Modelling the sensitivity of magnetotelluric monitoring data to geothermal fluids at depth in Northern Alsace

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Keywords: Magnetotelluric, Monitoring, Geothermal fluids, Electric resistivity, Modelling, Sensitvity.

ABSTRACT

Magnetotelluric (MT) is classically used in geophysical exploration for imaging electrical conductivity structures and is recently developing as a monitoring technique. In geothermic during fluid injections and/or EGS stimulation experiments, MT is used in addition to microseismic observations and can provide critical information to geothermal fluid flows because the electrical conductivity is related with temperature, porosity, water content and minerals of rocks. Some experiments have shown that such MT signals might difficult to be observed because they are at periods of 1-10 s, within the so-called MT dead-band. We consider the sensitivity of MT monitoring by forward modelling. We use ModEM open source code to build a 3-dimensional model of the northern Alsace, which includes topography and simple resistive layers inspired from geology. Modelling allows us to simulate different changes that could be caused by brine and/or acid injection within fractures at depth and show subsequent MT monitoring parameters with differences of the impedance response function (apparent resistivity and phase), phase tensor, and possibly magnetic transfer function (tipper vectors). From these models, it seems that MT monitoring in a sedimentary environment at 20 Ω.m could be sensitive to an increase of conductivity in a fault area at geothermal depths of 2-3 km if the size of the disturbed domain reaches about 10x0.3x2 km^3.

1. INTRODUCTION

Magnetotelluric (MT) is classically used in geophysical exploration for imaging electrical conductivity structures at depth of several kilometers. In geothermic, the electrical conductivity is an interesting parameter because it shows a relationship with temperature, porosity, water content and minerals of rocks, which are critical parameters for any geothermal project. First used as an exploration technique, MT is developing as a monitoring tool for instance on active volcanoes (Aizawa et al. 2011; Wawrzyniak et al. 2016).

In geothermic, MT monitoring experiments have been used to show information to fluid flows and have be combined to microseismic observations: Peacock et al. (2012) used MT apparent resistivity and phase tensor to monitor EGS stimulation at more than 3 km depth at Paralana Bassin (Australia). In order to explain the Paralana data, Peacock et al. (2013) considered forward modelling by using the code by Mackie et al. (1993): they proposed a crude layered model in which they included the appearance of a conductive prism of size 1.5x0.4x0.8 km^3 and top at 3.3 km depth with resistivity of 0.3 Ω.m. Actually this model is unrealistic because their experiment concerns a total volume of injected brine of 3100 m^3 only, and the value of 0.3 Ω.m is the resistivity of the brine itself. To make the model more realistic, MacFarlane et al. (2014) proposed to introduce anisotropy and made a 2D anisotropic modelling approach; they considered the decrease of conductivity within the fault where brine was injected by putting the electrical resistivity of 1 Ω.m in the fault direction while it is kept at the host value of 180 Ω.m in the direction normal to the fault. Since it is in 2D, this anisotropic approach is still limited.

We now consider the case of northern Alsace where several geothermal sites might be investigated by MT monitoring. As a typical target, we consider the area of the ECOGI geothermal project at Rittershoffen near Soultz-sous-Forêt, where we carried time-lapse and continuous MT monitoring experiments (Abdelfettah et al. 2014, 2016). Besides the importance of the quality of measurements and processing, we now specially address the question of sensitivity by forward modelling. Like Peacock et al. (2013), previous tests have been done by Braun (2009) using the 3-D code of Mackie et al. (1993). In order to get better resolution, include topography, and test different targets quickly from parallel computers, we use ModEM open source code for electromagnetic modelling (Kelbert et al., 2014). Hereafter we first detail the models, then we discuss about the sensitivity from calculated MT parameters and finally conclude about the perspectives of MT monitoring in environment with thick conductive sediments.

2. MODELS

In a way similar to that of Braun (2009), we consider simple models of northern Alsace with resistive units inspired from geology. We consider a simple two layer model, made of 3 km thick conductive sediments at 20 Ω.m on top of the resistive basement at 1500 Ω.m.

By using ModEM as a forward modelling code (Kelbert et al., 2014), we are able to generate synthetic MT impedance from several models with fine mesh, large borders, and topography. We use a modelling frame of 1000x1000x500 km^3 in which the size of blocks goes from 50 m up to 250 km depending on the distance to the study area located at the centre. The total number of blocks is 89x101x63 and we are interested only in the central area illustrated in Fig. 1; we put large borders around for the proper computation (very fine accuracy) within a large frequency band (including long periods larger than 100 s).

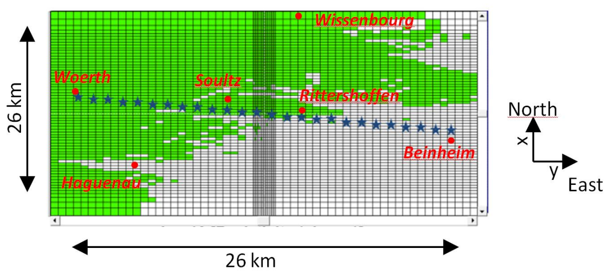

Figure 1: Top view of the central area of the model: stars indicate locations of calculated MT parameters along a East-West profile. Change in colours (green / white) illustrates the topographic limit (150 m altitude). Straight lines indicate the mesh (horizontal spacing from 100 m to 1500 m in this frame).

First we consider a model without topography (actual 1D model with flat ground surface). We use this model to test the modelling process which depends on several parameters such as mesh size, depth and horizontal location of receivers. We obtained realistic 1D apparent resistivity values, with 20 Ω.m at high frequency and a trend towards 1500 Ω.m at low frequency or long period (Fig. 2). Without topography, we are expecting equal values of the apparent resistivities ρ_{xy} and ρ_{yx} (classical for the 1D case): we use their difference or their ratio as an indicator to the quality of the modelling. By looking at this difference at all sites and all frequencies, we obtain a maximum error below 0.02 Ω.m: this is very good compared to the resistivity in the models (< 1%). This accuracy allows to compare variations between different models by computing resistivity differences as well as the phase tensor difference that is used in time-lapse MT to compare data at different dates (Thiel et al. 2011; Peacock et al. 2012; 2013; Abdelfettah et al. 2016).

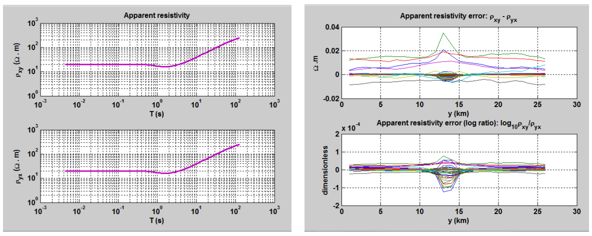

Figure 2: Quality of the modelling from the 1D case. Left: Plots of the apparent resistivity (two off diagonal elements ρ_{xy} and ρ_{yx}) as a function of period. Right: difference or ratio of apparent resistivities ρ_{xy} and ρ_{yx}.

Second case is the reference model, it is a simple two layer model which also includes topography. The topography was extracted from the SRTM (Shuttle Radar Topography Mission) and included to the model using 3D-Grid Visualizer which comes as a companion to ModEM. Actual topography in the study area is quite smooth and slightly dipping South-East; around the study area, blocks have increasing sizes (border line has 250 km width) and SRTM topography also includes Mountains which have been smoothed near the ends of the model (specially in the Alps). Resulting MT profile with topography slightly differs from the flat case (Fig. 3). Main differences appear as a decrease of the apparent resistivity at short periods (T < 0.1 s); there is no big variability at long periods which interest deep geothermal monitoring.

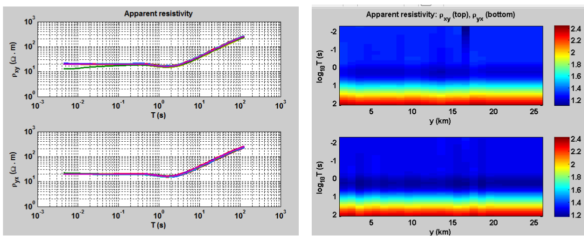

Figure 3: Variability from the topography. Plots of resistivity (two off diagonal elements ρ_{xy} and ρ_{yx}) as a function of period. Left: sounding curves with period along x-axis; Right: pseudo-section with period along along y-axis (as a pseudo-depth).

Third, MT sensitivity is addressed by putting conductive targets in the 1D model with topography in the area of ECCOGI project near Rittershoffen. The changes that could be caused by brine and/or acid injection within a North-South fault is tested by a simple vertical conductive prisms of 2 Ω.m. We consider cases with vertical extent between 1-3 km and horizontal extent of 10 km in the North-South direction (Fig. 4). Three models with different width are considered: 100, 300, or 500 meters.

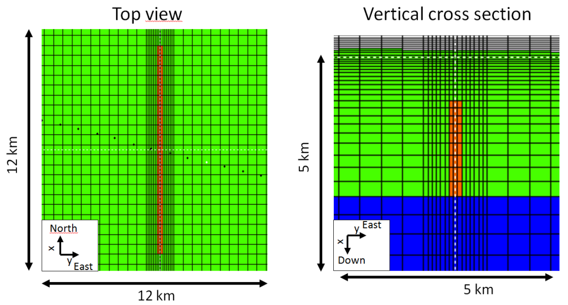

Figure 4: Perturbed model showing a 300m thick conductive anomaly at 2 Ω.m (red) in the sediment layer at 20 Ω.m (green) on top of the resistive basement at 1500 Ω.m (blue).

3. RESULTS

The reference model shown in Fig. 3 defines a reference or initial state prior to injection. Three models with different width of 100, 300, and 500 meters can be considered as successive limit states of injection experiments. To show the apparent resistivity differences, we simply use the ratio of the perturbed result to the reference case. A ratio near to 1 means no change in resistivity. As a result (Fig. 5), we got small changes in the component ρ_{yx} (no new features along y). The ratio of ρ_{xy} is systematically greater than the ratio of ρ_{yx}; this is typical for a conductive structure oriented along the *x* direction (North-South).

It is classical in MT that the apparent resistivity might be affected by distortion effects, and that it is useful in time-lapse MT to use the Phase tensor difference (Thiel et al. 2011; Peacock et al. 2012; 2013; Abdelfettah et al. 2016). Phase tensor difference would not be near to 1, but to 0 when there is no change between the new state and the reference one. As a result from our models (Fig. 6), we got $\Delta\Phi_{yy}$ systematically greater than $\Delta\Phi_{xx}$; again this is typical for a conductive structure oriented along the *x* direction (North-South).

If one considers the typical uncertainty in observed MT monitoring data (Abdelfettah et al. 2016), it is necessary to remark that the case having the thinnest conductive prism (width of 100 m) may be difficult to detect in practice. We consider the detection level around 0.8 for the ratio and 0.2 for the Phase tensor difference.

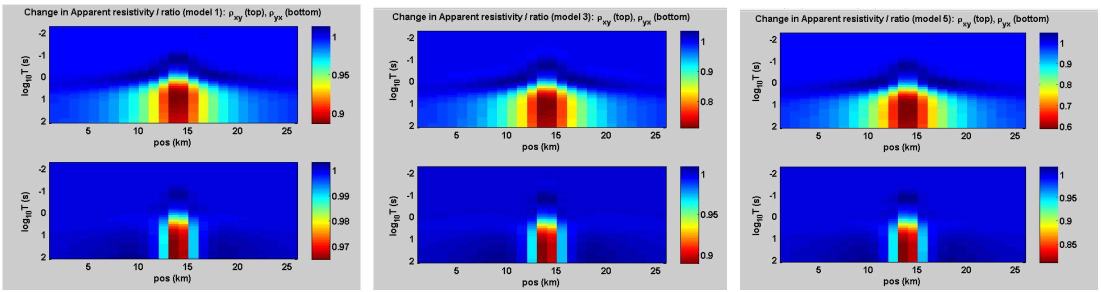

Figure 5: Apparent resistivity ratio (two off diagonal elements) showing sensitivity to the conductive anomaly with variable thickness of the conductive layer: 100, 300, 500 meters (from left to right, respectively).

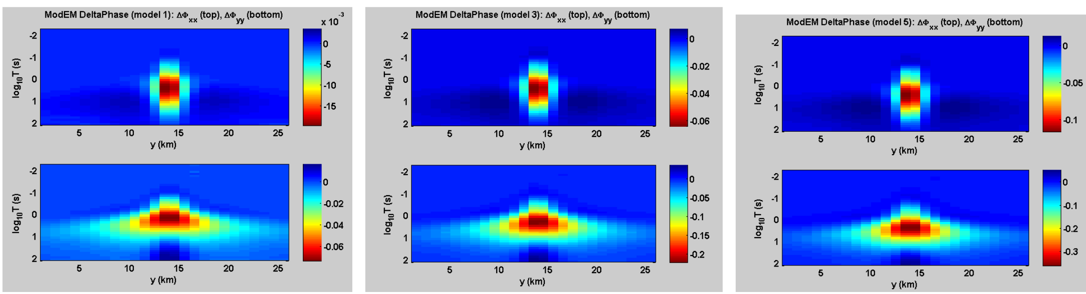

Figure 6: Phase tensor differences (two diagonal elements) showing sensitivity to the conductive anomaly with variable thickness of the conductive layer: 100, 300, 500 meters (from left to right, respectively).

3. CONCLUSIONS

Experimental data in MT monitoring and time-lapse MT will become useful only when a clear sensitivity analysis will be completed to define critical parameters and their critical thresholds. Our approach by forward modelling tells that brine injections within a fault like that of ECCOGI at Rittershoffen would be detected if its size is larger than about 10x0.3x2 km^3.

This statement results from a simple reference model and simple assumptions for the geometry of the plume in the fault area. Other cases with more realistic configurations must be tested. Besides, other MT parameters than the apparent resistivity ratio and the Phase tensor difference have to be investigated.

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Acknowledgements

The work benefited financial support by CNRS LABEX ñG- EAU-THERMIE PROFONDEò. Besides, we acknowledge Naser Meqbel for letting us use the academic licence of ModEM and 3D-Grid Visualizer. Juanjo Ledo and Anna Martì also gave us useful help in getting started with ModEM.