Magnetotelluric surface exploration at Tendaho, Afar (Ethiopia)

by

Ulrich Kalberkamp

Hannover, June 2010
Table of Contents

Preface .......................................................... ii
Acknowledgement ................................................. ii
Summary .......................................................... iii
Abbreviations ....................................................... iv

1 Introduction .................................................... 1
1.1 The GEOTHERM Programme .............................. 1
1.2 Aim of the MT survey .................................... 1
1.3 The project area ........................................... 3

2 Application of electromagnetic methods for geothermal investigations 5
2.1 The MT method .............................................. 8
2.2 Details on MT data acquisition ......................... 9
2.3 Details on MT data processing, data quality and inversion .... 11
2.3.1 Time series processing ............................... 12
2.3.2 Data quality ............................................. 13
2.3.3 Inversion and modelling ............................. 17

3 Results .......................................................... 18
3.1 Profile location ............................................. 18
3.2 1-d inversion ............................................... 20
3.3 2-d inversion ............................................... 20
3.3.1 Profile LINE 01 ....................................... 20
3.3.2 Profile LINE 02 ....................................... 21
3.3.3 Profile LINE 03 ....................................... 23
3.3.4 Profile LINE 97 ....................................... 24
3.3.5 Profile LINE 99 ....................................... 26

4 Interpretation and discussion .............................. 27

5 Conclusions and recommendations ...................... 29

6 References ...................................................... 30

7 Appendices
7.1 Appendix 1: UTM Coordinates of MT sounding locations .......... 33
7.2 Appendix 2: MT raw data- and EDI-files (DVD) ....................... 34
Preface

This report *Magnetotelluric surface exploration at Tendaho, Afar (Ethiopia)* deals with electrical resistivity soundings using the magnetotelluric (MT) method conducted by BGR and GSE within its joint GEOTHERM project during January and February 2007. The MT method complements DC geoelectric soundings of previous investigators, and allows insight into the deeper structure of the survey area not attainable by other electromagnetic exploration methods. Thus the geoscientific knowledge of the project area as a whole and of the deep seated heat source for the Tendaho manifestations in particular is extended. This work has been already presented to the GSE in technical review meetings in November 2007, and again in June 2009. Further presentations of this work have been given at the 2nd ARGeo conference in Entebbe (Uganda) in November 2008 and at the 23rd Schmucker-Weidelt-Colloquium 2009 (Kalberkamp, 2010).

Within the framework of the GEOTHERM project, and also independently, additional data has been acquired by the GSE at the Tendaho site in the fields of Geology, Geochemistry, and Geophysics (Transient Electromagnetics, Magnetics, Gravity). All this work is not covered in this report.

Acknowledgement

We highly appreciate the support and expertise of all personnel allocated by the Geological Survey of Ethiopia to participate in the joint GEOTHERM project. The very cooperative collaboration is very much appreciated.

In particular we would like to thank all personnel of the Geothermal group, who participated in preparation, and execution of the field work. Without their support the MT field work would not have been possible.

Special thanks go to Ato Tolesa Shagi (Director General, GSE) and Dr Meseret Teklemariam (former Department Head, Hydrogeology, Engineering Geology & Geothermal) to have supported the project as a whole and to endorse the overseas training of two Geophysicists in the field of Magnetotellurics, thus fostering the emergence of a MT expert group at the GSE.
Summary

Within a geothermal exploration survey various parameters linking the geological structure and the properties of the geothermal system are determined. As a result a geothermal resource may be detected and its location as well as spatial extension delineated.

In the frame of the BGR GEOTHERM programme, a Magnetotelluric (MT) field survey was conducted at the Tendaho prospect in Afar region of Ethiopia in January and February 2007. The surveys covered Dubti and Ayobera areas, both north of the Awash River.

The results from the MT survey which were conducted at the Tendaho prospect show zones of low resistivity which can possibly be correlated to alteration zones caused by geothermal activity. This might be an indication of a potential deeper seated geothermal reservoir in the Tendaho area. At greater depth (>4 km) NW-SE elongated low resistive structures have been modelled and could be interpreted as molten magma, serving as the heat source for the Tendaho geothermal system.

Additional measurements at sites close to assumed upflow zones and south of the Awash River, towards direction of Alalobad area, are recommended to narrow the potential location of the geothermal reservoir. As a second priority also additional MT profiles towards the NW across the Manda Hararo and Dabahu rift structures are recommended to investigate possible further geothermal systems at very shallow depth along the rift structures.

Nevertheless MT, as any geophysical method, cannot stand alone, but must be applied along with Structural Geology and Geochemistry to yield a joint conceptual model explaining the nature and extent of the proposed subsurface geothermal system. Locations for further exploratory drill holes may then be defined on these joint interpretation results.
Abbreviations

BGR       – Federal Institute for Geosciences and Natural Resources, Germany
BMZ       – Federal Ministry for Economic Cooperation and Development, Germany
DC        – Direct Current
EARS      – East African Rift System
GSE       – Geological Survey of Ethiopia, Ethiopia
MER       – Main Ethiopian Rift
MME       – Ministry of Mines and Energy, Ethiopia
MT        – Magnetotelluric
TEM       – Transient Electro Magnetic
TGD       – Tendaho-Goba’ad Discontinuity
1 Introduction

1.1 The GEOTHERM Programme

The GEOTHERM Programme promotes the use of geothermal energy in various partner countries by kicking off developments at sites or regions with a particularly high geothermal potential. East Africa is the major regional focus of the programme. The Federal Institute for Geosciences and Natural Resources (BGR) on behalf of the Federal Ministry for Economic Cooperation and Development (BMZ) started the programme in 2003 as a technical cooperation programme of the German government.

The Ministry of Mines and Energy (MME), Ethiopia, through its Geological Survey of Ethiopia (GSE), and the Federal Institute for Geosciences and Natural Resources (BGR), Germany, initiated the project entitled Geoscientific Exploration for Development of the Tendaho Geothermal System. This project lasted from October 2006 until June 2009 as part of the GEOTHERM programme. The selected project site for performing exploration activities in Ethiopia was Tendaho in the Afar region.

1.2 Aim of the Magnetotelluric survey

Magnetotelluric (MT) measurements have been applied in this project in January/February 2007 to reach a depth of interpretation down to approx. 10 km. Thus a typical geothermal reservoir, which is assumed to develop within a depth range from approx. 500 m to 5 km, could be detected if a zoning with a low resistive (alteration-) zone and an increase in resistivity underneath is associated with the reservoir. In the geological setting given in the Tendaho area an argillic alteration halo is common and as low resistivities as 2 $\Omega$m and below may be expected in association with this zone, connected to a hot (steam) reservoir.

The geothermal conceptual model used for planning of the geophysical exploration assumed as the exploration target up flow zones of the geothermal system being linked to fractures passing through producing wells in the Dubti plantation. Therefore
the MT measurements were located along approximately Northeast-Southwest trending profiles being roughly perpendicular to the predominant strike of the Tendaho rift structure. Due to difficult access and security problems measuring locations south of the Awash River could not be reached.

For shallow exploration depths down to approximately 500 m more closely spaced TEM soundings have been performed by the GSE and are not treated in this report. Due to their focused source field these data yield better resolution at shallow depth than MT and are appropriate for modelling shallow structures which might be indicative for up flow zones proposed close to the producing wells and possibly extending a few hundreds of meters to the south.
1.3 The project area

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 (figures 1-1, 2). 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).

![Survey area map](image)

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

Survey area Tendaho

*Figure 1-2:* 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 SW-NE bearing. TDS = productive exploratory well. Yellow line = main road to Djibouti. The NW-SE trending structures from the centre to NW direction are known as the Tendaho rift.
2 Application of electromagnetic methods for geothermal investigations

Unaltered volcanic rocks generally have high resistivities which can be changed by hydrothermal activity. Hydrothermal fluids tend to reduce the resistivity of rocks

- by altering the rocks,
- by increase in salinity and/or
- due to high temperature.

In high enthalpy reservoirs, i.e. fluid temperatures above 200 °C, hydrothermal alteration plays the predominant role. In a volcanic terrain (fig. 2-1) the acid-sulphate waters lead to different alteration products depending on the temperature and thus on the distance from the heat source. With basalts as country rock smectite becomes the dominant alteration product in the temperature range from 100 °C to 180 °C. At higher temperatures mixed layer clays and chlorite become dominant (fig. 2-2).

![Figure 2-1: Sketch of a geothermal resource in volcanic terrain of the acid sulphate type and associated alteration. Arrows indicate the circulation of meteoric water (after Evans 1997).](image-url)
Figure 2-2: Alteration mineralogy with increasing temperature in basaltic country rock. In the temperature range 100°C to 180°C smectite becomes the dominant alteration product and generally forms a smectite/bentonite clay cap (source: Geological Survey of Iceland ISOR).

Laboratory measurements indicate that smectite (expandable) clay minerals show very low resistivities even with resistive fluids as saturant (fig. 2-3, Emerson and Yang 1997). While smectite clay exhibit resistivities below 5 $\Omega$ m other (non expandable) clays have higher resistivities. Since the abundance of smectite is restricted to a temperature range from 100 °C to 180°C a smectite layer (or cap) is formed around a hot reservoir at the corresponding distance. Layers both above and below this smectite layer have higher resistivities, thus a succession of high-low-high resistivities with depth is indicative for a geothermal reservoir of this type (fig. 2-4) where the higher resistivities below the clay cap point to the core of the reservoir and represent a possible drilling target. All geophysical resistivity methods may detect this pattern whilst the MT is particularly useful to reach a depth range from several hundreds of meters down to several tens of kilometres. Usually the depth of interest within a geothermal exploration programme is restricted to a few kilometres due to feasibility reasons.
**Figure 2-3:** Bentonite clay (mineralogy: smectite) exhibits resistivities around 2 Ωm even if the saturant fluid has high resistivity (from Emerson & Yang 1997).

**Figure 2-4:** Schema of a generalised geothermal system. The smectite cap formed exhibits resistivities in the range of 2 Ohm·m, the mixed layer around 10 Ωm (modified after Johnston et al. 1992).
2.1 The MT method

The magnetotelluric (MT) method is a natural source electromagnetic method developed in the 1950s by Tikhonov (1950) and Cagniard (1953). Variations of the earth’s magnetic field cause current flow in conductive subsurface structures according to the laws of electromagnetic induction. The ratio of electrical and perpendicular magnetic field variations can be treated as a kind of impedance and is linked to the electrical conductivity of the penetrated structures.

Since the attenuation of electromagnetic fields depends on their frequency (and the electrical conductivity of the media) a depth sounding can be achieved by analysing the electrical and magnetic fields at certain frequencies, measured at the surface. Thus the measured data can be processed and displayed as sounding curves of apparent resistivities versus frequency (or alternatively period). As with other geoelectric measurements the MT data can then be converted to resistivity and depth by the use of numerical inverse modelling algorithms. The involved model may be 1d (horizontal layered earth, i.e. resistivity changes with depth only), 2d (in addition to 1d a variation of resistivity also in one horizontal direction is allowed) or 3d (resistivity may change in all three spatial directions). While 1d and 2d modelling software is readily available, 3d inverse modelling software is still under development.

Usually the soundings are aligned to profiles preferably perpendicular to known 2d structures, like faults. For these profiles resistivity sections are produced (based on the 1d or 2d inversion results). These sections may then be used to derive resistivity maps for specified depth values. Both, sections and maps derived from a MT survey serve as input for further interpretation jointly with data from other geoscientific methods.

Some aspects of processing and inversion are treated in the following paragraphs. A more detailed explanation of the MT method can be found e.g. in Dobrin and Savit (1988), Vozoff (1991) or Simpson and Bahr (2005).
2.2 Details on MT data acquisition

For data acquisition two full tensorial magnetotelluric stations from the BGR GEOTHERM Programme have been used. Each system consisted of a 5-channel data logger ADU-06 and three induction coil magnetometers MFS-06, all manufactured by Metronix GmbH (Germany). Two dipoles were formed by four low drift PbPbCl₂-type electrodes with a diameter of 121 mm manufactured by Wolf Ltd (Hungary). The sensors were set up in the standard configuration as shown in figure 2.2-1.

All magnetometers were buried into the ground to prevent any movement of them. In most cases the electric field sensors had been placed into a bentonite slurry to yield low contact resistance between the electrode and the ground. Dipole length was generally 100 m, in unfavourable terrain conditions 50 m.

Power supply to each station was granted by two 12 V / 18 Ah sealed lead acid batteries, providing sufficient energy for approximately 20 hrs of continuous operation.

The two stations were operated simultaneously at different locations under a fully synchronised recording time schedule covering four frequency bands ranging from 10 kHz to 0.01 Hz (100 s). Recordings started 18:00 hrs local time continued throughout the night and ended 08:00 next day. Thus 51 soundings at 33 locations could be recorded within 33 days in the field.

To ensure acceptable data quality for later processing and interpretation it is strongly recommended to inspect recorded data on-site (fig. 2.2-2) and perform a preliminary time series processing in the field camp on a daily basis.
Figure 2.2-1: MT sensor set-up consisting of three induction coil magnetometers (Hx, Hy, Hz) and two grounded dipoles (Ex, Ey), x pointing to the North, y to the East. (from Dobrin and Savit 1988).

Figure 2.2-2: On-site quality control of just acquired data on profile 97 using a laptop computer. The ADU-06 data logger with battery supply is in the white box. On the wooden stick placed to the right of the box the GPS antenna for time synchronisation is fixed by tape (Photograph by Mohammednur Desissa).
2.3 Details on MT data processing, data quality and inversion

Although both MT stations were operated fully synchronised by GPS clocks most of the processing was done on a single station basis, since no improvement by remote reference processing could be achieved due to coherent noise at both stations.

A processing overview is given in figure 2.3-1. The green part is referred to as time series processing performed by the software Mapros (Metronix) and explained briefly in section 2.3.1 below, whilst the red part is referred to as inversion performed by the software WinGLink (Geosystem) and treated in section MT 2.3.3.

![Figure 2.3-1: MT processing and inversion flow. Time series processing (green) was done by Mapros software (Metronix GmbH, Germany), inversion (red) was done by WinGLink software (Geosystem Srl, Italy).]
2.3.1 Time series processing

At each station five time series in five frequency bands have been recorded. Including a test run this sums up to 30 files with approx. 115 MB of raw data per sounding. All raw time series comprise 5.4 GB of data and are contained in the accompanying DVD.

The first step in time series processing is the visual inspection of the recorded data and excluding disturbances and heavily noise affected parts of the time series (fig. 2.3-2). Although this is a very time consuming procedure for the single site approach it is a very effective means to extract maximum information from noise contaminated time series. These preconditioned time series are then transformed into the frequency domain by a fast Fourier transform (FFT) using adapted window lengths. With a coherency based algorithm the Fourier spectra are then averaged and the impedance tensor estimated at predefined centre frequencies. The impedances from the five frequency bands are put together and saved in the internationally adopted EDI file format. All processed EDI files are contained in the accompanying DVD.

![Figure 2.3-2: Two hour time series segment from band LF2 of sounding TDO0501. X-axis: Time (UTC). From top to bottom: Ex, Ey, Hx, Hy, Hz (all in mV at the data logger input). Grey shaded parts show substantial disturbances (jumps in the Ex-field, high amplitude spikes in all H-fields, possibly due to somebody moving at the induction coil magnetometers) which will be discarded in further processing.](image-url)
2.3.2 Data quality

Most sounding data is of medium quality and can be used for interpretation up to 100 s period length. Some stations within the Dubti plantation seem to be affected by ground movement due to local villages close by and construction work as well as load changes on the local power grid generating transients propagating deeply even into non electrified regions. Additionally the so called *dead band* with naturally low energy stretch in the low frequency band from 0.6 Hz to 0.09 Hz (1.7 s to 11 s). At a few stations the impedance estimation is more uncertain in this range, indicated by large error bars in the apparent resistivity and phase curves (fig. 2.3-3).

Also the variations of the vertical magnetic field (Hz) have been acquired in good quality so the magnetic transfer function / induction arrows may be used in interpretation as well.

![Figure 2.3-3: Apparent resistivities (top) and phases (bottom) on location TDO0301. Recorded frequencies range from 10 kHz to 0.01 Hz (100 s). Note increased error bars in the *dead band* from about 1 to 0.1 Hz resulting in partly unstable estimation of phase values in particular. At high frequencies (> 3 kHz) electrode cable capacitance is not sufficiently corrected for, resulting in a phase increase beyond 90° for the highest frequency.](image)
To get an idea of the dimensionality of the acquired data, the off-diagonal and diagonal elements of the impedance tensor, i.e. $Z_{xy}$, $Z_{yx}$, $Z_{xx}$, $Z_{yy}$ respectively, may be plotted in polar diagrams (fig. 2.3-4).

**Figure 2.3-4:** Schematic behaviour of off-diagonal impedance tensor elements $Z_{xy}$ (at one frequency) due to rotation and across a 2d boundary. At location 1 the 2d boundary is far away for the given frequency and $Z_{xy}$ appears as a circle indicating 1d conditions. The closer the conductivity boundary the more 8-shaped the polar diagram becomes. Obey the change in size and orientation when crossing the boundary due to the conductivity change. At location 4 again 1d conditions are met for the given frequency (simplified from Vozoff 1991).

In a one dimensional (1d) case the resistivity structure is changing with depth only, there is no variation in resistivity in any horizontal direction. In other words: the resistivity structure consists of horizontal layers, each of them being homogeneous and isotropic with regard to electrical conductivity. Therefore estimated apparent resistivities are independent of the azimuthally direction, hence $Z_{xy}, yx$ are rotational invariant and will form a circle in the polar plot (locations 1 and 4 in fig. 2.3-4, $Z_{xy}$ shown only). Also the diagonal elements of the impedance tensor vanish or are very small in the 1d case (not shown in fig. 2.3-4).

If we allow in addition to the above mentioned 1d case changes in resistivity also in one horizontal direction, say the x-direction, and being constant in the other horizontal direction, say y-direction, then we have the so called two dimensional (2d) case as shown in figure 2.3-4. In this case we always can find a well defined rotation angle at which one of the electric field dipoles is parallel to the structure. At this angle the diagonal elements of $Z$ vanish (or become very small) and the off-diagonal elements $Z_{xy}$ and $Z_{yx}$ represent apparent resistivities in the so called TE and TM
modes respectively. Thus the polar diagram of Z shows in a 2d case some kind of 8-shaped Zxx and Zxy figures being shifted by 90 deg, i.e. when Zxx becomes minimal Zxy becomes maximal (locations 2 and 3 in fig. 2.3-4, Zxy shown only). In this 2d case one dimensional inversion models will yield erroneous models close to the lateral resistivity boundaries. Instead 2d inversion should be performed, taking both TE and TM modes into account.

In the general three dimensional (3d) case resistivities may change in all three spatial directions. This results in an impedance tensor where no element will vanish for any rotation angle. In this case our 2d modelling results will be questionable and should be treated as rough estimates only.

The dimensionality analysis of the data acquired at Tendaho, based on polar diagrams, yield the following results:

1. In the high frequency range from 10 kHz to at least 12.6 Hz (shallow depth penetration) most of the soundings show 1d characteristics. The only exceptions are stations TDO0101 and TDO0106 on Profile 1, showing a 2d structure also in this frequency range (fig. 2.3-5). Both stations are close to boreholes.

2. For frequencies below 3.9 Hz, 2d structures dominate (fig. 2.3-6). Significant 3d structures are not obvious.

Therefore we can conclude that 2d inversions of the acquired MT data taking both, the TE- and TM modes into account will be an adequate procedure.
Figure 2.3-5: Polar diagram map for all sounding locations at 12.6 Hz. Most of the soundings show 1d characteristics. Exceptions are the encircled soundings close to the boreholes on profile 1, showing 2d behaviour. Easting and Northing according to UTM projection in meters.

Figure 2.3-6: Polar diagram map for all sounding locations at 3.9 Hz. Most of the soundings show 2d characteristics. Easting and Northing according to UTM projection in meters.
2.3.3 Inversion and modelling

The off diagonal elements of the impedance tensor are used to calculate apparent resistivity and phase curves for the two perpendicular orientations: \( XY = \) North component of the electric field (\( E_x \)) and East component of the magnetic field (\( H_y \)), \( YX = \) East component of the electric field (\( E_y \)) and North component of the magnetic field (\( H_x \)). For further processing the impedance tensor is rotated mathematically by a constant angle derived from the swift angle at low frequencies. This results in the present data set in a consistent orientation with one axis approximately along the NW-SE trending Tendaho rift structure which is taken as direction for the E-field and assigned the TE-mode for the modelling procedure. A parallel shift of both resistivity curves, known as static shift, has been observed on a few stations only and has been removed by means of comparison with adjacent MT soundings, having no or only minor shifts.

The rotated and static shift corrected apparent resistivity curves (TE-mode) may be 1d inverted for a first overview. The subsequent 2d modelling is performed using an algorithm described by Rodi and Mackie (2001), implemented in the software WinGLink. All stations aligned along the NE-SW trending profiles (lines 1, 2, 3, 97 and 99) are used as input. As starting model an intermediate half-space resistivity of 5 \( \Omega m \) and a lateral fine grid dimension adapted to the station spacing has been used. Both, TE- and TM- modes are taken into account in the 2d modelling. Usually an overall RMS error of fit around 6% has been achieved for a single section. The 2d inverted results are plotted as vertical profile sections derived from the model grid.
3 Results

The sounding locations have been assigned to the five profiles LINE 01, LINE 02, LINE 03, LINE 97 and LINE 99, all of them being oriented NE-SW, i.e. roughly perpendicular to the strike of the Tendaho rift structure (c.f. figure 1.2).

The 2d models are the outcome of a processing and inversion procedure as briefly explained in section 2.3. Colour coding is depicting the electrical resistivity in a logarithmical scale ranging from $2 \, \Omega \text{m}$ to $2048 \, \Omega \text{m}$. Both, the vertical scale (elevation) and horizontal distance scale are linear and cover a depth range of 8 km and a distance of up to 27 km respectively. This scaling has been consistently used for all MT resistivity sections in this report to ease comparison.

As already mentioned all low resistive areas and areas around and south of the boreholes in the Dubti plantation (proposed up flow zones) are of utmost interest.

3.1 Profile location

Profile locations are given in figure 3.1-1 including altitude information. The locations stretch from Dubti village in the West up to the W flank of the Kurub volcano in the northeast. According to the initial conceptual working model, the boreholes and proposed up flow zones within the Dubti plantation have been covered. Elevation is varying little around 370 m.
Figure 3.1-1: Location of profiles LINE 01, LINE 02, LINE 03, LINE 97 and LINE 99. At the eastern ends between LINE 02 and LINE 97 the Kurub volcano is located. Triangles indicate MT sounding locations, asterisks indicate borehole locations. Colour coding is elevation as derived from GPS readings, Easting and Northing according to UTM projection in meters, ranging from 712500 to 755000 and 1295000 to 1322500 respectively. Grid interval = 2500 m.
3.2 1-d inversion

One dimensional (1d) inversion models are calculated on a standard basis prior to 2d modelling. Since they are not used for further interpretation in this report, they are not included here. For reference the 1d inversion by Desissa (2007) and Lemma (2007) may be taken.

3.3 2-d inversion

The 2d model sections are the outcome of a processing and inversion procedure as briefly explained in section 2.3.

3.3.1 Profile LINE 01

This profile consists of seven MT sounding locations. The 2d inversion section (fig. 3.3-1) shows a very low resistive surface layer (below 2 \( \Omega \)m), covering a lateral distance of the whole profile. Maximum thickness of approximately 600 m is being reached below station TDO0102 and covers the producing shallow reservoir. Below 1200 m depth resistivity is increasing in the central part up to 32 \( \Omega \)m. This could indicate the advancement towards a deeper reservoir where smectite clays disintegrate. Below 4000 m depth resistivity is falling again reaching values below 2 \( \Omega \)m at 5000 m depth, possibly due to magmatic melt.

![Figure 3.3-1: MT profile LINE 01. Lateral distance is 27 km; vertical depth covers 8 km, numbers indicating meters above/below sea level. Coloured contours: resistivities in \( \Omega \)m.](image)

The extremely low resistive surface structures are well documented in the apparent resistivity curves showing all very low values right from the beginning (fig. 3.3-2). Also all TEM soundings show very low resistivities for the shallow part (cf. TEM
The MT impedance tensor has been rotated mathematically by 10°, 45° and 110° for the soundings TDO0107, 0108 and 0104 respectively. Due to the 90° ambiguity of the estimated rotation angles, all these rotation angles support a strike direction of 100° to 135°, corresponding with the strike of the Tendaho rift. Blue symbols represent the apparent resistivities estimated from the Ey and Hx components of the recorded electric and magnetic fields (for details see chapter 2.3), the red symbols, representing apparent resistivities estimated from Ex and Hy components, have been assigned to the TE-mode and are the best 1d representation of the (at least) 2d subsurface.

Figure 3.3-2: MT apparent resistivity curves (top) and phase curves (bottom) for stations TDO0107, 0108 and 0104 on profile LINE 01. Period range (x-axis): 0.0001 s to 100 s, apparent resistivity axis: 0.1 to 1000 Ωm, phase axis: 0 to 90°. TE mode in red. Rotation angle 10°, 45° and 110° respectively. TDO0108 shows a low resistive structure in the period range 0.1 to 1 sec. All soundings show underlying low apparent resistivities beyond 50 sec.

3.3.2 Profile LINE 02

This profile lies about 3 km north of LINE 01 and contains six MT soundings. Lateral length is about 16 km, depth range as LINE 01, 8 km. Similar to profile LINE 01 an extremely low resistive surface layer is present throughout the profile (fig. 3.3-3) having a thickness up to 1000 m. This layer is possibly formed by the low resistive sedimentary infill of the Tendaho rift. Resistivities increase below this layer reaching some 20 Ωm around 1800 m depth. Below stations TDO0201 and 02 a zone of maximum resistivity up to 200 Ωm has been modelled at a centre depth of around 4500 m. Below this anomaly resistivities drop again, reaching values below 8 Ωm between stations TDO0204 and 05.
The low resistive surface layer is well documented in all apparent resistivity curves (e.g. fig. 3.3-4). Also the increase in resistivity around 20 sec and a following decrease beyond 30 sec can be seen in some of these sounding curves (e.g. TDO0205).

Figure 3.3-3: MT profile LINE 02. Lateral distance is 16 km; vertical depth covers 8 km, numbers indicating meters above/below sea level. Coloured contours: resistivities in $\Omega m$.

Figure 3.3-4: MT apparent resistivity curves (top) and phase curves (bottom) for stations TDO0201, 0203 and 0205 on profile LINE 02. Period range (x-axis): 0.0001 s to 100 s, apparent resistivity axis: 0.1 to 1000 $\Omega$ m, phase axis: 0 to 90°. TE mode in red. Rotation angles range from -30° to -40°. All soundings show apparent resistivities below 10 $\Omega$ m. Soundings 01 and 03 are even better conductors around 1 sec, although low signal strength degrades impedance estimation. All soundings show an increase in apparent resistivity from around 3 sec to 30 sec dropping again for increasing periods, quite well documented in sounding TDO0205.
3.3.3 Profile LINE 03

Profile LINE 03 is the southernmost profile and consists of 7 MT soundings. A low resistive surface layer showing resistivities below 2 Ωm is being modelled all along the profile, reaching its maximum thickness of about 1000 m between soundings TDO0306 and 05 (figure 3.3-5). Again the low resistivities are thought to be caused by sedimentary infill. Below these soundings resistivity is slightly rising to a maximum 8 Ωm while dropping again below 2 Ωm at elevations below 6 km. As in LINE 01 this may be due to magmatic melt. The resistivities of the in-between structures do not exceed 8 Ωm thus not showing a clear picture. Possibly these resistivities remain low due to up flow of highly mineralised waters dominating the resistivity structure against evolving mixed layer clays. Rotation angles are generally in direction of the rift strike direction, although the mediocre data quality of some of the soundings does not always allow a useful estimate. All soundings show a broad resistivity low around 0.2 sec. (fig. 3.3-6) and rise to some 10 Ωm for longer periods. At the eastern end of the profile TDO0301 indicate a further resistivity low beyond 30 sec., which is not resolved in the 2d model.

Figure 3.3-5: MT profile LINE 03. Lateral distance is 23 km; vertical depth covers 8 km, numbers indicating meters above/below sea level. Coloured contours: resistivities in Ωm.
Figure 3.3-6: MT apparent resistivity curves (top) and phase curves (bottom) for stations TDO0304, TDO0305 and TDO0301 on profile LINE 03. Period range (x-axis): 0.0001 s to 100 s, apparent resistivity axis: 0.1 to 1000 Ωm, phase axis: 0 to 90°. TE mode in red. Rotation angle: -60°, -80°, and -50° i.e. roughly the strike direction of the Tendaho rift. All soundings show a resistivity low around 0.2 sec and rise to some 10 Ωm for longer periods. TDO0301 indicates a drop in resistivity for periods beyond 30 sec.

3.3.4 Profile LINE 97

Profile LINE 97 is located further to the North in the Ayobera area, passing by the geothermal manifestations observed there. It consists of 5 soundings. The 2d inversion shows a surface layer resistivity of around 7 Ωm, intersected by some patches of very low resistivities even below 2 Ωm (around sounding TDO9702). At an elevation of 7 km resistivities gradually drop down below 2 Ωm, possibly indicating molten magma at greater depth than further south. In between these two structures resistivities rise to a maximum of about 30 Ωm at about 2500 m depth, possibly due to disintegration of smectite by exceeding 200 °C.
Figure 3.3-7: MT profile LINE 97. Lateral distance is 15 km; vertical depth covers 8 km, numbers indicating meters above/below sea level. Coloured contours: resistivities in Ω·m.

Figure 3.3-8: MT apparent resistivity curves (top) and phase curves (bottom) for stations TDO9713, 9732 and 9705 on profile LINE 97. Period range (x-axis): 0.0001 s to 100 s, apparent resistivity axis: 0.1 to 1000 Ω·m, phase axis: 0 to 90°. TE mode in red (TDO9713) and blue (TDO9732, 9705) respectively. Rotation angle: -20°, 70° (i.e. -20° taking the 90° ambiguity into account), and -80° (around N taking the 90° ambiguity into account). All three soundings show interbedding of low and high resistive structures in the period range from around 0.002 s via 1 s to beyond 100 s. The soundings indicate a departure from 1d to the long period end, when the rift structure results in a split of the two apparent resistivity curves. In between, from 0.1 to 1 s there seems to be a multidimensional structure appearing. All apparent resistivity curves show this split-up consistently.
3.3.5 Profile LINE 99

Profile LINE 99 is the northernmost profile of the survey, north of the geothermal manifestations observed in the Ayobera area (compare LINE 97). It consists of 2 soundings. The 2d inversion shows a surface layer resistivity of around $10 \, \Omega \text{m}$. From the west a resistive structure may be due to the basalts of the *Afar stratoid series*, which are believed to have very low permeability. At greater depth ($> 7 \, \text{km}$) resistivities gradually drop down below $4 \, \Omega \text{m}$, possibly indicating molten magma at greater depth than further south.

![Figure 3.3-9: MT profile LINE 99. Lateral distance is 7 km; vertical depth covers 8 km, numbers indicating meters above/below sea level. Coloured contours: resistivities in $\Omega \text{m}$.](image)

![Figure 3.3-10: MT apparent resistivity curves (top) and phase curves (bottom) for stations TDO9908 and 9901 on profile LINE 99. Period range (x-axis): 0.0001 s to 100 s, apparent resistivity axis: 0.1 to 1000 $\Omega \text{m}$, phase axis: 0 to 90°. TE mode in red (TDO9908) and blue (TDO9901) respectively. Rotation angle: -45° and -110° (i.e. -20° taking the 90° ambiguity into account). Both soundings show a low resistive structure around 1 s and beyond 100 s. At the short period range (0.0001 to 0.001 s) apparent resistivity values are somehow scattered for unknown reasons.](image)
4 Interpretation and discussion

As has been elaborated in chapter 3.3 the magnetotelluric soundings show in their 2-dimensional inverted resistivity sections regions with resistivities as low as 2 \( \Omega \text{m} \), especially in near surface layers along profiles LINE 1, 2, and 3 as well as at greater depth (below 7 km) in profiles LINE 1, 3, and 97. When using the 2d MT sections to construct resistivity maps for constant elevations each, thus based on the inverted resistivities, we get a good overview of the lateral resistivity structure as presented in figure 4-1 for selected elevations.

![Figure 4-1: Resistivity maps of the survey area as covered by red frame in figure 1-2. Based on 2d inversion results of the MT method, resistivity range from 2 (red) – 2048 (blue) \( \Omega \text{m} \), Easting and Northing according to UTM projection in meters, ranging from 712500 to 755000 and 1295000 to 1322500 respectively. 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 \( \Omega \text{m} \)) 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 \( \Omega \text{m} \) 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 7000m and beyond a resistivity anomaly below 2 \( \Omega \text{m} \) appears elongating in NW-SE direction. This direction coincides with the strike direction of the Tendaho rift and rift structures further to the NW, up to the Dabahu rift and Boina vent, where lava ascended along the fault, almost reaching the surface. Therefore it seems likely, that the low resistive structures at greater depth are caused by lava filled fracture zones. (fig. 4-1 right).

It would be interesting to compare and discuss our findings with those of the research work done further to the NW across the Dabahu magmatic system where partly molten magma ascended up to approx. 2 km depth (Ebinger et al, 2008). From that a
rise of the magma source further to the NW direction would be expected. This trend is not found in our data but might be evident further north. Magnetotelluric investigations 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.
5 Conclusions and recommendations

We can conclude from the magnetotelluric results the following:

- The MT method detected a low resistive surface layer (< 2 $\Omega$ m) of up to 1 km thickness. The low resistivities could be attributed to sedimentary (volcanoclastic, lacustrine) infill, smectite alteration and hydrothermal fluid flow.

- Below this low resistive layer resistivities are increasing in some areas, indicating the advancement to a possible reservoir at depth below 1000 m.

- Resistivities below 8 $\Omega$ m throughout the southernmost section of LINE 03 could hint to an up flow zone of highly mineralised fluids.

- At depth below 4 km very low resistive structures elongate in SE-NW direction. This can be interpreted as magma along fault structures, serving as the heat source of the Tendaho field.

The proposed up flow zone in LINE 03 could serve as an easy access to the deeper reservoir. To increase resolution within that zone it is recommended to use densely spaced TEM soundings for investigating the upper 500 m or so and use 3d inversion modelling for that data set. Another drilling target could be the zones with increasing resistivities up to the 30 $\Omega$ m range, since the increase could be attributed to the disintegration of smectite due to the advancement to a deeper system. Additional infill MT soundings would enhance the certainty of the models presented and are therefore recommended prior to any drilling.

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.
6 References


7 Appendices

7.1 Appendix 1: UTM Coordinates of MT sounding locations

UTM Zone 37, Adindan

<table>
<thead>
<tr>
<th>Site</th>
<th>East  [m]</th>
<th>North  [m]</th>
<th>Elev.  [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDO0101</td>
<td>731528</td>
<td>1303229</td>
<td>360</td>
</tr>
<tr>
<td>TDO0102</td>
<td>728867</td>
<td>1301928</td>
<td>373</td>
</tr>
<tr>
<td>TDO0103</td>
<td>720448</td>
<td>1298520</td>
<td>386</td>
</tr>
<tr>
<td>TDO0104</td>
<td>744376</td>
<td>1307810</td>
<td>370</td>
</tr>
<tr>
<td>TDO0105</td>
<td>737498</td>
<td>1305198</td>
<td>371</td>
</tr>
<tr>
<td>TDO0106</td>
<td>734513</td>
<td>1304095</td>
<td>372</td>
</tr>
<tr>
<td>TDO0107</td>
<td>726042</td>
<td>1300475</td>
<td>381</td>
</tr>
<tr>
<td>TDO0108</td>
<td>730699</td>
<td>1302544</td>
<td>369</td>
</tr>
<tr>
<td>TDO0201</td>
<td>725595</td>
<td>1303705</td>
<td>372</td>
</tr>
<tr>
<td>TDO0202</td>
<td>727455</td>
<td>1304567</td>
<td>365</td>
</tr>
<tr>
<td>TDO0203</td>
<td>729267</td>
<td>1305441</td>
<td>371</td>
</tr>
<tr>
<td>TDO0204</td>
<td>732999</td>
<td>1307200</td>
<td>373</td>
</tr>
<tr>
<td>TDO0205</td>
<td>735999</td>
<td>1308601</td>
<td>372</td>
</tr>
<tr>
<td>TDO0206</td>
<td>739003</td>
<td>1309997</td>
<td>380</td>
</tr>
<tr>
<td>TDO0301</td>
<td>744376</td>
<td>1303801</td>
<td>365</td>
</tr>
<tr>
<td>TDO0302</td>
<td>724313</td>
<td>1297356</td>
<td>380</td>
</tr>
<tr>
<td>TDO0303</td>
<td>727434</td>
<td>1299446</td>
<td>378</td>
</tr>
<tr>
<td>TDO0304</td>
<td>730805</td>
<td>1300042</td>
<td>367</td>
</tr>
<tr>
<td>TDO0305</td>
<td>737907</td>
<td>1301852</td>
<td>365</td>
</tr>
<tr>
<td>TDO0306</td>
<td>733628</td>
<td>130877</td>
<td>364</td>
</tr>
<tr>
<td>TDO0307</td>
<td>741203</td>
<td>1302940</td>
<td>353</td>
</tr>
<tr>
<td>TDO0401</td>
<td>732449</td>
<td>1309452</td>
<td>372</td>
</tr>
<tr>
<td>TDO0501</td>
<td>732712</td>
<td>1301547</td>
<td>350</td>
</tr>
<tr>
<td>TDO0502</td>
<td>735455</td>
<td>1300293</td>
<td>361</td>
</tr>
<tr>
<td>TDO0503</td>
<td>734240</td>
<td>1299416</td>
<td>371</td>
</tr>
<tr>
<td>TDO9701</td>
<td>725483</td>
<td>1313946</td>
<td>361</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site</th>
<th>East  [m]</th>
<th>North  [m]</th>
<th>Elev.  [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDO9702</td>
<td>72351</td>
<td>1315301</td>
<td>380</td>
</tr>
<tr>
<td>TDO9703</td>
<td>731538</td>
<td>1317130</td>
<td>375</td>
</tr>
<tr>
<td>TDO9704</td>
<td>734282</td>
<td>1318524</td>
<td>380</td>
</tr>
<tr>
<td>TDO9705</td>
<td>737495</td>
<td>1320418</td>
<td>376</td>
</tr>
<tr>
<td>TDO9711</td>
<td>725483</td>
<td>1313946</td>
<td>361</td>
</tr>
<tr>
<td>TDO9712</td>
<td>725483</td>
<td>1313946</td>
<td>361</td>
</tr>
<tr>
<td>TDO9731</td>
<td>731538</td>
<td>1317130</td>
<td>375</td>
</tr>
<tr>
<td>TDO9732</td>
<td>731538</td>
<td>1317130</td>
<td>375</td>
</tr>
<tr>
<td>TDO9733</td>
<td>731538</td>
<td>1317130</td>
<td>375</td>
</tr>
<tr>
<td>TDO9734</td>
<td>731538</td>
<td>1317130</td>
<td>375</td>
</tr>
<tr>
<td>TDO9741</td>
<td>734282</td>
<td>1318524</td>
<td>380</td>
</tr>
<tr>
<td>TDO9742</td>
<td>734282</td>
<td>1318524</td>
<td>380</td>
</tr>
<tr>
<td>TDO9751</td>
<td>734795</td>
<td>1320418</td>
<td>376</td>
</tr>
<tr>
<td>TDO9801</td>
<td>724351</td>
<td>1314578</td>
<td>366</td>
</tr>
<tr>
<td>TDO9802</td>
<td>724351</td>
<td>1314578</td>
<td>366</td>
</tr>
<tr>
<td>TDO9803</td>
<td>724351</td>
<td>1314578</td>
<td>366</td>
</tr>
<tr>
<td>TDO9804</td>
<td>724351</td>
<td>1314578</td>
<td>366</td>
</tr>
<tr>
<td>TDO9805</td>
<td>724892</td>
<td>1317043</td>
<td>363</td>
</tr>
<tr>
<td>TDO9891</td>
<td>730644</td>
<td>1320122</td>
<td>363</td>
</tr>
<tr>
<td>TDO9903</td>
<td>730644</td>
<td>1320122</td>
<td>363</td>
</tr>
<tr>
<td>TDO9904</td>
<td>724892</td>
<td>1317043</td>
<td>363</td>
</tr>
<tr>
<td>TDO9905</td>
<td>724892</td>
<td>1317043</td>
<td>363</td>
</tr>
<tr>
<td>TDO9906</td>
<td>724892</td>
<td>1317043</td>
<td>363</td>
</tr>
<tr>
<td>TDO9907</td>
<td>724892</td>
<td>1317043</td>
<td>363</td>
</tr>
<tr>
<td>TDO9908</td>
<td>724892</td>
<td>1317043</td>
<td>363</td>
</tr>
</tbody>
</table>
7.2 Appendix 2: MT raw data- and EDI-files (DVD)

See attached DVD.

MT time series are in the binary *filename.ats* format of Metronix. The filename consists of 8 digits and letters coded as follows:

<table>
<thead>
<tr>
<th>Position</th>
<th>coding</th>
</tr>
</thead>
<tbody>
<tr>
<td>123</td>
<td>serial number of recording ADU (e.g. 086)</td>
</tr>
<tr>
<td>4</td>
<td>hardware channel assignment inside ADU (usually A = ch1, B = ch2, C = ch3, D = ch4 and E = ch5)</td>
</tr>
<tr>
<td>56</td>
<td>run number (e.g. 01)</td>
</tr>
<tr>
<td>7</td>
<td>component assignment (usually A = Ex, B = Ey, X = Hx, Y = Hy, Z = Hz)</td>
</tr>
<tr>
<td>8</td>
<td>frequency band: A = HF, B = LF1, C = LF2, D = LF3, E = LF4, F = free</td>
</tr>
</tbody>
</table>

E.g. the file 086A01AB.ats has been recorded with ADU number 086 using the standard hardware channel assignment. The file contains run 01 of the Ex component in frequency band LF1.

The supplied EDI files are in accordance with the internationally agreed standards in ASCII and contain impedance tensor elements, Tipper elements and spectra.