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Continuous and time-lapse geothermal monitoring at Rittershoffen EGS project, northern Alsace, using magnetotellurics

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ABSTRACT

Two fieldwork measurements were achieved in 2013 and 2014 in frame of short geothermal well test productions achieved at Rittershoffen geothermal project to perform continuous magnetotelluric monitoring. In 2013, time series were recorded during short period (~4 weeks) in two sites; 1) at Rittershoffen (RITT) seismic station, about 1.6 km eastward to the GRT-1 geothermal well, and 2) at OPS4, at the seismic observation station of the Soultz-Sous-Forêt (~5 km to the West of the GRT-1 borehole). This field experiment is considered as a test-period and as an introduction to a second field campaign achieved during 2014 and another one started in 2016. In 2014, we recorded the time series quasi-continuously at RITT site from June to mid-December. Moreover, 5 other sites were acquired before and after well-test production to achieve time-lapse monitoring. These sites were located around GRT-1/2 geothermal wells. In total, six MT sites were acquired in 2014; one continuously and 5 temporary. MT Remote reference site was installed at Welschbruch Geophysical Station, about 70 km South from the studied area. The data were recorded by blocks of 24 hours using a sampling frequency of 512 Hz.

To handle natural transient effects in the electromagnetic sources such as variable intensity, polarities and frequencies, data processing was carried out using the well-known, robust Chave's code to estimate Z tensor. The phase tensor is computed from modulus and phase of each component of MT-impedance Z. This phase tensor has been shown to be independent of distortion. For monitoring applications where the objective is to quantify the transient effects, e.g. prior and after stimulation or pumping/fluid injection, the relative phase difference tensor defined from the phase tensor at two different dates is introduced. The obtained results shows unexplained oscillations: there are several maxima of the signal (anomaly) that do not clearly correspond to known geothermal activity except two of them during well-stimulation periods, i) during acid injection and ii) during brine injection. Current work is done to test different hypothesis about these signals that could be generated, not just by geothermal activity at depth but additionally to the man-made geothermal activity, or from the compression and extension of the geothermal reservoir induced by earth tides causing electromagnetic signal.

1. INTRODUCTION

Changes in fluid pathways in the subsurface of a geothermal project during stimulation and operation are mainly recovered from micro-seismic monitoring. Micro-seismicity provides the location of fractures shear and open, but neither on fracture connectivity nor on the fluid content. Electromagnetic methods however are sensitive to conductivity contrasts and are typically used as a complementary tool to delineate reservoir boundaries (e.g. Geiermann et Schill 2010).

In this respect, in July 2011, an injection test for a ~3.6 km deep Enhanced Geothermal System (EGS) at Paralana, South Australia, was monitored by both micro-seismic and magnetotellurics (Peacock et al. 2013). First results from magnetotelluric (MT) measurement suggest transient variations in subsurface conductivity structure generated from the introduction of fluids at depth. Phase tensor representation of the time dependent MT response suggests fluids migrated in Northeast direction from the injection well. Results from this experiment support the extension of MT to be used as a monitoring tool for not only EGS project but also for other hydraulic stimulations.

Magnetotellurics is developing as a monitoring technique able to enhance changes in underground fluids or pore structures (see e.g. Peacock et al 2013 and references therein). In first attempts to use MT monitoring, classical parameters such as MT impedance or apparent resistivities have been used over volcanoes in order to show the relationship to volcanic activity (e.g. Wawrzyniak 2011). However in some cases (e.g. time changes of local shallow conductivity heterogeneities, i.e. well known galvanic problem), these classical quantities may yield misinterpretations because of their sensitivity to distortions; so we follow geothermal monitoring approaches based on phase tensors (Heise et al. 2008; Thiel et al. 2011; Peacock et al. 2013) rather than resistivity and phase analysis alone.

We consider the methodology of Thiel and Peacock (e.g. Thiel et al. 2011; Peacock et al. 2012, 2013) and add uncertainty estimates, with tests on our data sets collected in 2014 at the end of the first drilling experiment. Especially, we consider the possibility of MT to monitor a new enhanced geothermal site of a small injected water-volume, at Rittershoffen geothermal area apart from micro seismicity. This may contribute to the hydro – thermo – mechanical modeling and in hazard assessment. Well-test productions of the doublet wells are conducted in July-October at mean depth of 2.5 – 2.8 km.

We present the results obtained from continuous MT monitoring at RITT site (Fig. 1) around Rittershoffen geothermal site. We will focus on two tests: i) acid injection achieved in July 29-31st, and ii) brine injection achieved in August 21-30th.

2. MONITORING USING PHASE TENSOR

We used the basic principles of MT monitoring which consists in the processing of continuous records of the electric and magnetic field components to compute the phase tensor and phase tensor difference. First, the classical impedance tensor Z is defined in spectral domain as the solution to the linear relationship between the horizontal components H of the magnetic field and that of the electric field E; E = Z H. Each component of Z is represented by a complex value with real and imaginary parts; Z=X+iY, where X and Y are real numbers and i is the imaginary parameter. The apparent resistivity and phase are then classically determined from modulus and phase of each component of Z. In our case, we use the phase tensor (Caldwell et al. 2004) approach

$$\varphi = Y^{-1} X \qquad [1]$$

This phase tensor has been shown to be distortion-independent. In the monitoring application, Thiel et al (2011) and Peacock et al (2013) used the relative phase difference tensor defined from the phase tensor at two different dates (e.g. prior and after stimulation or pumping/fluid injection)

$$\Delta\phi_{1,2} = I_d - \phi_1^{-1}\,\phi_2 = \Delta\,\phi \qquad [2]$$

where indices 1 and 2 represent the dates 1 and 2 respectively.

Schematically, an ellipse can represent the relative phase difference tensor at a given frequency. In this way, a simple scalar can be used to represent the amplitude of relative phase difference: the average radius of the phase difference tensor with respect to the main (max) axis (Heise et al. 2008; Thiel et al. 2011)

$$\delta\phi_{1,2} = (\Delta\phi_{1,2}^{max}\,\Delta\phi_{1,2}^{min})^{0.5} \qquad [3]$$

Thiel et al. (2011) and Peacock et al. (2013) performed time lapse MT by comparing two measurement campaigns before and after injection at several locations around the stimulated area. In this study, we consider the possibility of continuous monitoring, in which phase tensor difference is accessed according to time that can be defined relatively to the initial state, or any other date or reference model.

3. FIELD EXPERIMENT

In 2013, MT fieldwork included three MT stations (Metronix-Cooper Tools) has been achieved. One station was installed at Welschbruch (WELSCH) Geophysical Station (about 75 km South of Rittershoffen, Fig. 1) as a remote reference (with MFS06 soft-coils magnetic sensors). A second one was installed at Rittershoffen at the RITT seismic station (about 1.5 km East to GRT1 geothermal well, Fig. 1); it was done using MFS06 soft-coils for the two horizontal components and MFS07e for vertical component. A third one was installed at OPS4 seismic observation station of the Soultz project (5 km to the West of the GRT1) using MFS07e soft-coils magnetic sensors. MT sample frequency for all stations was continuously 512 Hz.

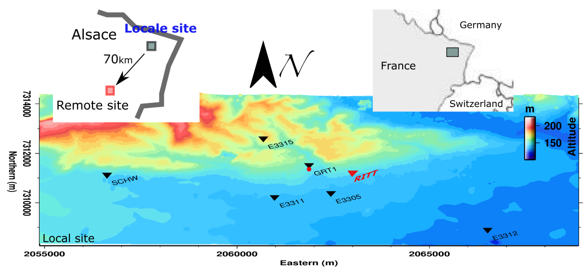

Figure 1: Location of MT sites used to monitor ECOGI geothermal well test production. GRT1 is the 1st geothermal well.

In 2014, a total of six MT stations (one permanent and five temporary) were installed from May to mid December (Abdelfettah et al 2015). As the experiment done in 2013, one station was installed in WELSCH and considered as a remote reference station (this time using CM13 magnetic coils). The permanent station is located at RITT (using MFS07 magnetic coils) in local site (Fig. 1) and is synced with reference remote station. In these two sites; i.e. RITT and WELSCH, the data are acquired continuously from June 1st to December 16th, 2014 (except a few gaps).

The time series, electrical (E) and magnetic (H) components, were recorded continuously with 512 Hz. During data acquisition, the time series were recorded in form of block having 23h59 of length (86340s). This daily basis is useful to avoid recording computation problems that might happen when dealing with big and huge .ats files.

4. DATA PROCESSING

To handle natural transient effects in the electromagnetic sources such as variable intensity, polarities and frequencies, data processing to estimate Z tensor was carried out using the well-known, robust Chave's code (Chave and Thomson 2004).
Handling the time series recorded with this sampling frequency (i.e. 512 Hz during 86340s), we can recover a maximum frequency of 4 Hz (using window length of 1048576). To recover the great periods, which may interest in geothermal depth (> 1 s), we need to process in the same run more than one day and decimate the complete signal. Basically, we used a series of three consecutive days in the single data processing reach the largest period of 100 s. Acceptable data uncertainties for both apparent resistivity and phase are obtained (Fig. 2). Notice however that uncertainties can be large at the minimum of the apparent resistivity around 10 Hz.

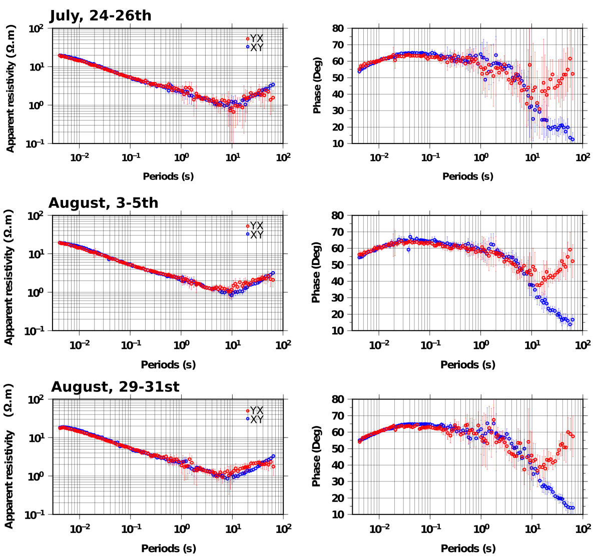

Figure 2: Representative apparent resistivity and phase computed at RITT for different periods between July and August.

Once the MT tensor Z is assessed, we used its components to compute the apparent resistivity and phase variations for each time series (i.e. 3 days block). Then, Z is converted to the phase tensor ϕ (PT) and phase difference tensor $\Delta\phi$ (PDT), parameters used in the continuous MT monitoring.

Additionally to PT and PDT, we decide to assess other related parameters as ϕ_{min}, ϕ_{max}, $\Delta\phi_{max}$ (also computed between 2 states), α, β, α-β and Δ(α-β). These parameters are interesting because they have scalar values and could be easily plotted as functions of frequency and time. The parameters $\phi_{min/max}$ and the angles α and β are used to represent graphically the tensor as an ellipse in the 2D assumption (see e.g. Caldwell and al. 2004, Fig. 1). The parameter α-β (or Δ(α-β)) is the skew angle which represents the angle variation of the tensor before and after specific event (like a geothermal well-test production).

5. RESULTS ANALYSIS

Several parameters are computed to evaluate the results obtained in MT monitoring experiment done in 2014, ECOGI geothermal site. We show and discuss hereafter from those, the critical parameters in time-lapse monitoring (temporary site) and in continuous monitoring (permanent site). Between mid-July and mid-October, several well test productions were performed in order to test the production but also to increase the secondary permeability and the hydraulic permeability. The 1st well-test production is done in 29-30th July where a quantity of Acid (HCl) was injected in GRT-1 in different depth (from 2.2 to > 3 km depth, done in 4 steps). The 2nd one is performed between 21 and 29th August, where water was injected in GRT-1. These two steps aims to clean and increase hydraulic permeability in the existing natural fractured system. Other well-test productions have been done after these two periods, but in this study we focused only to Brine and Acid injections.

5.1 Time-lapse monitoring

Five temporary sites were recorded in July-August 2014 before and after well test production was done. After this production test, we had been access to only four sites. Indeed, the site named E3311 located in Betschdorf forest (Fig. 1) wasn't possible to access again in Nov-Dec 2014. Finally, we have only four sites to analyze in time-lapse monitoring. In this study, we showed and discussed only SCHW site.

Our MT monitoring experiment is comparable to that performed in Paralana, south Australia, by Peacock et al (2013), where, in our case, four MT sites are recorded before and after well test production, but no purely hydraulic/chemical stimulation act was done compared to Paralana 2 experiment. Time-lapse monitoring results obtained for SCHW site are showed in Fig. 3, where ϕ_{max}, $\Delta\phi_{max}$, $\Delta\phi$ [equation 2] and α-β are presented. For each parameter, reference day was chosen according to the data uncertainty, giving priority to the day showing small and comparable uncertainties as that considered to continuous monitoring. It means that the day showing small data uncertainties is considered as the reference day and for all parameters. The aim is to be able to compare the time-lapse with continuous monitoring results, if comparable reference day (i.e. quite day!) was used. According to data uncertainties, the reference day chosen for SCHW site is August 1st. The reference day, which has been chosen, is quite stable and presents a small data uncertainties.

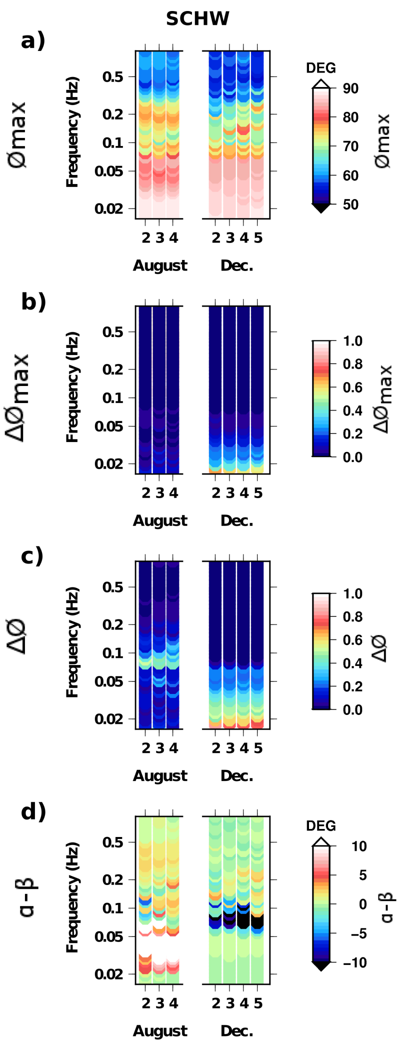

Figure 3: Time-lapse monitoring results obtained for SCHW temporary site showed in Fig.1. a) ϕ_{max}, b) $\Delta\phi_{max}$, c) $\Delta\phi$ and d) α-β.

In terms of monitoring, the studied parameters for SCHW showed a comparable behavior and values between before and after well test production. The values of ϕ_{max}, $\Delta\phi$ and α-β parameters acquired in August showed comparable values with those acquired during December. Few variations are visible nevertheless at specific frequencies for α-β and $\Delta\phi$. In general, the different studied parameters showed comparable values before and after well test production, which is expected because the quantity of injected fluid was very small compared with a real hydraulic stimulation which have done till now (e.g. at Basel and Soultz).

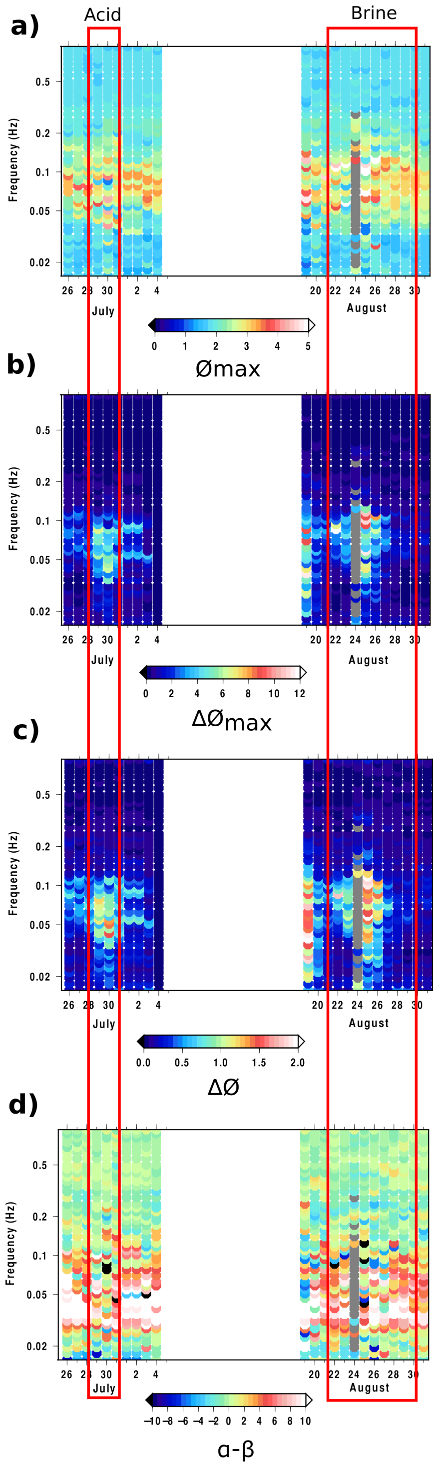

Figure 4: a) Quasi-continuous monitoring results obtained at Rittershoffen site (installed at ~1.5 km from GRT1) where two periods are only showed. a) ϕmax vs. days, b) ϕmax vs. days compared to ϕmax of August 4th, c) Phase tensor (Δϕ) relative to the reference day (August 4th) and d) Skew angle (α-β).

5.2 Continuous monitoring

Results obtained from the continuous monitoring experiment done in 2014, applied to Rittershoffen EGS geothermal project, are shown in Fig. 4. We consider only the critical parameters obtained from the permanent site named RITT: ϕ_{max}, $\Delta\phi_{max}$, $\Delta\phi$ and α-β. Depths of the geothermal reservoir are in the range of 2.5-2.8 km; if the skin depth is used as an estimate of the penetration depth, one can expect that any geothermal activity will be observed in the frequency range of 0.15-003 Hz. From our results at these frequencies, we observe that $\Delta\phi$ and $\Delta\phi_{max}$ (fig. 4b-c) parameters show successive positive anomalies that are not restricted to the geothermal events; for instance in July and August there are no other geothermal stimulation that have been conducted at ECOGI but we obtained additional phase variations with amplitude similar to those observed during the controlled activity (fig. 6), observed mainly immediately before brine stimulation. It is caused either by actual resistivity change at depth or by an artefact from signal noise; this can be discussed. The beginning of August is the period of withdrawal of the drilling platform. Although the frequencies are not comparable, it could generate some electromagnetic distortions that may, in addition to geothermal activity, affect MT response. Moreover, we thought that when the earth tides occur, the geothermal reservoir is deformed consequently, and electromagnetic signal may be generated when hot water moves throughout fractures and then generate electromagnetic signal that infer with the MT signal. This behaviour is mainly observed in the bottom of deep boreholes (e.g. at Soultz-Sous-Forêt) when water level oscillates according to tides. The variations of depth water vary from few centimeters to 0.5 m. More studies are conducted to quantify the expansion of the geothermal reservoir according to earth tides effect.

3. CONCLUSIONS

The first results obtained from Time-lapse and continuous MT monitoring in Rittershoffen area, showed small positive values of parameters $\Delta\phi$ and $\Delta\phi_{max}$. These signal anomalies obtained in frequency range (0.15-0.03 Hz) that are in agreement with both skin depth of MT and known geothermal depth of GRT1-2. Two of these anomalies are observed during acid and brine injection done in July and August in GRT1 geothermal well. However, other anomaly is observed in a period without controlled geothermal activity. More investigations are necessary to better understand the origin of this signal and analyse the days before. One hypothesis about the origin of this signal is the expansion of the geothermal reservoir by earth tides effect. We are undergoing more investigation to compute the residual between the synthetic earth tides and the computed one using water-level variation recorded in the bottom of the borehole. Besides, it is important to mention that ECCOGI project is concerned with geothermal circulation within existing fractures: there was no strong stimulation with huge injection; expected change in the electric properties is smaller than those concerned by other MT monitoring experiments published earlier.

Acknowledgements

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