Magnetotelluric measurements to explore for deeper structures of the Tendaho geothermal field, Afar, NE Ethiopia

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Introduction

In regions with high heat flow, like at volcanically active plate margins, high total thermodynamic energy is accumulated in the so called high enthalpy resources. The East African Rift System is one of the privileged areas to yield numerous sites for potential geothermal energy extraction including power generation. Along the Ethiopian part of the rift high temperature geothermal resources are associated with zones of quaternary tectonic and magmatic activity. Including the Afar depression at least 120 independent geothermal systems have been identified since the 1970s (UNEP 1973) about 24 of them are judged to have high enthalpy potential. To explore for these resources up to a pre feasibility stage a range of geoscientific methods is used in a defined sequence starting with regional reviews and remote sensing followed by geologic, hydrologic, geochemical and geophysical surveys.

The applied geophysical methods usually comprise temperature measurements (gradient boreholes), seismology, magnetics and resistivity methods, including Magnetotellurics (MT). Geothermal surface manifestations like hot springs, fumaroles, geysers and the associated geological and geochemical settings are indicating the presence of a geothermal reservoir.

Particularly resistivity methods may be used for delineating the lateral and depth extensions of such potential reservoirs. The MT method is frequently used for this purpose since it easily covers the necessary exploration depth down to approximately 10 km.

In the following paper MT data and interpretation is presented, showing the already known shallow reservoir of the Tendaho geothermal field and its so far unknown deep structure, possibly feeding the shallow reservoir.

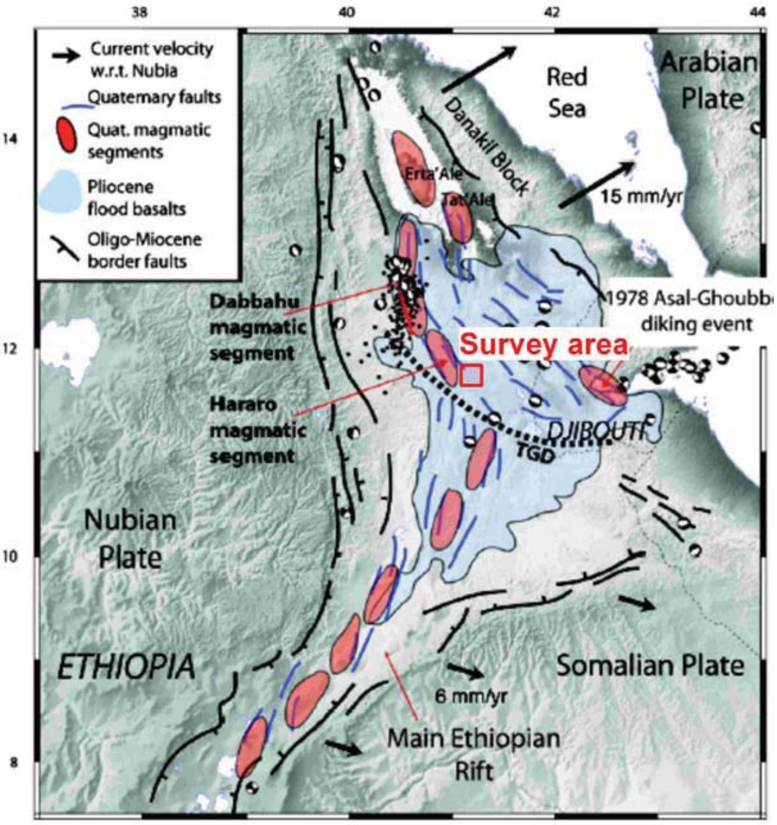

Figure 1: Survey area at the SE end of the Hararo and Dabbahu magmatic segments. TGD = Tendaho-Goba'ad Discontinuity (after Ebinger et al. 2008).

Survey area and tectonic setting

The Tendaho geothermal field is located in the Afar depression (NE Ethiopia), at or very close to the assumed triple junction formed by the Red Sea, Gulf of Aden and East African rift arms. The extension of the Manda-Hararo axial rift zone in its south-easterly strike direction ends up at the Tendaho geothermal system (figure 1). The Red Sea and Aden rifts are characterised by oceanic crust. The Afar triple junction is therefore a zone where thinned continental crust of the Main Ethiopian rift joins with crust of oceanic character (Barberi et al. 1972).

Within this area of active extensional tectonics several geothermal manifestations can be observed. Quaternary faulting and volcanism formed chains of fissural flows, basaltic cones and stratovolcanoes, usually accompanied by shallow seismicity and positive gravity anomalies. These active magmatic segments are comparable to slow spreading mid oceanic ridge segments and are thought to form new igneous crust by dyke like intrusions as demonstrated in the recent Dabbahu rift events (since 2005 up to now) just 80 km NW of the survey area. A previously mapped magmatic segment within the Manda-Hararo rift zone had been ruptured. Earthquake recordings indicated a 60 km long and about 8 m wide dyke intrusion (Ebinger et al. 2008, figures 8 & 9).

Tendaho geothermal field

The Tendaho geothermal field has been investigated in detail since the 1980s. Geological, geochemical as well as magnetic, seismological and resistivity data (DC soundings) were acquired by an extensive Ethiopian-Italian cooperation (Aquater, 1996). Based on this results, six exploratory wells had been drilled, three of them hitting a production horizon at approx. 300 m depth yielding steam temperatures above 250 °C (figure 2). Additional gravity and magnetic data had been acquired recently by Lemma and Hailu (2006) to delineate fractured zones which could serve as potential pathways for hydrothermal fluid flow from a deeper reservoir.

Figure 2: Production test of well TD5 (at well head: T >250 °C, p > 18 bar). The well is located inside the MT survey area.

To further investigate the proposed deep reservoir and/or heat source, deep reaching resistivity methods had to be applied. Due to the generally low resistivities the penetration depths of the DC soundings were limited to a few hundred meters. To extend this depth of exploration the MT method has been applied by BGR in collaboration with the Geological Survey of Ethiopia (GSE) during a field survey in 2007 (figure 3). To reach the desired exploration depth of about 5 km a frequency range from

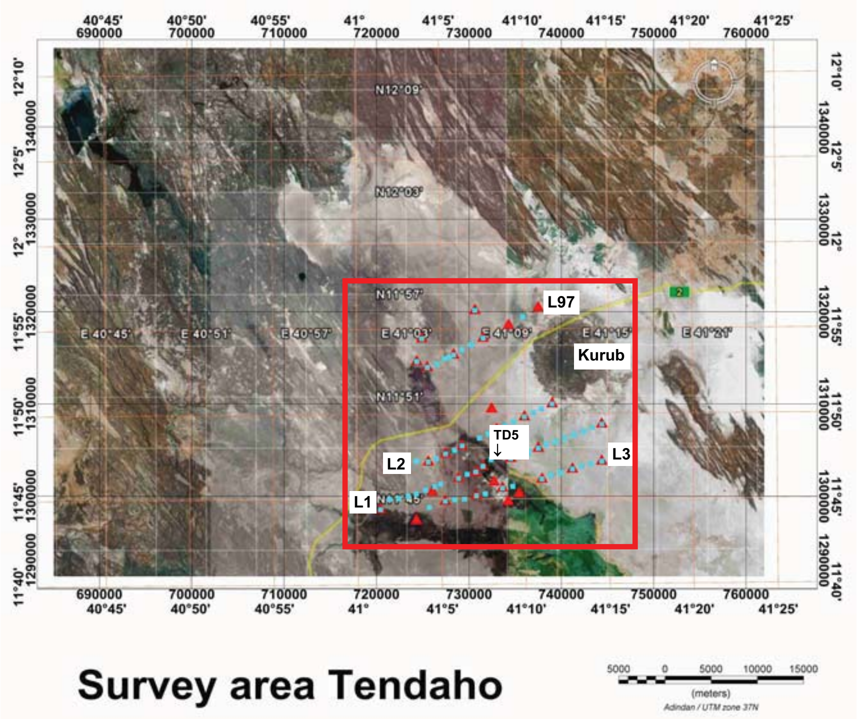

Figure 3: Survey area Tendaho geothermal field (red frame) projected onto satellite images (google earth). Red triangles = MT stations, blue squares = TEM stations. Line nos. L1, L2, L3 and L97 refer to MT lines in SE-NW bearing. TD5 = productive exploratory well. Yellow line = main road to Djibouti.

10 kHz to 0.01 Hz (100 s) has been acquired.

MT resistivity signature

Due to alluvial and lacustrine infill of the Tendaho graben apparent resistivity curves show generally values below 10 Ohm*m, even at high frequencies. A typical sounding curve is shown in figure 4. The minimum is reached at approximately 4 Hz with apparent resistivities just below 1 Ohm*m. With decreasing frequency the apparent resistivity rises again. Source signal was generally quite low, especially within the *dead band* region ranging from approximately 1 to 0.1 Hz (1 to 10 sec.). Nonetheless 16 hrs of recording time proved to be sufficient to yield acceptable estimates of the impedance tensor, using mainly single site processing.

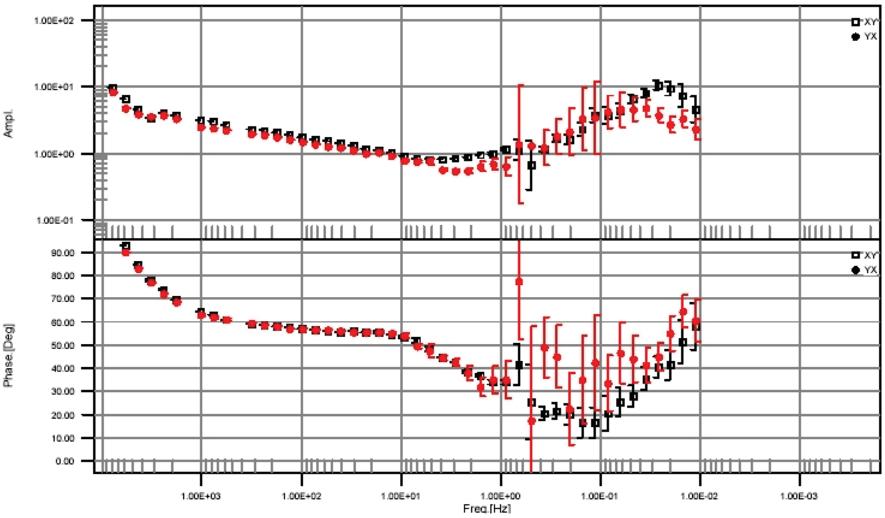

Figure 4: Typical sounding curve. Apparent resistivities (top) and phases (bottom). Due to low signal strength in the dead band from about 1 to 0.1 Hz unstable estimation especially of phase values, resulting in increased error bars.

This apparent resistivity pattern, which is also reflected in the resistivity models (see below), is indicative for high temperature geothermal reservoirs (figure 5, see also e.g. Kalberkamp 2007) where the resistivity low is interpreted as the clay cap while the increasing resistivities below the clay cap point to the core of the reservoir and represent a possible drilling target.

In the 2d inverted resistivity sections, exemplarily shown for profile L1 in figure 6, this resistivity pattern can be seen quite clearly. Although resistivities are generally low, they show signatures typical for hydrothermal alteration halos (see e.g. Johnston et al. 1992, Kalberkamp 2007) and (partly) molten magma intrusions at depth below 4 km. Taking the Dabbahu rift events into account it seems to be likely that the heat source for the geothermal reservoir is formed by magma intrusions along dyke like fracture zones as it is suggested by our interpretation of the MT data. Areas with high resistivities (>300 Ohm*m) may be associated with basalts from the Afar *Stratoid* Series, constituting the borders of the Tendaho graben structure.

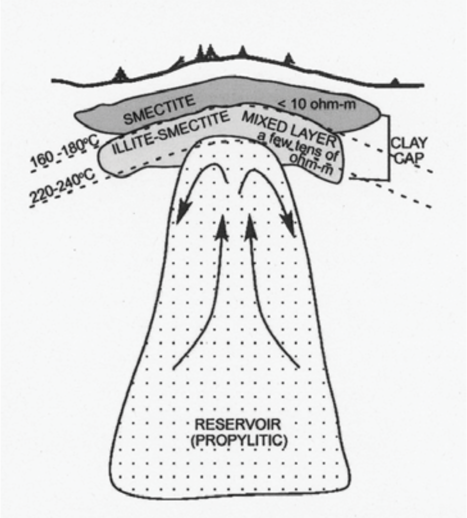

Figure 5: Schema of a generalised geothermal system. The smectite cap formed exhibits resistivities in the range of 2 Ohm*m, the mixed layer around 10 Ohm*m (modified after Johnston et al. 1992).

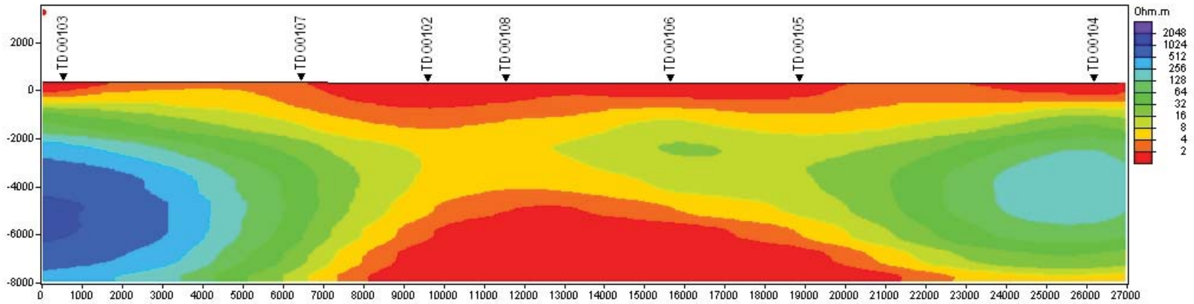

Figure 6: 2 d inverted resistivity section (L1). Lateral extension is 27 km; vertical depth covers 8 km.

Interpretation and recommendations

As has been shown for profile L1 exemplarily the magnetotelluric soundings show in their 2-dimensional inverted resistivity sections regions with resistivities as low as 2 Ohm*m, especially in near surface layers along profiles L1, 2, and 3 as well as at greater depth (below 5 km) in profiles P1, 3, and 97. When using the 2d MT sections to compile resistivity maps for constant elevations each, thus based on the inverted resistivities, we get a general view of the lateral resistivity structure as presented in figure 7 for selected elevations.

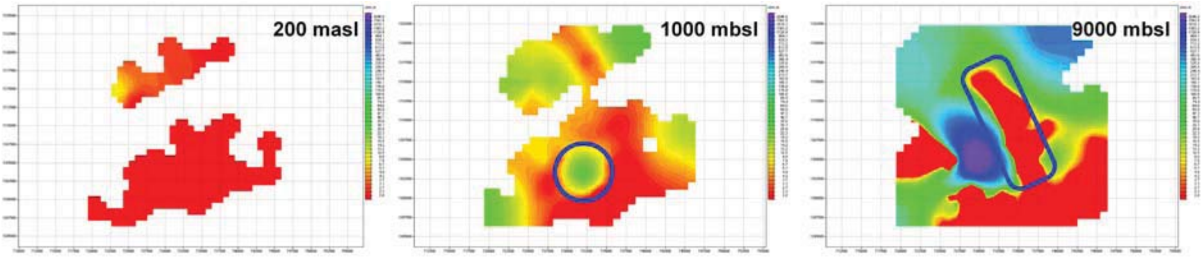

Figure 7: Resistivity maps of survey area as covered by red frame in figure 3, resistivity range 2 (red) – 2048 (blue) Ohm*m. *Left:* at 200 masl (150 m below surface). Shallow low resistive layer (red) due to sedimentary infill. The sediments are up to 1 km thick. *Centre:* at 1000 mbsl (1350 m below surface). Slight increase of resistivity (> 10 Ohm*m) possibly due to mixed layer clays and advancement towards deeper reservoir (blue circle). *Right:* at 9000 mbsl (9350 m below surface). Resistivity drop below 2 Ohm*m along NW-SE trending feature (partly molten magma dyke?). This may form the deep heat source feeding the shallow geothermal reservoir.

At greater depth of around 7 km a resistivity anomaly below 2 Ohm*m appears elongating in NW-SE direction. This direction coincides with the strike direction of the Tendaho graben and rift structures further to the NW, up to the Dabbahu rift and Boina vent, where lava ascended along a fault system, almost reaching the surface (figure 8). Therefore it seems likely, that the low resistive structures at greater depth are caused by lava filled fracture zones. (figure 7 *right*).

Figure 8: Volcanic vent, created during 2006 eruption event (Photo by J. Rowland).

Ebinger et al. (2008) have presented a working model of the Dabbahu magmatic

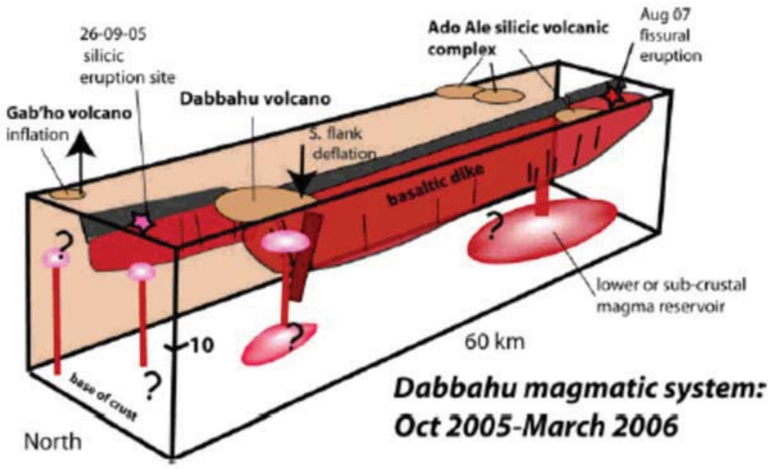

Figure 9: Working model of the Dabbahu magmatic system as presented by Ebinger et al. (2008). Pink ellipses = shallow magma chambers, connected to assumed lower crust/upper mantle feeding zones.

system (figure 9) based mainly on seismological, radar interferometric and structural data. They suggest that lower crustal/upper mantle source zones are feeding the basaltic dyke and shallow magma chambers at a few kilometres depth.

Magnetotelluric measurements by the Afar Rift Consortium / University of Edinburgh (Scotland, U.K.) are ongoing in that area and results thereof may help to refine the interpretation of the Tendaho geothermal field data.

With the current data therefore the following preliminary conclusions may be drawn:

- The deep heat source feeding the currently drilled reservoir at 300 m depth is most likely (partly) molten magma along NW-SE trending dykes or faults. In the Tendaho geothermal field these structures may be as shallow as 4 km depth.
- A deep reservoir may be expected below 1300 m.
- An up flow zone could be present at the S end of the survey area indicated by low resistivities throughout the acquired depth range.

To identify the proposed up flow zone at the S end of the current survey area it is recommended to apply additional TEM soundings which could enhance the resolution at shallow depth.

Additional MT sounding profiles are recommended further towards the Hararo and Dabbahu magmatic segments NW of the survey area. Since rift events including ascending magma are evident further to the NW it may be assumed that high temperature reservoirs could be reached at comparatively shallow depth there. First MT results from the research work within the Afar Rift Consortium do support this assumption (Desissa et al., 2009).

Also additional MT soundings beyond the Awash river up to the geothermal manifestations of Alalobad in the south would be helpful to establish either the extension of one large reservoir or the existence of a separate second geothermal system.

Acknowledgements

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