Magnetotelluric investigation of the Northern Swiss Heat Flow Anomaly

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ABSTRACT

The North of Switzerland hosts a prominent heat flow anomaly, with an enhanced near-surface heat flux compared to the Swiss average. The anomaly is situated within the permo-carboniferous trough and one hypothesis about its origin is that geothermal fluids migrate upwards along permeable pathways, carrying heat from the crystalline basement into shallower layers. We performed a magnetotelluric (MT) survey covering the extent of the anomaly over the permo-carboniferous trough. In order to overcome the noise problem related to power-lines and local infrastructure we tested different processing methods using multiple remote reference sites and discuss the feasibility of MT measurements in densely populated regions. Ultimately, MT responses are planned to be inverted for a 3-D conductivity model using state-of-the-art inverse solvers, which have been recently developed at ETH Zurich. Besides the impedance tensor, which is the standard MT response, we interpret newly introduced inter-site transfer functions, which are free of galvanic distortion effects such as static shifts. A recovered 3-D resistivity model could help to determine the geometry of the permo-carboniferous trough and to identify permeable structures within it and the crystalline basement. These results would provide important information about the nature and origin of the heat flow anomaly

1. INTRODUCTION

Northern Switzerland exhibits near-surface heat fluxes that exceed the Swiss average by a factor of two (Figure 1; Medici and Rybach, 1995). The anomaly lies above a permo-carboniferous trough. Information about the region comes mainly from geologic studies of the Swiss Molasse basin (Mazurek et al., 2006), 2-D seismic data (Naef et al., 2014), logging data from boreholes (Weber et al., 1985), and analysis of thermal springs (Sonney and Vuataz, 2008). Though these, and related studies offer some insights, significant uncertainties about the nature of the elevated heat flux remain. Two main, non-exclusive hypotheses exist (Figure 2): I) Heat advection by groundwater could transport heat from recharge areas of higher altitude in the north (Black Forest) and/or the south (Alps) laterally at relatively shallow depths to the region (Pearson et al., 1991) increasing the geothermal gradient and thus heat flux near the surface.

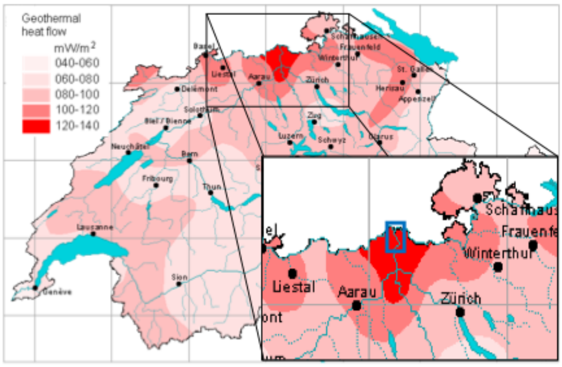

Figure 1: Geothermal heat flow map of Switzerland (modified from Medici and Rybach, 1995). The blue rectangle is the region of our study depicted in Figure 3.

II) Groundwater from permeable zones in the crystalline basement underneath the permo-carboniferous trough (Pearson et al., 1991, Kohl et al., 2003) could ascend along tectonic faults and mix with shallow groundwater. The chemical and isotopic signature of thermal waters, sampled in the region, indicates that it may stem from deep-rooted circulation in "aquifers" within the crystalline basement underneath the permo-carboniferous trough (Pearson et al., 1991, Kohl et al., 2003).

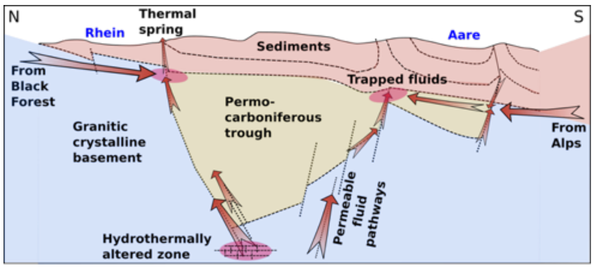

Figure 2: Conceptual model cross section (for location see Figure 3) of the permo-carboniferous trough based on a seismic 2-D section (Naef et al., 2014). Note that the exact extent of the trough could not be determined from seismic data. The figure shows possible, but highly uncertain, fluid pathways and storage within the trough and the basement.

If Hypothesis II is true, then the heat-flow anomaly would be much deeper-rooted than when Hypothesis I is true. A deeper-rooted geothermal system would suggest that geothermal temperatures are elevated, relative to the Swiss' average at a given depth, down to several kilometers and not just a near-surface phenomenon, thereby making these zones at depths of several kilometers (3-5 km) potential targets for geothermal energy production (Kohl et al., 2003). Geophysical tools that allow mapping of the basement structure could provide important information in order to identify weak zones in the crystalline basement that act as deep-rooted fluid pathways.

However, seismic studies, conducted in the permo-carboniferous trough, have faced difficulties in mapping the transition between the strongly folded trough and the crystalline basement, so that the trough's structure remains unclear (Naef et al, 2014). If MT data of sufficient quality can be acquired in the region of the surface heat flux anomaly, an electrical conductivity model, recovered from MT data, would significantly improve knowledge about the underlying nature of the anomaly.

2. MT SURVEY

A first-time MT survey in the region of the Aargau heat flow anomaly was conducted in early 2016. The study aims at getting an overview on local EM-noise and ultimately to generate a first subsurface 3D electrical conductivity model of the region.

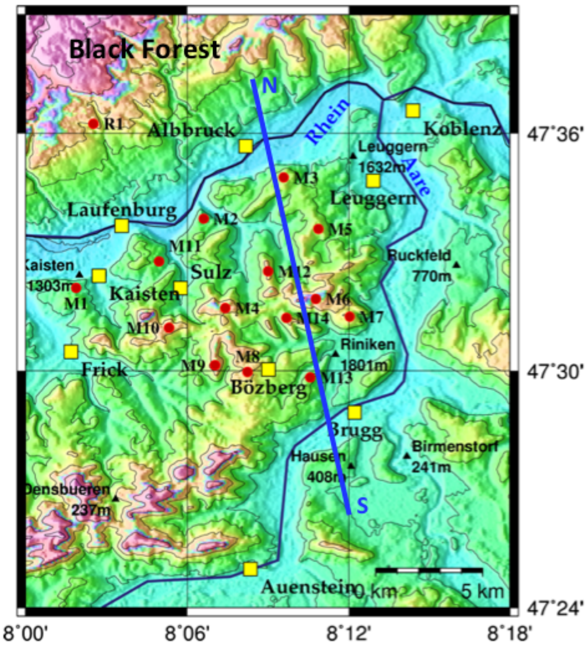

Figure 3: Map of the MT survey region of the Aargau heat flow anomaly (Figure 1). Red dots: measured MT sites M1-M14. R1: reference site; Black triangles: well locations and their depths; Yellow squares: cities. The N-S section is shown in Figure 2.

The survey design allows estimation of MT responses with robust remote reference techniques using a reference site. The current MT measurement grid can be refined and expanded in the future. The measurements were carried out using 3 broad-band Metronix ADU-07e MT stations. Over two and a half months, fourteen sites were measured in addition to the permanent remote reference station in the Black Forest, Germany (R1 in Figure 3). Of the fourteen sites visited in Aargau, two failed, one due to excessive noise (M3) and the other due to a cut cable (M12).

Each site was occupied for at least three days and sampling frequencies of 128Hz and 4096Hz were used. High frequency data was recorded on site setup and dismantling.

3. CURRENT STATUS OF RESEARCH

3.1 MT data

The twelve successfully measured sites show varying degrees of noise. Clearly visible at all sites is noise related to powerlines and electrified railways, which can be seen in the power spectral density plots of site M6 (Figure 4). Impedance tensors were calculated for all sites using both single site and remote reference processing. In Figure 5, the remote reference processing result for site M6 is shown.

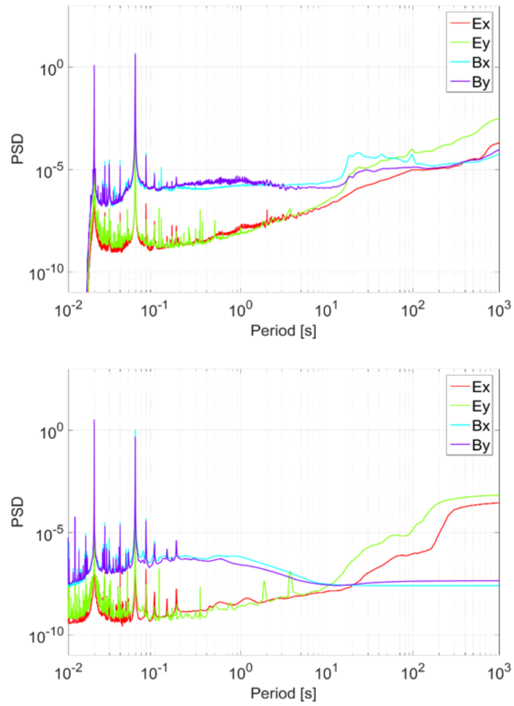

Figure 4: Power spectral densities for site M6 for sampling rates of 128Hz (top) and 4096Hz (bottom).

From Figure 5, it is evident that the phase drops to around zero in the period range 0.1s-100s. This is possibly indicative of a controlled source effect and has to be analysed further.

In a report produced by Becken et al. (2015) for NAGRA, a 1-D electrical resistivity model was created using resistivity logs from the Benken borehole as a reference. The MT response of the so constructed model (Figure 6) also shows a drop in phase between a similar period range as the results from site M6, though the drop in phase is not quite as severe.

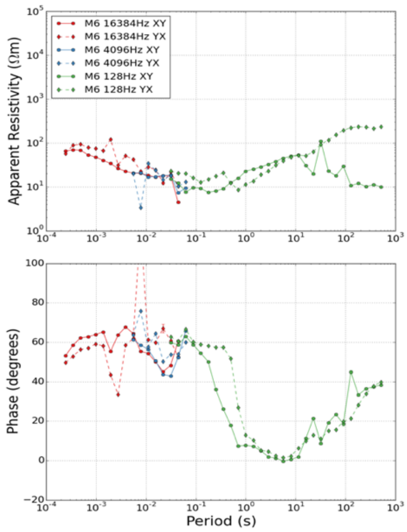

Figure 5: Apparent resistivity and phase for site M6. Note the drop in phase in the period range 0.1-100s.

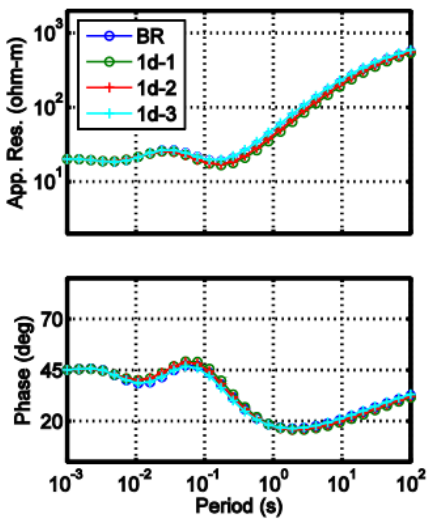

Figure 6: Apparent resistivity and phase from a 1-D model study by Becken et al. (2015)

3.1 Modelling studies

In addition to the field campaign and upcoming inversion of MT data, a 2-D modelling study is underway to understand the sensitivity of MT responses to various subsurface structures.

The structure of the initial model is based on an interpretation of seismic data in Naef at al. (2014). Electrical resistivity values are taken from Becken et al. (2015) in addition to resistivity log data from various boreholes, including Riniken, Weiach and others (Weber et al., 1985). The initial model can be seen in Figure 7.

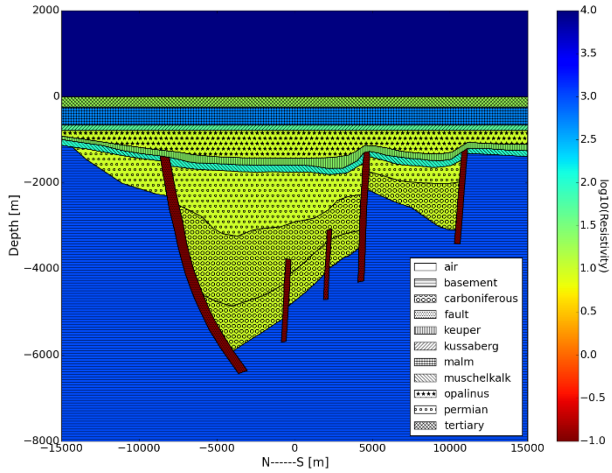

Figure 7: Electrical resistivity model for the modelling study. The resistivity data are based on borehole logs (Weber et al., 1985, Becken et al., 2015).

The plan for the modelling study is to begin with simple models before moving to increasingly complex models, with smaller-scale, electrically conductive features which are representative for permeable fluid pathways. If possible, the effect of topography will be investigated by including a model with an eroded and deformed surface. The aim of the study is to understand the types of structures which can be successfully recovered through an inversion of real data and the extent to which local topography may influence the MT data. As part of the study, modelled data will be corrupted with noise and inverted to see how sensitive measurements might be to noise.

For the modelling studies we use the GOFEM code developed by Grayver (2015). GOFEM is based on a high-order FE method and exploits frequency-dependent automatic mesh refinement techniques for both forward and inverse model parameterizations. The adaptive meshing procedure allows refinement of meshes at discontinuities such as faults. Further advantages of GOFEM can be found in the source paper.

4. CONCLUSIONS AND OUTLOOK

For the first-time, MT data have been measured at the Northern Switzerland heat flow anomaly. Difficulties have been faced obtaining high data quality using standard MT data processing techniques and more work will be done in order to obtain higher-quality MT responses. Modelling studies are conducted to analyse the capability of the MT method to recover the general shape of the permo-carboniferous through and identifying electrically conductive structures within the through and the basement that might represent permeable fluid-saturated regions at depth.

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