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Electromagnetic monitoring of the Groβ Schönebeck stimulation experiment

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Introduction

The sensitivity of electrical and electromagnetic (EM) methods to the presence, distribution, and flow of fluids within the earth makes them ideal for studying a range of geological and engineering problems. These methods are commonly applied to a range of engineering problems ranging from site characterization for bridges and dams to the monitoring of effluent plumes to mineral exploration [*Pellerin,* 2002]. In recent years, EM methods have further gained acceptance as a valuable monitoring tool for volcanic hazards, and are currently being employed to investigate the dynamics of the earthquake cycle [*Mueller and Johnston,* 1998].

The Molasse and North German basins are the source of most of Germany's geothermal heat production [*Clauser,* 1997]. Temperatures and transmissivities in these basins are high enough for direct heat production, however a lack of natural steam reservoirs, has prevented electrical power generation. The feasibility of electric power generation is currently being investigated in the North German basin using concepts traditionally applied at hot dry (crystalline) rock sites. Using a pair of boreholes, a fracture network is created via fluid stimulation. This fracture network functions as an underground heat exchanger during the injection and uptake of cold and warm waters, respectively.

The Groβ Schönebeck borehole, with a downhole temperature of ~140°C, is located ~50 km north of Berlin [http://www.gfz-potsdam.de/pb5/pb52/projects/GeothermieLabor/]. This 4300m deep borehole, originally a natural gas exploration well, terminates in (relatively) impermeable volcanic basement. Immediately overlying the basement is the Rotliegend sandstone. With its high porosity and transmissivity, the Rotliegend (4100-4250 m depth) is the target of fluid injection at Groβ Schönebeck.

Both the self-potential (SP) and magnetotelluric (MT) methods are well suited to the monitoring of subsurface fluid stimulation. SP is sensitive to the flow of waters through a porous network, while MT is sensitive to changes in conductivity due to the connected fluid network formed during stimulation. SP studies at the Soultz hot dry rock site found a clear correlation between fluid injection (5km depth), induced seismicity, and measured SP data [*Marquis et al.,* 2002]. We present a MT monitoring study of the GS borehole aimed at determining the sensitivity of surface based MT data to fracturing processes at depth.

For the purpose of magnetotelluric monitoring, we are interested in changes in bulk resistivity at 4 km depth associated with the stimulation. There are three primary mechanisms which may produce a resistivity change: 1) a change in pore geometry, 2) a change in porosity, and 3) a change in fluid resistivity. The first two processes are expected to give rise to a decrease in resistivity during and for some time after stimulation. The third could produce a decrease or increase in resistivity depending on the relative salinities of the host and injected fluids. Given the known chemistry of the host and injected fluids, it is unlikely that the third mechanism will result in a significant resistivity change. Furthermore, the constraining pressures at 4km depth make it unlikely that a significant increase in porosity will accompany stimulation. The first mechanism, in which stimulation produces a more crack-like pore geometry is expected to be the dominant process. The question remains whether MT can detect a resistivity change at 4 km depth during the stimulation? The size of the area stimulated, the magnitude of the resistivity decrease, the resistivity of the overburden, and the amount of noise in the data will all effect the results.

Data Acquisition and Analysis

Data were acquired over a one month period in winter 2003. The monitoring layout consisted of two magnetotelluric sites located at 500m and 2500m distance from the borehole. In addition, 16 sites measuring only electric fields were aligned along two orthogonal profiles extending SE and SW from the borehole (Figure 1). These profiles followed existing dirt paths and the presence of a major road prohibited the placement of sites north of the borehole. Sites were further located a minimum of 500m from the borehole in order to minimize electrical noise associated with the stimulation itself. A remote reference site was occupied ~15 km north of the borehole, however a combination of equipment failures and cultural noise rendered date from this site unusable.

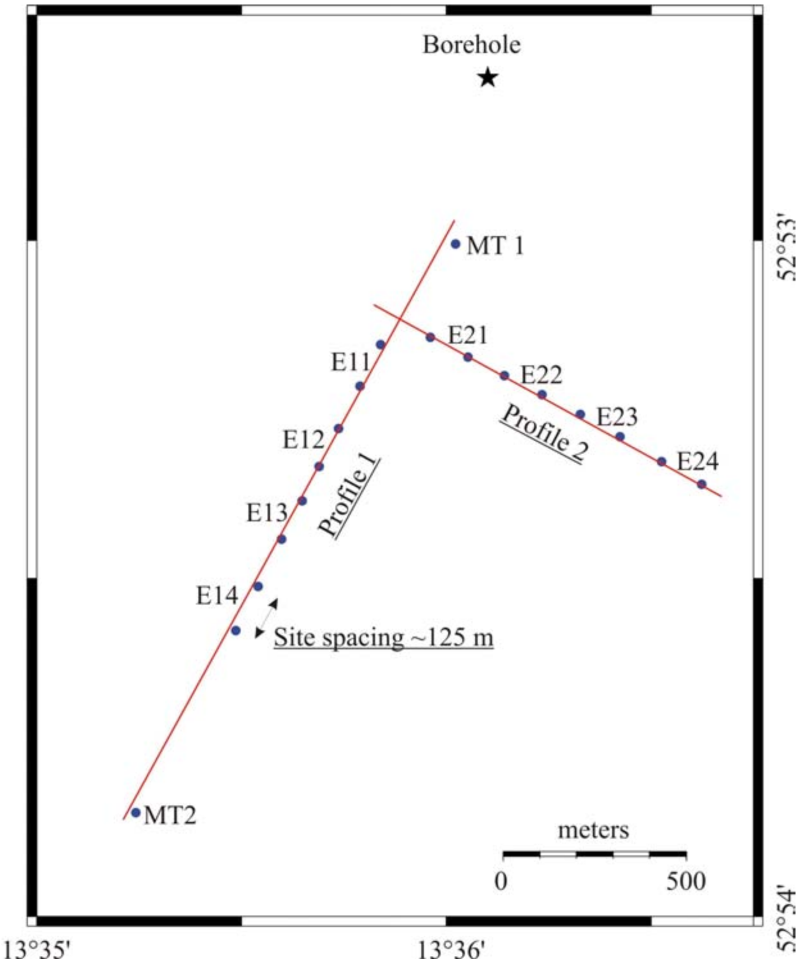

Figure 1: Local EM monitoring array surrounding the Groß Schönebeck borehole. Layout consisted of 16 electric field sites in addition to two 5 channel MT sites.

Data were recorded continuously at 125 Hz with GPS synchronization for the duration of the survey. Some time gaps occurred due to battery and equipment failure (Figure 2). The magnetic fields recorded at the MT sites were combined with the electric field data to produce full impedance estimates at 18 sites. For monitoring purposes, impedances were calculated in 2-4 day time windows stretching from one week before to one week after the stimulation. Figure 3 shows MT sounding curves for site MT1, closest to the borehole, for the two days prior to the stimulation. The period range of interest, denoted by the red box, is based upon the depth of the injection (4km) and the average resistivity of the overburden (1-10 Ω•m). Unfortunately, there is significant up-bias in the curves in this band, hindering our monitoring efforts. This noise is present on all sites during all but the first and last time windows.

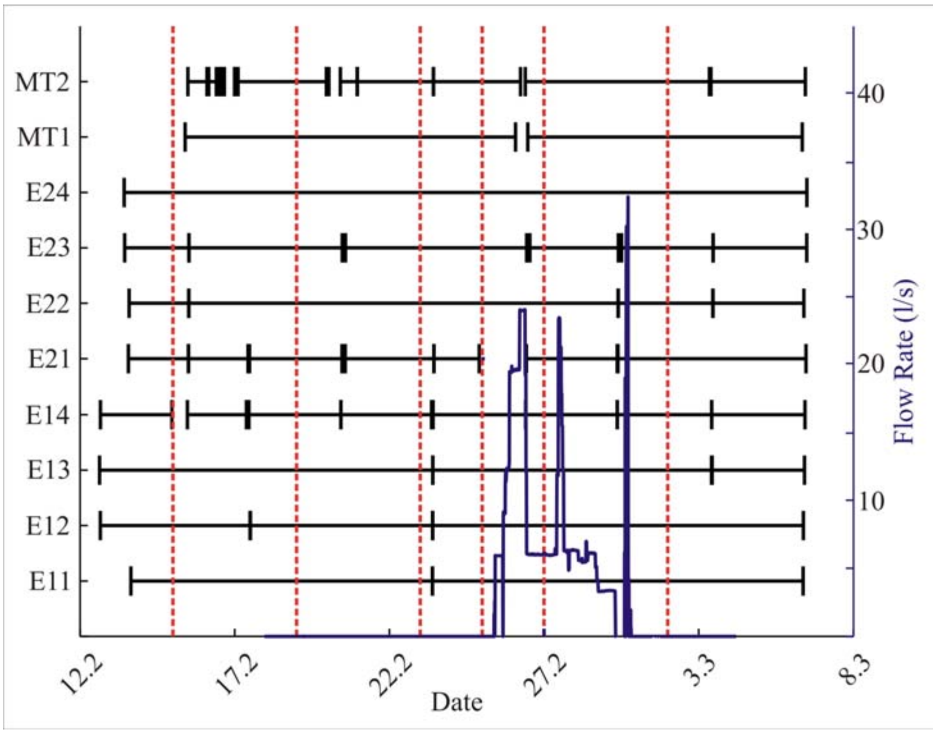

Figure 2: Timeline of the Groß Schönebeck MT experiment. Horizontal lines indicate the time periods during which the electric sites (E11-E24) and MT sites (MT1,MT2) were recording. Superimposed curve specifies flow rate during the primary injection. The timeline has been divided into 6 time segments (dotted lines) for monitoring purposes.

Given the problems with noise, we proceeded to isolate the cleanest impedance estimates in order to arrive at some comparison of resistivity structure before and after stimulation. Two segments, each of one day duration, were selected for further analysis. These segments occurred six days prior and eight days following the stimulation. Impedance estimates from sites along profiles 1 and 2 (Figure1) were then inverted to give resistivity models both before and after stimulation. The similarity in model structure and data misfit for inversions of profiles 1 and 2 (not shown) suggest a one-dimensional earth structure from the surface to ~5 km depth. This can additionally be seen in the individual sounding curves (Figure3), which lie coincident at periods less than ~100s.

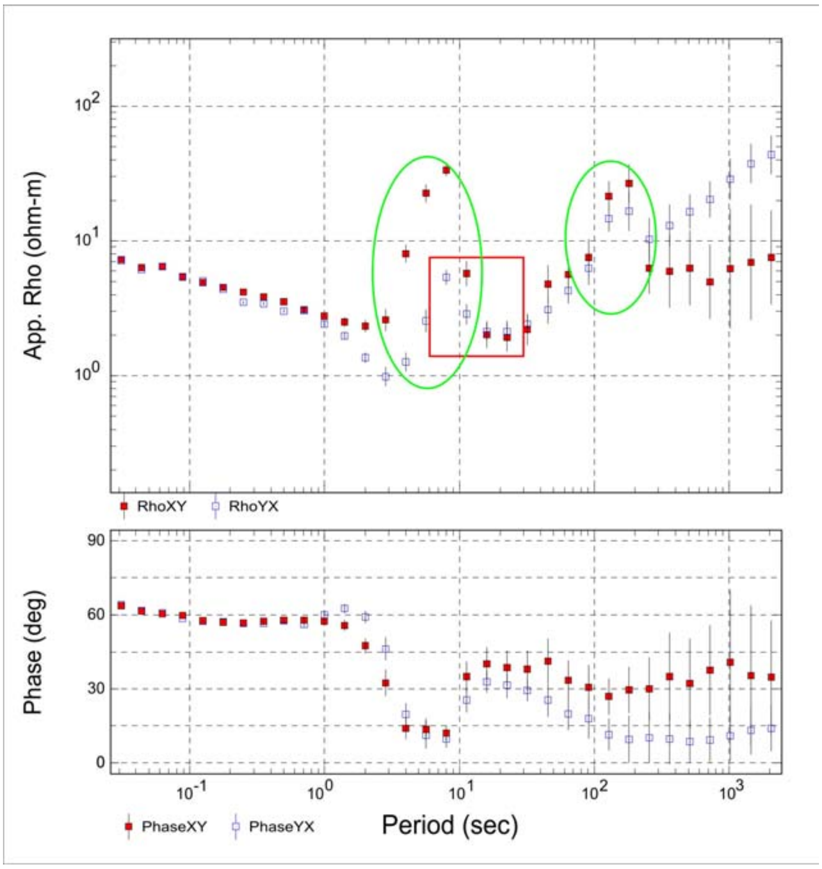

Figure 3: MT sounding curves at site MT1 for a two day window immediately prior to the stimulation. For monitoring purposes, the period range of interest is from 6-30 seconds and is based on the depth of the injection (4km) and the average resistivity of the overburden (1-10 Ω•m). This region is denoted by the box; ellipses indicate period bands with significant noise disturbance.

The inversion algorithm of Mackie and Rodi [2003] was used, which minimizes both the smoothness of the model and the misfit to the data. The resulting resistivity models for profile 1 are shown in Figure 4. The resistivity structure surrounding the GS borehole consists of a surface layer of intermediate resistivity overlying a thick, highly conductive layer (depth: 0.5km to >2 km). This high conductivity lies primarily within the Cenozoic sediments and drops to resistivities of less than 1 Ω·m. The presence of such a layer, with a conductance of 750 - 1000 S, above our target is problematic, as regions of high conductivity act to screen underlying structure.

Note that little difference is seen between the two models. This suggests that any resistivity changes associated with the stimulation either 1) occur on length scales shorter than one week, and/or 2) are masked at the surface by the aforementioned upper-crustal conductor. In order to further investigate these possibilities, a modeling study has been undertaken.

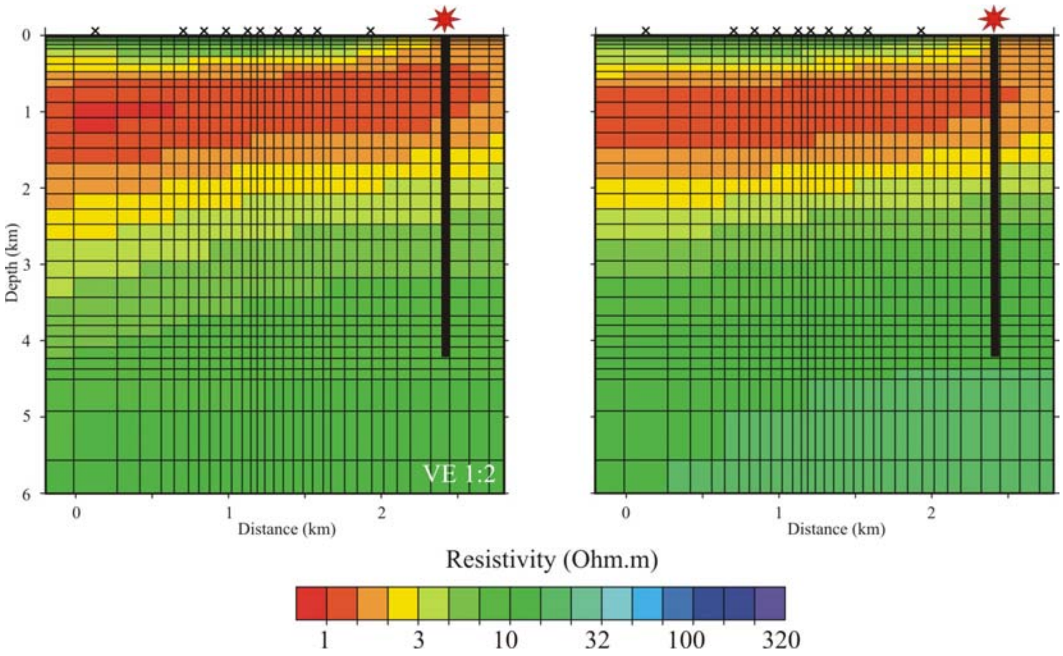

Figure 4: Resistivity models for profile 1 based upon a single day of clean data a) six days prior to the stimulation, and b) one week following the stimulation. The location and depth extent of the borehole are indicated. Negligible differences can be seen between the two models indicating that any resistivity change associated with the stimulation is no longer observable one week later. This does not preclude the possibility of an observable change during or immediately following the stimulation.

Modeling Studies

In order to evaluate the feasibility of magnetotelluric monitoring in this environment, it is useful to examine the sensitivity of MT to conductivity changes at depth. In particular, given the prominent conductor between the surface and the injection point, how large of a change is measurable? Through forward modeling, we can artificially impose a conductive fracture zone around the injection point. We can then calculate the surface response and compare this to the response of the unaltered model.

Assuming the stimulation creates a fractured 'halo' about the injection point, the surface sensitivity will primarily depend upon the resistivity change (relative to the background resistivity) and the spatial extent of the fracture zone. The size of the fracture zone can be estimated from the rate and duration of fluid injection together with an average porosity of 10% (based on borehole logs). For the stimulation profile shown in Figure 2, it is estimated that a spherical region of roughly 50m diameter will be affected (word suggests to use affected?!). The magnitude of the resistivity change can also be estimated given the resistivity at 4km depth (~10 Ω·m, see Figure 4). Using Archie's law, and assuming a change from a spherical to crack-like pore geometry, a ten-fold decrease in bulk resistivity can be expected.

The question is thus whether MT can differentiate between models with and without a 50 m diameter sphere of 1 Ω·m embedded at 4km depth within the model in Figure 4. As is to be expected by anyone familiar with the MT method, the answer is a resounding no. Given the diffusive nature of MT, combined with the screening effect of the overlying conductor, it is not surprising that such a model perturbation is invisible to MT. It is, however, of interest to examine how large a region must be effected before MT can ‘see’ the stimulation. Toward this end we modeled a range of fracture volumes (200m to 1000m diameter) and resistivity changes (10x to 100x decrease). One such result is shown in Figure 5, for a spherical fracture zone of 1000m diameter and a resistivity decrease of 30x relative to the surroundings. A small, but measurable change is observed in the TE mode, primarily in the phase response. From the range of forward models studied, it is found that a large resistivity decrease (30x or greater) and/or a large fracture volume (800m+ diameter) is necessary to produce a measurable change in surface MT measurements.

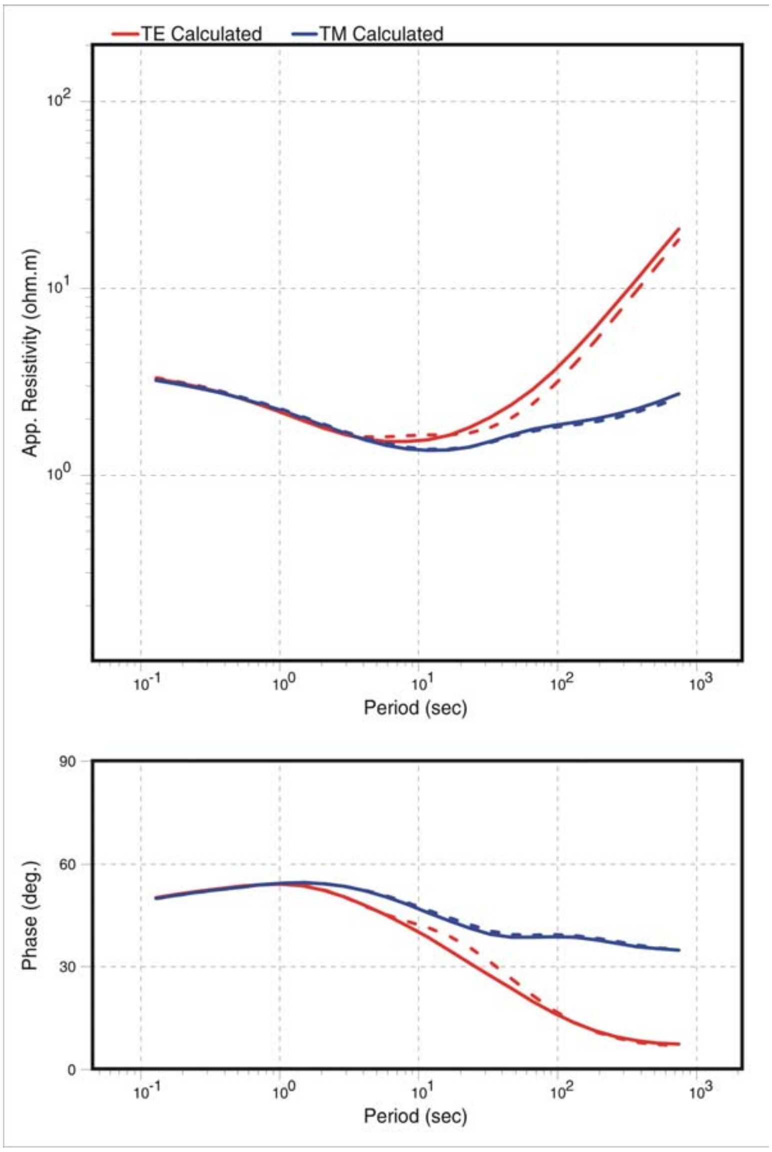

Figure 5: Surface MT response above a 1000 m diameter spherical fracture zone (dashed line) with a 30x resistivity decrease. Response of unaltered resistivity model (solid line) is shown for comparison. An observable surface responses require either a relatively large fracture volume, a strong decrease in resistivity, or a combination of the two. Based on the injection flow rate and average porosities, a more modest fracture volume is expected. Additionally, a resistivity decrease beyond 10x is not expected.

Conclusions

Magnetotelluric monitoring was carried out during winter 2003 at the Groβ Schönebeck stimulation site. Two MT sites and sixteen electric-field sites continuously monitored a stimulation reaching flow rates of 20 l/s during this period. Significant electromagnetic noise in the frequency range of interest precluded the analysis of data during and immediately following the stimulation.

A comparison of undisturbed data acquired one week before and after the stimulation showed no observable change in the resistivity structure. This suggests that long-term (1 week) effects on the resistivity, if any, are not resolved by surface data.

Modeling studies were undertaken to evaluate the sensitivity of MT data to resistivity changes at the injection depth. These studies find that a large resistivity decrease and/or large fracture volume are required to produce a measurable surface change. The highly conductive near-surface layer surrounding the Groβ Schönebeck borehole effectively masks deeper changes associated with the stimulation. MT monitoring offers more promise in more resistive regions, such as the Soultz HDR site, where the background resistivity is ~1000 Ω·m [*Marquis et al.,* 2002]

There is evidence that the nature of fracturing is different than that assumed. Post-injection logging suggests that stimulation resulted in a few primary conduits for fluid transport rather than a distributed fracture network. This is not, however expected to change the results presented here. To the contrary, fluid transport via focused conduits would effect a volume smaller than that estimated herein. Though highly conductive, these fluid-filled fractures would have a minor effect on the volume-averaged bulk resistivity.

References

Clauser, C., Geothermal energy use in Germany – status and potential, *Geothermics, 26,* 203-220, 1997.

Marquis, G., M. Darnet, P. Sailhac, and A. K. Singh, Surface electric variations induced by deep hydraulic stimulation: an example from the Soultz HDR site, *Geophys. Res. Lett, 29,* doi:10.1029/2002GL015046, 2002.

Mueller, R. J. and M. J. S. Johnston, Review of magnetic field monitoring near active faults and volcanic calderas in California: 1974–1995, *Phys. Earth and Planet. Int., 105,* 131-144, 1998.

Pellerin, L. , Application of electrical and electromagnetic methods for environmental and geotechnical investigations, *Surv. in Geophys., 23,* 101-132, 2002.

Rodi, W., and R.L. Mackie, Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion, *Geophysics, 66*, 174-187, 2001.