Fluid injection monitoring of Rittershoffen geothermal project, northern Alsace, using magnetotelluric

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Keywords: Magnetotelluric, monitoring, Rittershoffen, Phase tensor analysis

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 ~3.6km deep EGS at Paralana, South Australia, was monitored by both micro-seismic and magnetotellurics (Peacock et al., 2012). First results from continuous magnetotelluric (MT) measurement suggest transient variations in subsurface conductivity structure generated from the introduction of fluids at depth. Furthermore, 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 a monitoring tool for not only Enhanced Geothermal System (EGS) 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, 2012). 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 (eg. 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 (Thiel et al. 2011; Peacock et al. 2013) rather than resistivity and phase analysis.

We consider the methodology of Thiel & Peacock 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 in the monitoring of a new enhanced geothermal site, at Rittershoffen geothermal area apart from micro seismicity, this may contribute to the hydro – thermo – mechanical modelling and in hazard assessment. Test productions of the double wells are conducted in July-October at mean depth of 2.5-2.8 km.

In this paper, we present the results obtained from continuous MT monitoring at RITT site (Fig. 1) around Rittershoffen geothermal site, northern Alsace before and after main hydraulic/chemical stimulations, which held in July-October.

MONITORING USING PHASE TENSOR

Basic principles of MT monitoring include 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 as the solution to following linear relationship between Fourier transforms of the horizontal components H of the magnetic field and that of the electric field E

$$E = ZH$$

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 determined from modulus and phase of each component of Z. In our case, we use the phase tensor (Caldwell et al. 2004)

$$\phi = Y^{-1}X$$

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

$$\Delta\phi_{1,2} = I_d - \phi_1^{-1}\phi_2 = \Delta\emptyset$$

where indices 1 and 2 stand the dates 1 and 2 respectively. In practice, these dates are the prior and after specific event. 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 relative phase difference: the average radius of the phase difference tensor with respect to the main axis (Thiel and Peacock, 2011)

$$\delta\phi_{1,2} = \sqrt{\Delta\phi_{1,2}^{max}\Delta\phi_{1,2}^{min}}$$

While Thiel and Peacock (2011) 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 difference is a time functional that can be defined relatively to the initial state (or any other date or reference model).

FIELD EXPERIMENT

In 2013, MT setup included three MT stations (Metronix-Cooper Tools). One station was installed at Welschbruch (WELSCH) Geophysical Station (about 75 km South from 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 to the East from the 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.

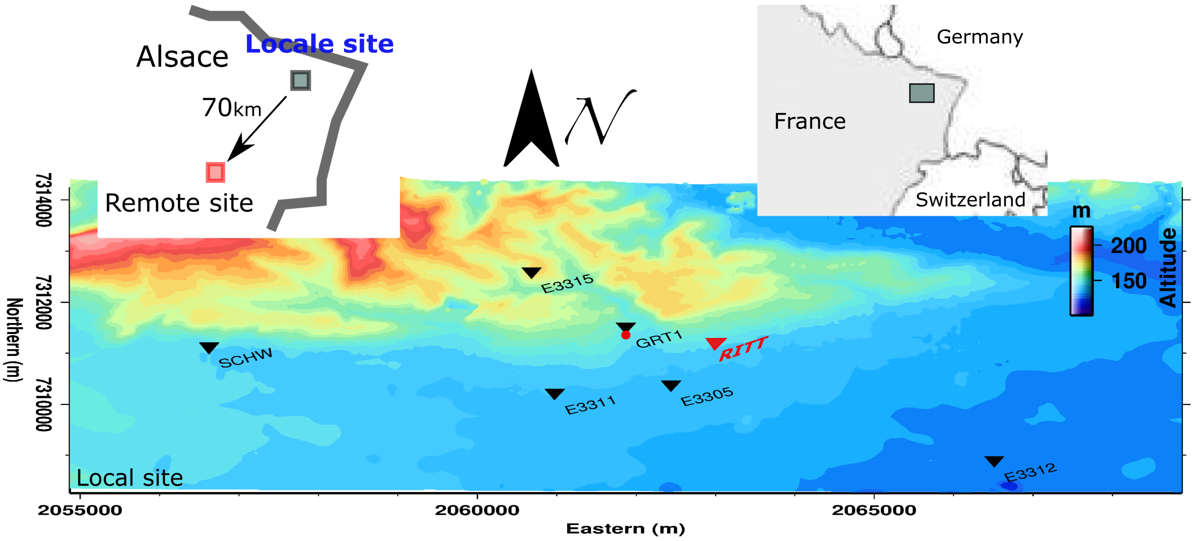

Fig. 1 sites location used to monitor Rittershoffen geothermal well test.

In 2014, a total of six MT stations (one permanent and five temporary) were installed from May 2014 to mid December. As the experiment done in 2013, one station was installed in WELSCH and considered as a remote reference station (using MC13 magnetic coils). The permanent station is located at RITT (using MFS07 magnetic coils) in local site (Fig. 1) and is synchronized with reference remote station located at WELSCH. In these two sites; i.e. RITT and WELSCH, the data are acquired continuously; accept few gaps, from June 1st to December 16th, 2014.

The temporary MT sites namely SCHW, E3305, E3311, E3312 and E3315 are located around GRT1 geothermal well in Rittershoffen city (Fig. 1a). Three stations (E3305, E3311 and E3312) had been installed in the southern part, in the Betschdorf forest, and two outside of it (E3315 and SCHW, Fig. 1a). Temporary sites recorded continuously for at least four days at each site, in July-August 2014, before well-test circulation. These last measurements are repeated in November-December 2014, more than one month after the well – test production was achieved which is done in Sept-Oct.

The time series, electrical (E) and magnetic (H) components, were recorded quasi-continuously with 512 Hz. During data acquisition, the time series were recorded in form of block having 23h59 of length (86340s). This is done to avoid the big and huge .ats files, which need strong computation tools to manage them.

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). Error bars were obtained using the error tensor of Wawrzyniak et al. (2013). Furthermore, uncertainties on the impedance were used to estimate uncertainties on the phase differences (Tartrat, 2014; Sailhac et al. 2014).

Handling the time series recorded with this sampling frequency (i.e. 512 Hz during 86340s), we can recover a maximum frequency of 1Hz. To recover the great periods, which may interest in geothermal depth (> 1s), we need to process in the same run several days and decimate the complete signal. Basically, we used a series of three consecutive days in the single data processing to get at the end a maximum period of 100s. Acceptable data uncertainties for both apparent resistivities and phase are obtained.

Once the MT tensor Z is assessed, we used it to compute the apparent resistivity and phase variations for each time series block that held to results showed in Fig. 3. Moreover and as discussed in section 2, we used it to compute the phase tensor ϕ (PT) and phase difference tensor $\Delta\phi$ (PDT), the parameters which used to perform 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 $\Delta(\alpha$-$\beta)$. 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 can help us to represent graphically the tensor in 2D assumption as an ellipse (see Caldwell and al., 2004, Fig. 1). The parameter α-β (or $\Delta(\alpha$-$\beta)$) represents the skew angle which shows the angle variation of the tensor before and after specific event (like a geothermal well-test production).

RESULTS ANALYSIS

Let us focus on results obtained in MT monitoring experiment done in 2014, in Rittershoffen geothermal area. We show and discuss only on critical parameters obtained during continuous monitoring (permanent site): ϕ_{max}, $\Delta\phi_{max}$, $\Delta\phi$ and α-β (Fig. 2).

Two geothermal events are currently analysed; i) acid injection held between July 28th and 30th and ii) brine injection held between August 21th and 29th (Fig. 2). MT parameters exhibit changes during these two events. The amplitude increases of $\Delta\phi$ and $\Delta\phi_{max}$ is the indication that the second state (during Acid/Brine) is different from the first one (i.e. reference day). Whereas $\Delta\phi$ and $\Delta\phi_{max}$ parameters show positive values, α-β varies to the negative values, and ϕ_{max} rather in positive values. The frequencies of these changes which we interpret as anomaly signals (0.15-0.03 Hz) correspond to geothermal depth known in this area. Concurrently, other anomaly signals are visible outside of the two main geothermal events, for instance in July and August. In the beginning of August, this 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 (Fig. 2). Moreover, we are analysing the three other well-test production which were achieved from September to end of October.

CONCLUSION

The first results obtained from continuous MT monitoring in Rittershoffen area, showed a signal anomaly during acid and brine injection done in July and August in GRT1 geothermal well. Significant positive values are observed in two parameters mainly $\Delta\phi$ and $\Delta\phi_{max}$, and significant negative values are obtained for α-β. These signal anomalies obtained in frequency range (0.15-0.03 Hz) that are in agreement with both skin depth of MT method and known geothermal depth of GRT1-2. However, an others signal anomalies are also observed in the period without "human" geothermal activity. More investigations are necessary to better interpret these results in conjunction with hydraulic data as well as anthropogenic information and forward modelling.

Acknowledgements

This work benefited from the support of LABEX "G- EAU-THERMIE PROFONDE" and of the Institut für Nukleare Entsorgung INE-KIT.

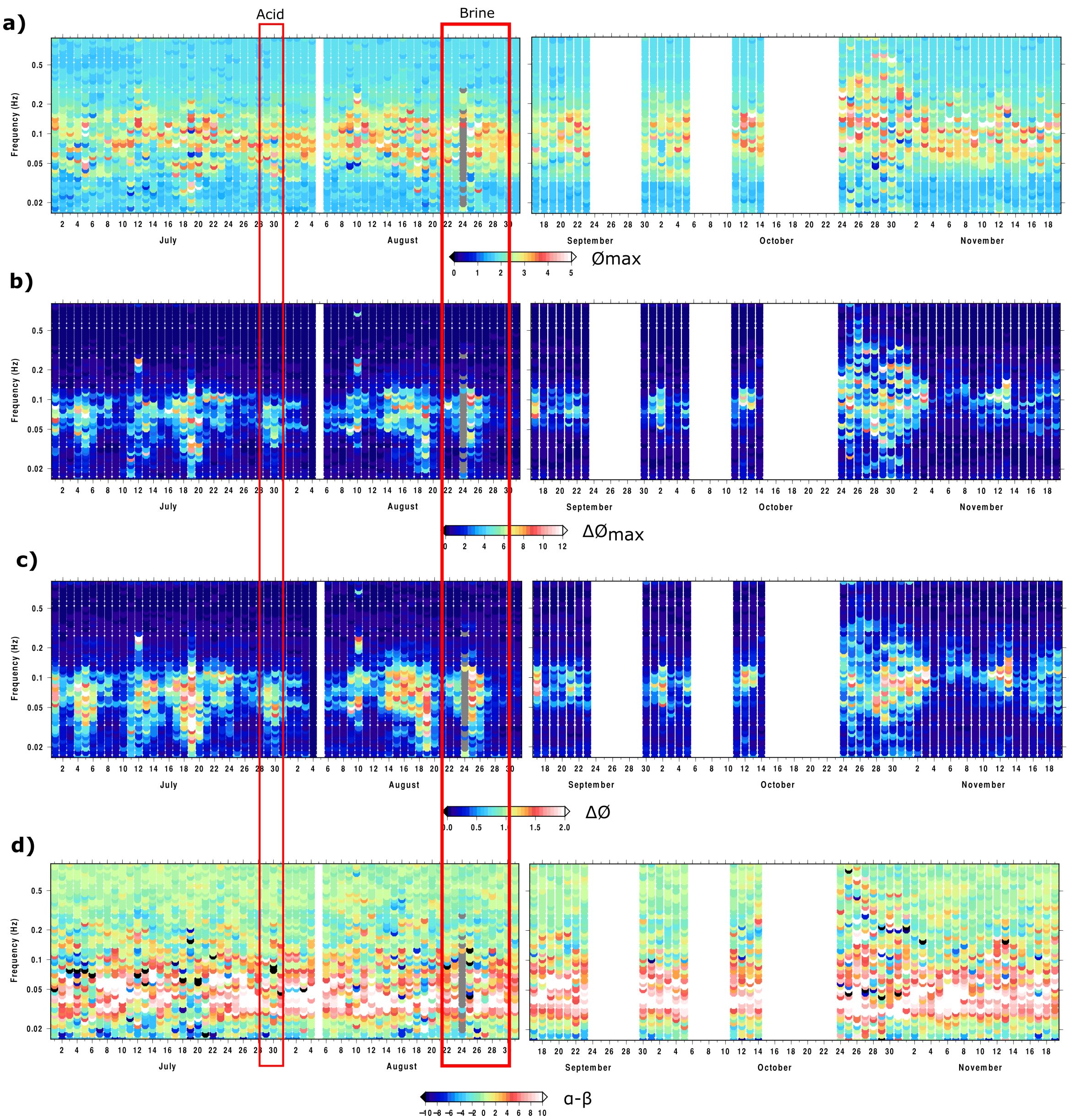

Fig. 2 : a) Quasi-continuous monitoring results obtained at Rittershoffen site (installed ~1.5 km from GRT1) from July to November 2014. a) ϕ_{max} vs. days, b) ϕ_{max} vs. days compared to ϕ_{max} of August 4th, c) Phase tensor ($\Delta\phi$) relative to the reference day (August 4th) and d) Skew angle (α-β).

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