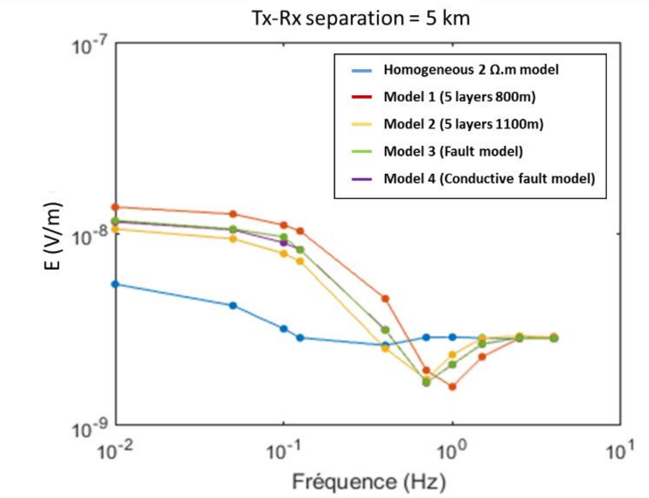

Figure 6: Modelled amplitude of the horizontal electric field at 5km offset from a horizontal electric dipole for the four models described on figure 5.

3.3 CSEM field trials

In the section, we present results from a field trial performed in the Upper Rhine Graben near the Strasbourg city. A 1km long electric dipole (TXM22 transmitter from Metronix) was deployed while a total number of 25 CSEM stations (ADU07 MT stations from Metronix) were installed along two parallel NW-SE profiles and one transverse SW-NE profile (figure 7). Square waves of fundamental frequencies from 0.0625 Hz until 128 Hz with increment factor of four were successively injected. Injected current was of 35 A for the lowest frequencies and about 29 A for the highest frequencies. After processing of the CSEM data, the maximum usable receiver offset from the transmitter survey is about 7 km. All data further than 7 km from the transmitter suffer from high levels of noise due to the proximity of the Strasbourg city. Therefore, the eastern part of the survey area was not successfully covered.

We performed a 2.5D inversion of the CSEM along a line crossing the major normal fault (figure 8) using the 2.5D MARE2DEM inversion code (Key, 2016). We inverted the amplitudes of the PE major axis of the horizontal electric field from six CSEM stations located in the vicinity of the selected profile. Inverted frequencies were ranging from 0.0625 until 1000 Hz. The resulting resistivity model is shown on figure 8. It displays relatively homogeneous laterally resistivity variations, in agreement with the geometry of the sedimentary layers. The shallow resistive layer is consistent with recent sandy sediments. The deeper thick conductive layer is in agreement with the clay-rich Tertiary sediments. The deeper resistivity increase at depth corresponds to the Cretaceous and Jurassic resistive limestones and salt. Within this resistive layer, we introduced artificially a discontinuity in the resistivity model to represent the regional normal fault. The resulting resistivity model shows indeed a resistivity change across this feature but a sensitivity analysis also showed that the resolution of such a feature with the acquired survey layout is limited. In addition, we have no indication of a deep highly resistive layer (>1000 Ω.m) that could corresponds to the granitic basement. Here also, a sensitivity study shows that the receiver-transmitter distances are not long enough to image the resistivity variations of the basement, most likely due to the high level of electromagnetic noise and great depth of the basement (>4km)

In agreement with the synthetic study, this field trial shows that imaging deep resistivity variations within granitic basement of the Upper Rhine Graben requires CSEM measurements with high signal to noise ratios. To do so, we are planning to deploy more powerful CSEM transmitters, either by increasing the dipole length (from 1 to 3km) or the injected current (from 30A to 150A) or both. 2D and 3D CSEM field trials are planned in summer 2019 and 2020, respectively over the Soultz-sous-Forêts and Rittershoffen - geothermal plants to validate this approach (figure 9). In addition, 3D seismic data is available on both sites and will facilitate the integration of structural constraints in the CSEM inversion process and maximize our chance to image deep resistivity variations within the granitic basement and transition zone with the sedimentary cover.

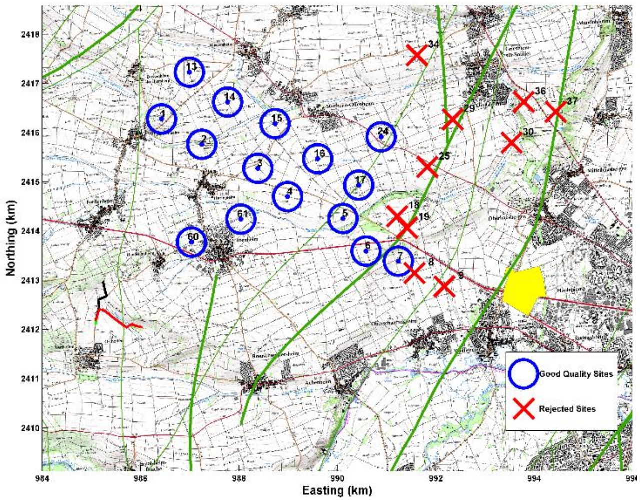

Figure 7**: Distribution of the CSEM receivers with sufficient signal to noise (blue receivers) and rejected sites (red crossed). Large green lines show the major faults crossing the area. The source cables for the electric dipoles are shown in black and red. CSEM receiver positions are blue points.**

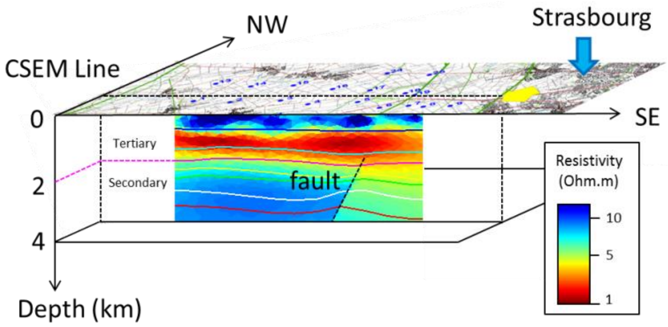

Figure 8: Resistivity cross-section obtained from the 2.5D inversion of the CSEM data along a NW-SE line crossing a major fault of the Upper Rhine Graben.

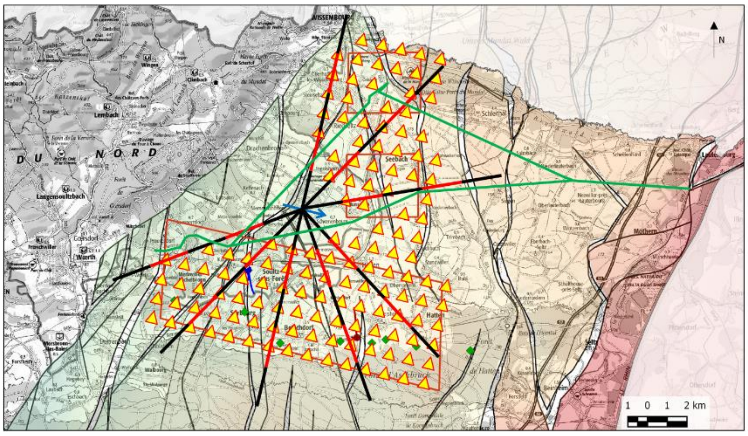

Figure 9: Planned 3D CSEM survey (receivers as yellow triangles, transmitter as a blue arrow) over the Soultz-sous-Forêts and Rittershoffen geothermal plants.

CONCLUSION

The analysis of core, well and field-scale resistivity measurements, show that the knowledge of the electrical properties of the transition zone between the sedimentary cover and basement can help assess its porosity/permeability and hence guide the exploration and development of deep geothermal resources. It also demonstrates that the main challenges for imaging with EM methods such a zone reside in the ability of imaging with high accuracy resistivity variations within the thick sedimentary cover but also in the ability of acquiring EM datasets with high signal to noise ratios despite the presence of strong cultural noise. It also showed that the integration of the EM data with other datasets, especially structural constraints (e.g. horizons from seismic imaging), will be key to achieve sufficient resolution at target depth. The 2D and 3D CSEM field trials planned within the frame of the ADEME-funded DEEP-EM project over the Soultz-sous-Forêts and Rittershoffen - geothermal plants aims at overcoming these issues.

ACKNOWLEDGEMENTS

The authors wish to thank the ADEME for funding the DEEP-EM project, the ANR for funding the CANTARE project and the EU-FP7 program for funding the IMAGE project.

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