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PROCESSING AND JOINT 1D INVERSION OF MT AND TEM DATA FROM ALALLOBEDA GEOTHERMAL FIELD NE-ETHIOPIA

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ABSTRACT

Tendaho is one of the high temperature geothermal field in the Main Ethiopian Rift, NE-Ethiopia and a promising area for geothermal development with respect to both its size and location. Alallobeda is one of the three prospects found in Tendaho geothermal field. Understanding the resistivity structure of Alallobeda prospect could give a good understanding of the subsurface and enhance the possibility of developing the geothermal resource. The resistivity structure of Alallobeda prospect was carried out by the combined use of MT and TEM soundings. The soundings were jointly inverted to get a better result and interpretation. Joint 1-D inversion of 54 MT/TEM sounding pairs was performed.

From the resistivity Cross-sections in Alallobeda three main resistivity layers were observed. The first is a thin layer of very low resistivity (< 10Ωm) at shallow depth down to 300 m b.s.l. which is correlated with sedimentary formation or smectite zeolite zone. The second layer is a high resistivity core appears down to a depth of 1000 to 5000 m b.s.l. which can be correlated to the less Afar Stratoid Series and high alteration minerals. Beneath the high resistivity layer a deep conductor is revealed that could be associated with heat source. Effect of geothermal up flow is seen in the iso-resistivity map associated with known geothermal structures. Results from the strike analysis are in an agreement with the resistivity model.

1. INTRODUCTION

Ethiopia has high geothermal energy potential which is good for power generation. Geothermal exploration began in the Main Ethiopian Rift (MER) in 1969, carried out by the Ethiopian Government and the United Nation Development Programme (UNDP) (Bekele, 2012). Since 1969 around 23 promising geothermal prospects has been identified for electricity development and direct use. However, most of the geothermal resources has not been explored and evaluated in detail. The development stage varies from site to site. Geothermal prospects in Ethiopia lie in the MER System. Among this Tendaho is one of the most promising geothermal areas in the MER System and it has a multiple geothermal prospect.

Between 2014-2015 a detail geo-scientific exploration were conducted in Alallobeda prospect by Geological Survey of Ethiopia (GSE) and an Italian consulting company (ELC) financed by Icelandic International development Agency (ICEIDA) and Nordic development fund (NDF). Part of the project was a resistivity survey consisting of MT/TEM survey. A total of 132 MT/TEM soundings were done out of this 27 MT stations were done in 2013 by GSE. The results were presented as in 1-D model for individual soundings, Iso resistivity depth map, and cross sections.

Geophysical methods especially resistivity methods, and in particular magnetotellurics (MT) and Transient electromagnetics (TEM) play an important role in geothermal exploration. The main reason is that resistivity is highly sensitive to temperature, salinity, porosity and geothermal alteration and is directly related to the physical properties of the reservoir. Resistivity surveys identify variations in the electrical resistivity of the sub-surface that are caused by different rock types and ground water. The main task of geophysical methods in geothermal exploration is to detect geothermal prospect, delineate geothermal resources and to further the understanding of their characteristics, as well as the locating exploitable reservoir, and to help placing boreholes through which hot fluids can be extracted from depth (Flóvenz et al., 2012).

The MT method has the greatest exploration depth of all resistivity methods and is a powerful method to probe deep resistivity structure depending on the period. TEM data is used for static shift correction of the MT data at the same site.

1.1. Objective of the study

- To acquire high resolution magnetotelluric and transient electromagnetic data.
- To obtain the subsurface resistivity model, to detect and characterize the possible geothermal reservoir of Allalobeda geothermal prospect.

1.2. Location of Tendaho

Tendaho is located 600 km northeast of Addis Ababa in the central Afar depression. Afar depression is found in the triple junction where the three propagators join together (MER, Read Sea and Gulf of Aden). Alallobeda is one of the three prospects in Tendaho Graben, the other two are Dubti and Ayrobera. Alallobeda is located in the western part of Tendaho Graben, 15 km southeast of Dubti plantation. Figure 1 shows the location of the study area.

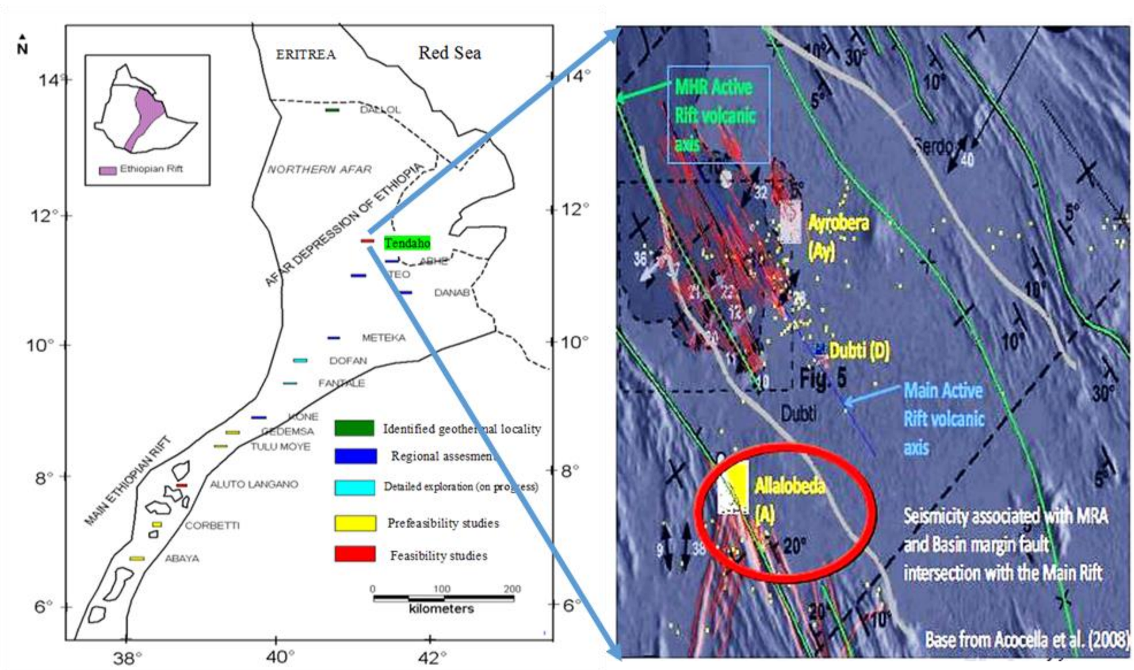

FIGURE 1: Location of Tendaho and other prospects along the Main Ethiopian Rift (After UNDP, 1973 and Kebede, 2014).

2. PREVIOUS WORK

2.1 Pervious geophysical work

An MT survey was carried out in the Afar region in 1971 to investigate the electrical resistivity distribution at depth (Berktold, 1975). The results of the cross-structural model from profile I in the Afar Depression and under the western plateau have shown that the electrical resistivity layers vary from 200-500 Ωm in the uppermost kilometre, to 5-10 Ωm at about 15 km depth.

A geophysical survey was carried out in 2013 (Kebede et al., 2013) from impedance strike and tipper strike at different depth levels indicated that most of the stations show a general NW-SE strike direction; coincident with the major trend of the Tendaho rift axis N 25 ° W. From the erratic nature of the orientation of the resistivity contour lines at different depth levels indicates that the Allalobeda field is structurally complex, indicating the presence of different faults and fractures in different orientations. The offset seen in the high resistivity contour reflect the influence of major fault systems, the tectonic trend of the Tendaho graben and the Main Ethiopian Rift (MER).

2.2. Pervious geochemical work

Alallobeda gases differ from those of Dubti because of their lower H_2 and CO content. The Alallobeda and Bagalodoma hot spring waters are of sodium chloride type with high sulphate contents. Na,K,Mg diagram shows that Alalodeda water have a trend towards full equilibrium. On contrary the cold water in tendaho area, are classified among the immature water, regardless of their salinity (Aquater, 1996). A radon soil gas geochemical survey by Teclu and Mekonen (2013) has enabled to reveal the distribution of buried faults, joints or fractures. The investigation confirms that the anomalous values are concentrated in the NNE/SSW and NS direction of the Alallobeda area.

2.3. Previous geological work

The northern Tendaho rift is tectonically characterized by open fissures and active faults which define a pattern of NW-SE elongated blocks with typical wave length of some hundreds of metres. The northeast-trending Tendaho Graben, where the Alallobeda manifestations are located, has a width of about 50 km and joins the Ethiopian Rift close to Dama Ale the volcano west of Lake Abhe. The border of the graben consists of products of the Afar Stratoid Series (ASS) and the graben itself is filled with lacustrine and alluvial deposits and post-Stratoid basalt flows. The filling is overlain by recent volcanoes, including the historically active Kurub volcano (young products: 4,000-10,000 years) and Dama Ale (younger products: 2,500 years). In Tendaho Graben, under the recent sediments and the trachybasalt; the plagioclase pyric and perlite basalt rocks could be important aquifers due to their microfractures and close jointing and constitute reservoir formations for the geothermal system of Alallobeda

In the vicinity of geothermal areas, the most identifiable point of intersection is near Alallobeda, where NNE-SSW-trending faults of the MER terminate and deflect into the major NW-SE-trending that bounds the graben on its southwest edge (Stimac et al., 2014).

3. RESISTIVITY STRUCTURE OF HIGH TEMPRATURE GEOTHERMAL FIELDS

Alteration minerals are formed through hydrothermal alteration processes when hydrothermal water reacts with rock. The alteration process and the resulting type of minerals depend on primary minerals, temperature, fluid chemistry, porosity and permeability of rocks (Árnason et al., 2000). Figure 2 shows the resistivity structure at high temperature geothermal field. In the upper most part of the subsurface the resistivity is high indicating unaltered rock, the main conduction mechanism is pore fluid conduction. Below the resistivity zone the conductive cap is found consisting of smectite and zeolite , that have high cation exchange capacity with surface conduction mechanism. As increasing of temperature and alteration at depth the resistivity decreases future until a core of high resistivity appears. The transition from the conductive cap to the high resistivity core coincides with a change in mineral alteration at a temperature range 230-250 °C smectite is transformed to mixed-layered clay zone. At about 250°C smectite disappears and chlorite is the dominant mineral, marking the beginning of the chlorite zone. At higher temperature 250-270 °C, epidote becomes abundant. The resistivity increased because epidote has bound cations that are fixed in the crystal lattice making them resistive. Here, surface and pore fluid conduction are dominant (Hersir et al., 2013).

Resistivity is directly proportional to the alteration mineral and not necessary related to temperature, since the geothermal system might be fossil (might not be active in the present day).

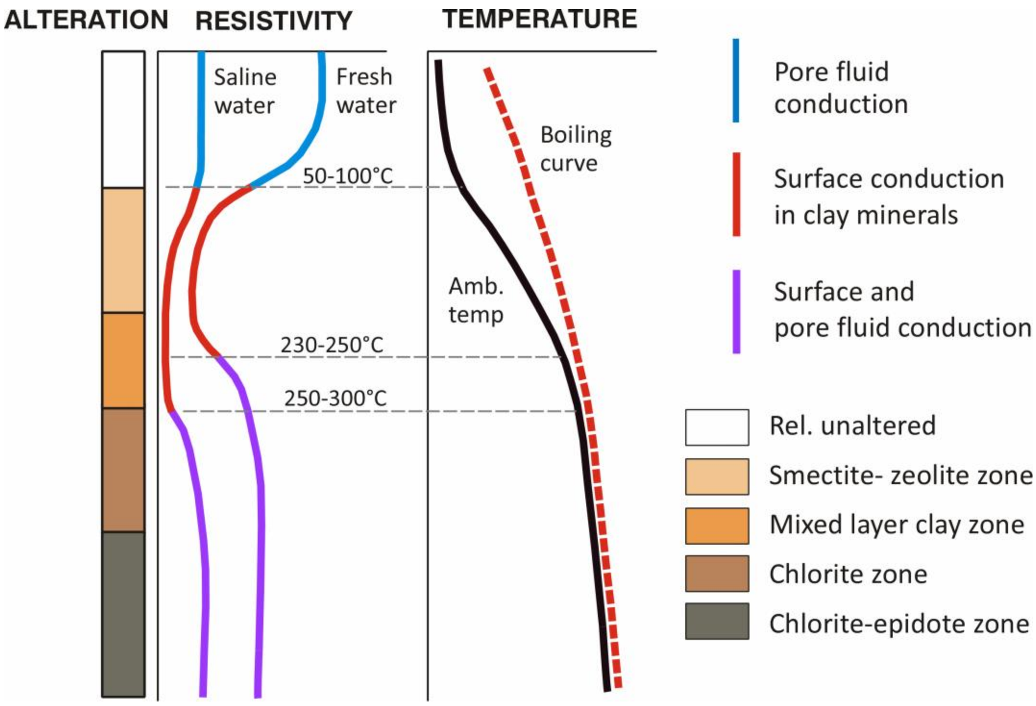

FIGURE 2: The general resistivity structure of a high-temperature geothermal system in basaltic environment showing resistivity variations with alteration and temperature (Flóvenz et al., 2012)

4. ELECTROMAGNETIC (EM) METHODS

Electromagnetic (EM) methods are commonly used in surface exploration of geothermal areas to determine the spatial distribution of the electrical conductivity in the subsurface.

4.1. Magnetotelluric (MT) methods

MT is a passive EM geophysical methods which measure the electric field (E_x and E_y) and magnetic fields (H_x, H_y and H_z) in the orthogonal direction at the surface of the earth. MT signals have a very wide frequency spectrum caused at high frequencies (>1 Hz) by worldwide thunder storm activity and at low frequency (<1 Hz) by geomagnetic phenomena. Those fluctuations induce current in the ground which is measured on the surface. As shown Figure 3, MT method uses lead chloride filled electrodes which measure the electric field (E_x and E_y) and uses induction coil to measure magnetic field (H_x, H_y and H_z) in orthogonal direction.

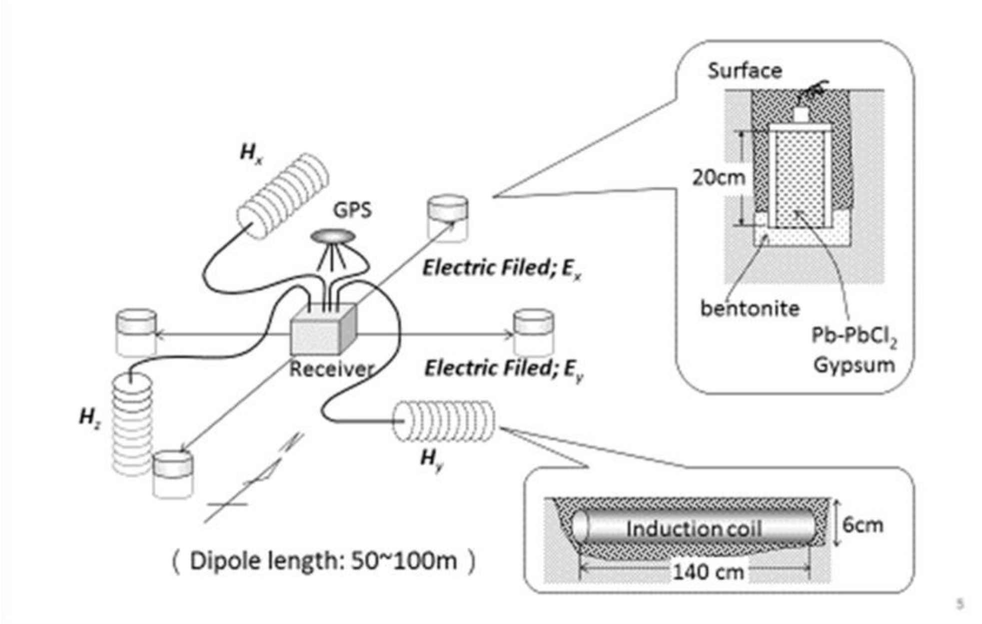

FIGURE 3: Schematic drawing of MT survey layout (JICA, 2015)

4.2. Transient electromagnetic (TEM) methods

TEM is an active EM geophysical method, which does not use electrode and mostly it is used to correct MT static shift (Pellerin and Hohmann, 1990). The setup of TEM is shown in Figure 4. A loop of wire is placed on the ground and a constant magnetic field of known strength is built up by transmitting a constant current into the loop. The current is then abruptly turned off. The decaying magnetic field induces electrical current in the ground. The current distribution in the ground induces a secondary magnetic field decaying time. The decay rate of the secondary magnetic field is monitored by measuring the voltage induced in a receiver coil at the centre of the transmitter loop. The current distribution and the decay rate of the secondary magnetic field depend on the resistivity structure of the earth. The decay rate, recorded as a function of time after the current in the transmitter loop is turned off, can therefore be interpreted in terms of the subsurface resistivity structure.

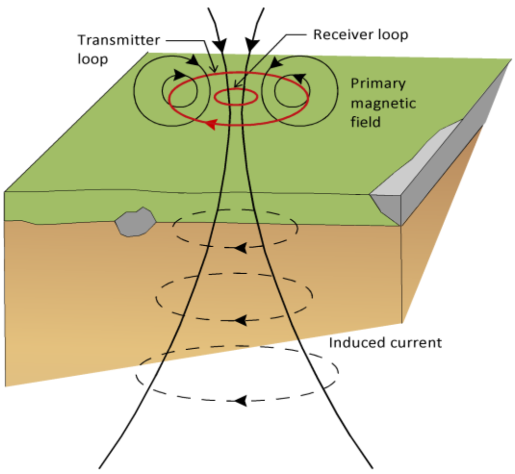

FIGURE 4: The central loop TEM sounding configuration
(Flóvenz et al., 2012; based on Hersir and Björnsson, 1991)

5. MT AND TEM SURVEY AND DATA AQUSITION IN ALALLOBEDA FIELD

5.1. MT survey and instrumentation

MT data were collected using a 5-channel MTU unit data acquisition system from Phoenix Geophysics Company Canada. The instrument used for MT survey, data logger (MTU-5A), compact flash card, power, GPS (global positioning system), two pairs of lead chloride filled electrodes (which used for measuring electrical field),telluric cable, coil cable and three magnetic sensors for measuring magnetic field. In Alallodeda, most of the MT stations the electrode dipole length was 100 m and the recording hours is more than18 hours of continues time series. To avoid local correlated noise remote reference method was used. The layout of MT survey was as shown in Figure 3.

5.2. TEM survey and instrumentation

The TEM data in Alallobeda were acquired by using two instruments from different manufacturing companies, Zonge GDP-32 and Phoenix V8 TEM systems. For most stations, the TEM measurement used a 200 x 200 m square source loop but occasionally, in some difficult terrains 100 x 100 m square was employed. For Zonge TEM the measurement were made at the frequencies 32, 16, 8 and 4 Hz, and for Phoenix 25, 5 and 1 Hz.

6. DATA PROCESSING AND INVERSION

6.1. Inversion

Inversion is used to estimate the model parameters from the measured data. To solve the inversion problem one has to know how to calculate the forward problem. At first a starting model is chosen and the forward algorithm calculates the response. If the calculated response does not fit with the measured data, an inversion algorithm improves on the model in order to improve fit with the measured data.

Forward modelling is most important inversion method, and it has to be accurate, fast and reliable. The Inversion process uses forward modelling to compute the sensitivity matrix and the response for calculated the misfit. The most commonly used inversion method for geoelectric soundings is the least-square inversion method. After each iteration step one gets a sensitivity matrix which gets us nearer the exact model, characterized by the chi-square(χ).

6.2. MT data processing and inversion

In this work, 54 soundings were processed from the time series data and used for interpretation. Figure 8 shows the location map of MT and TEM soundings. The time series data were downloaded from the compact flash card of MTU-5A. The SSMT2000 program, which is provided by Phoenix Geophysics in Canada (Phoenix Geophysics, 2005), takes as input raw time series files, calibration files, and site parameter files. In an intermediate step, it produces Fourier coefficients, which are then reprocessed with data from reference sites, using robust routines. Using MT-editor program cross powers that were affected by noise can be automatically or manually excluded from the calculation. When the final cross power and auto-powers as well as all relevant MT parameters have been calculated, the files were converted and stored to industry-standard Electronic Data Interchange (EDI) files suitable for use with Geophysical interpretation software like TEMTD where they were joint inversion with TEM data from the same site is carried out. In this work, EDI files were processed and inverted with the program TEMTD.

An example of the processed MT data is given in Figure 5. The plots show the apparent resistivity and phase derived from the xy (red) and yx (blue) components of the impedance tensor and the determinant invariant (black), the Z-strike or Swift angle (black dots), and multiple coherency of xy (red) and yx (blue), and skew (black dots) and ellipticity (gray dots).

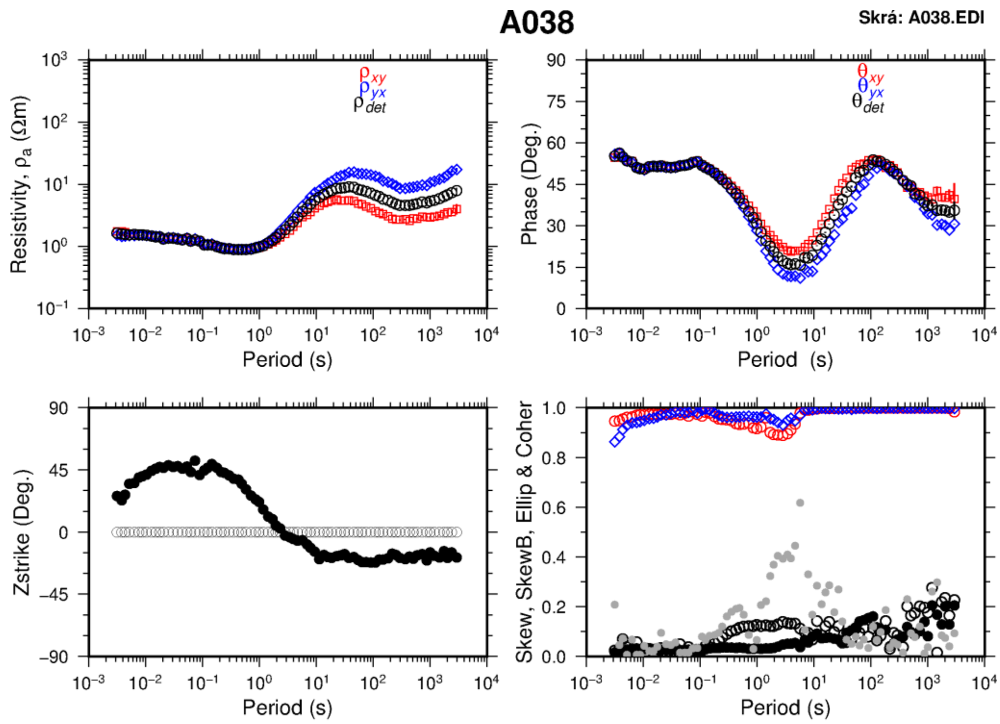

FIGURE 5: An example of processed MT data from the Alallobeda prospect area

6.3. TEM data processing and inversion

To read and process the TEM data, a software called TemX was used (Árnason, 2006a). The program calculates average and standard deviations of repeated transient voltage measurements and calculates late time apparent resistivity as a function of time. The program has graphical interface offering the possibility of editing or omitting outliers of the noisy raw data. In this work the raw data from Zonge was processed by using the software temxUSF.

The TEMTD program for inversion process assumes that the source loop is a square loop and that the receiver coil/loop is at the centre of the source loop (Árnason, 2006b). The current wave form is assumed to be half-duty bipolar semi-square wave with exponential current turn-on and linear current turn-off. The program is written in ANSI-C and runs under UNIX/LINUX operating systems. It uses the gnuplot graphics program for graphical display during the inversion process.

All the TEM sounding were 1D inverted using TEMTD and Occam inversion. An initial model is given and the best fitting model based on layered model followed by running TEMTD. The output from the layered model is used as an initial model in the Occam inversion. To get a smooth model and good fit, several parameters can be changed. An example of 1D Occam inversion of TEM data is given in Figure 6. Red circles: measured late-time apparent resistivity; black line: apparent resistivity calculated from the model shown in green. The number on the top of the Figure (A050Z and A053Z) corresponds to the name of the station.

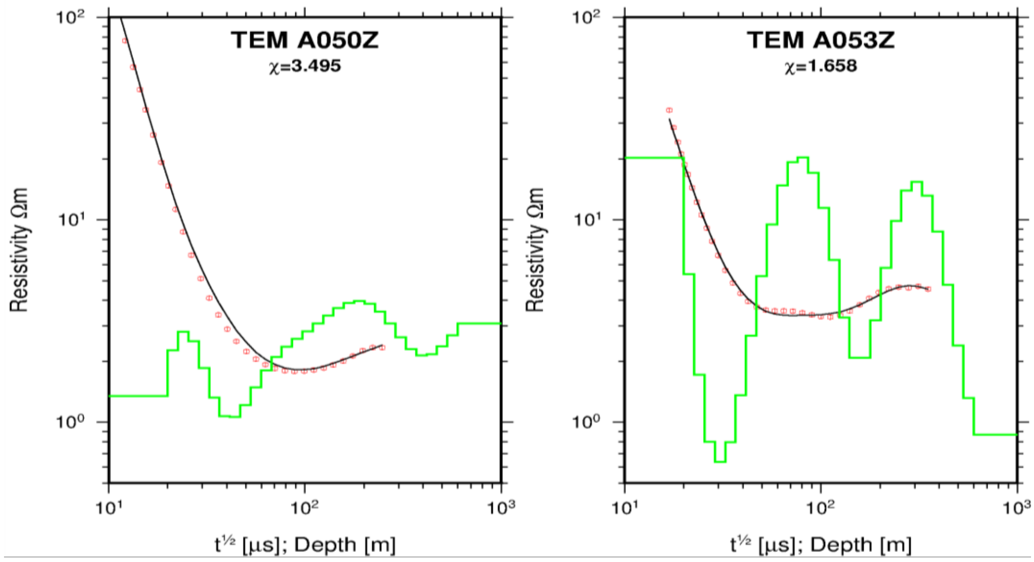

FIGURE 6: 1D Occam inversion of TEM data

7. STATIC SHIFT CORRECTION

Static shift is happening in MT methods caused by local near surface resistivity in-homogeneities due to the electric field distortion. The static shift problem in MT can be solved using join inversion of TEM and MT sounding from the same site. After joint 1D Occam inversion of MT and TEM data the best static shift parameter were determined. In the left of Figure 6 shows the histogram of the static shift parameters. The multipliers for all 54 MT soundings is given with all except one found to be in the range of 0.2-1.6. The spatial distribution of static shift multipliers map in the Alallobeda prospect is shown in the right of Figure 7. From the map in most area of the prospect the apparent resistivity is shifted downwards, but upwards at its border.

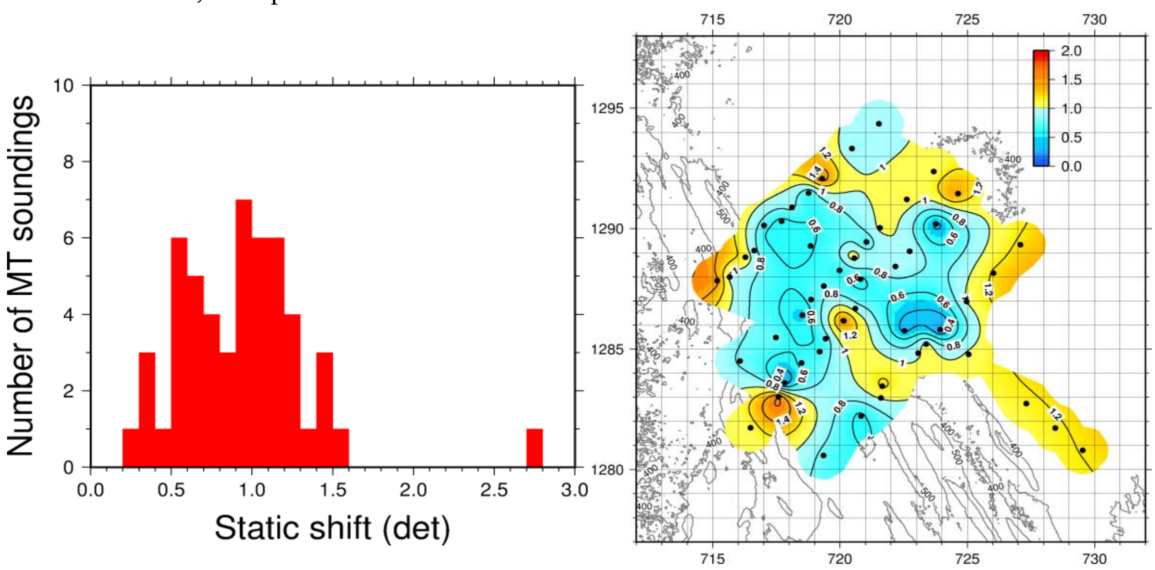

FIGURE 7: Histogram of static shift parameters and spatial distribution map of static shift parameters in Alalobeda prospect

8. JOINT 1-D OCCAM INVERSION

The inversion program TEMTD was used to perform joint 1D Occam inversion of TEM and MT data using the apparent resistivity and phase derived from the rotationally invariant determinant of the impedance tensor. The program determines the best static shift parameter for the MT data. Figure 8 shows an example of joint 1D inversion of MT and TEM soundings. Right panel: results of the 1D resistivity inversion model, Static shift correction was 1.01. Figure 9 shows the location map of MT and TEM soundings.

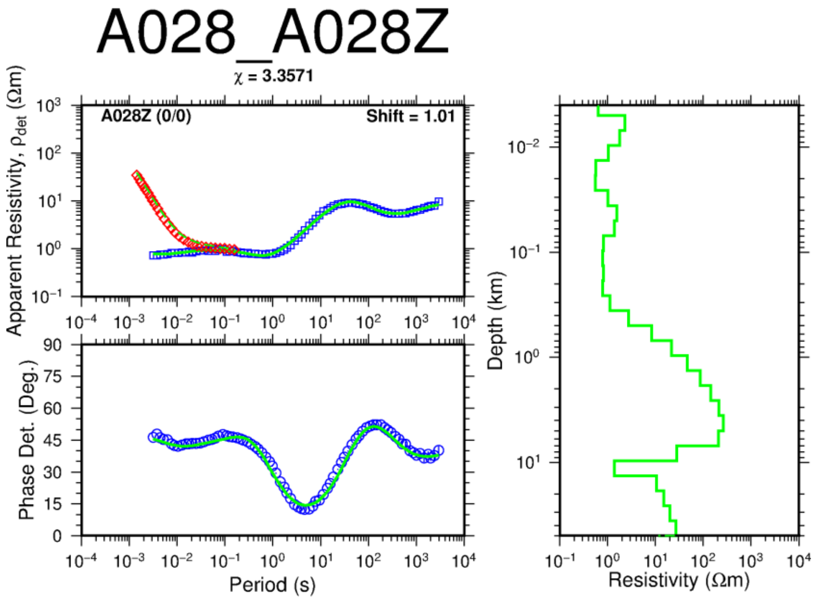

FIGURE 8: Joint 1D inversion of MT and TEM soundings

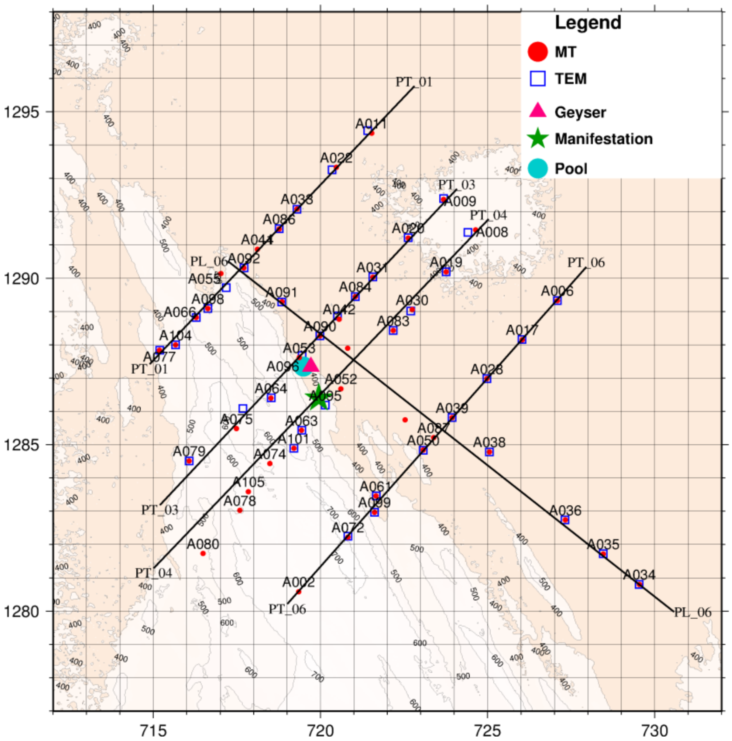

FIGURE 9: Location map of MT and TEM soundings, the circles are MT soundings and the blue diamond are TEM soundings

9. RESULTS AND DISCUSSION

9.1. Resistivity cross-sections

The program TEMCROSS which was developed at ÍSOR-Iceland GeoSurvey (Eysteinson, 1998), was used to create the resistivity cross-sections based on the joint 1D Occam inversion of MT and TEM data. Here are some cross-sections presented shown in Figure 10 and Figure 11. The two cross-sections run NW SE perpendicular to the main geological structure. Generally, it can be said that the resistivity structure seen in these cross-sections is quite similar, with three main resistivity layers.

The uppermost part of cross-section PT_03 is characterized by a thin layer of very low resistivity, <10 Ωm, down to a depth of 200 m b.s.l. Below station A053 and A079 the resistivity is slightly higher, with a value of 10 Ωm, indicating unaltered lava. This low-resistivity layer is associated with the sedimentary formation and possibly also influenced by low-temperature alteration like smectite and zeolites. Below the low-resistivity top layer there is a high-resistivity body with resistivity values about 100 Ωm reaching from appro. 700 m down to the depth 5000m b.s.l., correlating to the Afar Stratoid basalt series possibly with some influence from high-temperature alteration minerals like chlorite and epidote. This high-resistivity layer is mainly seen in the southwest part of the profile, while in the northeast part a low-resistivity anomaly is dominant. At greater depth the resistivity decreases to a value of < 10 Ωm. This low-resistivity layer is seen both in the northeast and southwest part of the profile, while between stations A084 and A053 the deep resistivity is high with a value of 100 Ωm seen to the bottom of the cross-section.

The uppermost part of the cross-section PT_04 is characterized by a thin layer of very low resistivity like in the other cross-section. The second layer is high-resistivity layer with resistivity values between 100 and 1000 Ωm is seen, reaching down to depths of 1000-5000 m b.s.l. The resistivity structure around stations A041, A083 and A105 may indicate an up flow zone in that area. As before, the high resistivity is believed to correlate to the Afar Stratoid basalt series, possibly also influenced by high-temperature alteration minerals like chlorite and epidote. Like in the other cross-section, at greater depth the resistivity decreases again, reaching quite low values, < 10 Ωm which may indicate the deeper lying conductor, related to the heat source. This low-resistivity zone is found below all stations except station A041 which shows very high resistivity down to great depth.

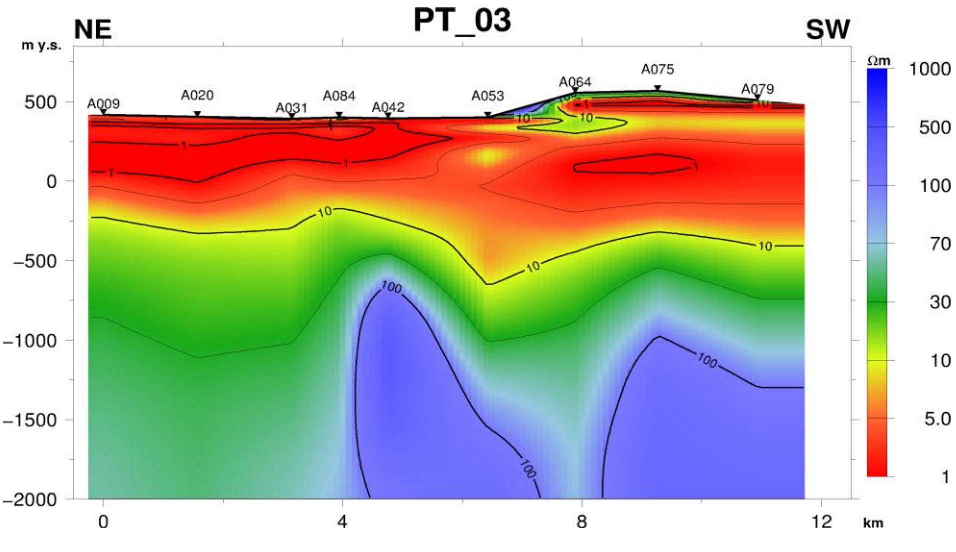

Figure 10: Resistivity cross-sections for location see Figure 9.

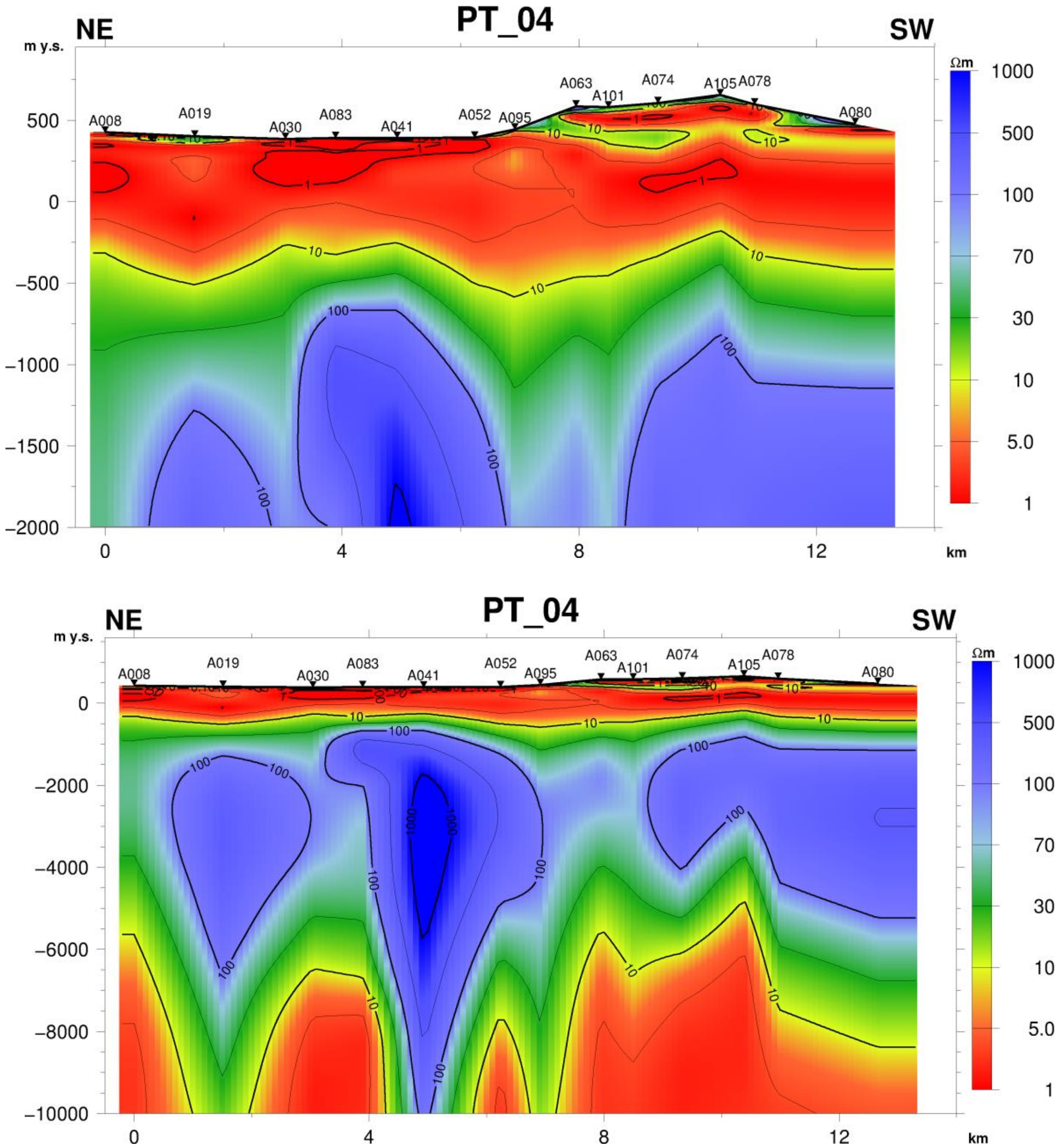

Figure 11: Resistivity cross-sections from joint 1D Occam inversion PT-04 down to 2000 and 1000 m b.s.l. for location see Figure 9.

9.2. Iso-resistivity depth map

The program TEMRESD developed at ÍSOR (Eysteinsson, 1998) was used to plot the iso-resistivity maps based on joint 1D Occam inversion models of MT and TEM data. Figure 12 shows iso-resistivity maps at 300 m b.s.l. and 1000 m b.s.l. At 300 m b.s.l., the higher resistivity associated with unaltered Afar Stratoid basalt Series are influencing the map with resistivity around 30 Ωm. A structure of relatively low resistivity is seen along the geological NE-SW structure. This might be correlated with lateral flow of geothermal fluids, fractures or low alteration minerals like smectite and zeolite. At 1000 m b.s.l., the resistive layer correlated with Afar Stratoid basalt series is seen in the whole area showing values 100 Ωm. However, along the geological structure trending NW-SE the resistivity is still fairly low at this depth, indicating lateral flow of geothermal fluids along the main fracture and low temperature alteration minerals like smectite and zeolite.

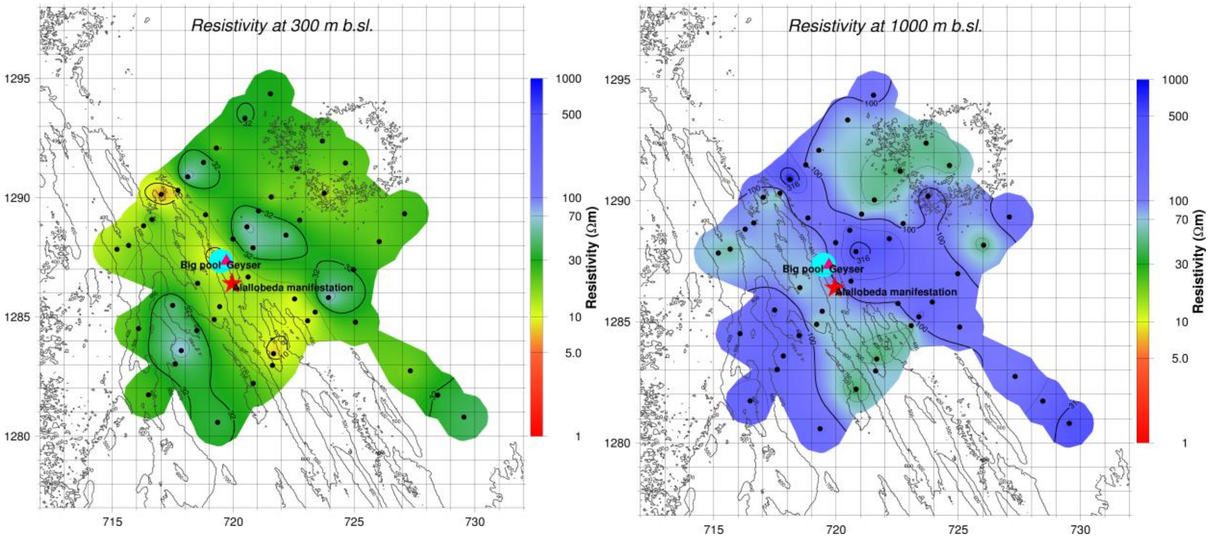

Figure 12: Iso-resistivity map of Alallobeda prospect based on join 1D Occam inversion at 300 and 1000 m b.s.l. the black dotes indicates the location of soundings, light blue filled circle the big pool, pink triangle denoting the geysers and the green star indicates surface manifestation

10. COCLUSIONS AND RECOMMENDATIONS

From the result of joint 1D inversion the combined use of MT and TEM soundings, improve resolution and the accuracy. Based on the results of the joint 1D inversion of 54 MT and TEM soundings the resistivity structure reveals three main resistivity layers seen in the cross-section presented. At shallow depth down to about 500 m b.s.l., a thin layer of low resistivity value exists (< 10 Ωm), which can be correlated to the shallow sedimentary formation in the area, with some influence noted from lateral flow of geothermal fluids in fractures. Below the sediments, the resistivity increases considerably and reaches values of 100 Ωm at a depth of 1000m b.s.l. This layer is associated with the low-permeability Afar Stratoid basalt Series. As can be from the cross-section, this layer stretches to deep levels often the order of 5-6000 m b.s.l. Below the high resistivity layer, another low resistivity layer is seen (< 5Ωm). This deep conductor is either related to the heat source or highly saline sediments at deep levels. Effect of geothermal up flow is seen in the iso-resistivity map associated with known geothermal structures. Results from the strike analysis are in an agreement with the resistivity model.

- In this report only some of the MT and TEM data were processed and jointly inverted. In order to get a better result and interpretation it is recommended that all MT and TEM soundings which were collected in the field survey must be processed and jointly inverted. This would greatly helpful in refining the results currently discussed in this report because a large coverage of the area would improve the resistivity image of the field.
- 3D inversion modelling is recommended to better map the resistivity structure of the subsurface of the Alallodea prospect.

REFERENCES

Aquater 1996: *Tendaho geothermal project, final report.* MME, EIGS - Government of Italy, Ministry of Foreign Affairs, San Lorenzo in Campo.

Árnason, K., Karlsdóttir, R., Eysteinsson, H., Flóvenz, Ó.G., and Gudlaugsson, S.Th., 2000: The resistivity structure of high-temperature geothermal systems in Iceland. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan,* 923-928

Árnason, K., 2006a: TemX, short manual. ISOR, Reykjavík, internal report, 17 pp.

Árnason, K., 2006b: *TEMTD (Program for 1D inversion of central-loop TEM and MT data).* ISOR, Reykjavík, short manual 16 pp.

Bekele, B., 2012: *Review and reinterpretation of geophysical data of Tendaho geothermal field*. GSE, Addis Ababa, unpublished report, 96 pp.

Berktold, A., 1975: Magnetotelluric measurements in the Afar area. Afar Depression of Ethiopia. *Proceedings of the International Symposium on the Afar Region and Related Rift Problems, Schweizerbart, I, Stuttgart*, 262-275.

Eysteinsson, H., 1998: *TEMRESD, TEMMAP and TEMCROSS plotting programs*. ÍSOR – Iceland GeoSurvey, unpublished programs and manual.

Flóvenz, Ó.G., Hersir, G.P., Saemundsson, K., Ármannsson, H., and Fridriksson, Th., 2012: Geothermal energy exploration techniques. In: Sayigh, A. (ed.), *Comprehensive Renewable Energy,* 7, Elsevier, Oxford, 51-95.

Hersir, G.P., and Björnsson, A., 1991: *Geophysical exploration for geothermal resources. Principles and applications*. UNU-GTP, Iceland, report 15, 94 pp

JICA., 2015 : *The Project for Formulating Master Plan on Development of Geothermal Energy in Ethiopia, Geophysical Report. P.P 5.*

Kebede, Y., Mengiste, A., Woledesemayet, B., Abera, F., Hailegiorgis, Abebe G., Dandir, K., and Mengesha, K., 2013: Magnetotelluric survey in Tendaho geothermal prospect North-East Ethiopia. Afar National Regional Government and GSE, Addis Ababa, unpubl. report..

Pellerin, L., and Hohman, G., 1990. ‘‘Transient electromagnetic inversion: A remedy for magnetotelluric static shift.’’ *Geophysics 55*: 1242-1250.

Kebede, S., 2014: Geothermal Exploration and Development in Ethiopia, *Presented at Short course IX, organized by UNU-GTP, KenGen and GDC, Lake Naivasha, Kenya.*

Phoenix Geophysics, 2005: Data processing. User guide´s. Phoenix Geophysics, Ltd., Toronto.

Stimac, J., Armadillo, E., Rizzello, D., Mandeno, E., 2014*: Geothermal resource assessment of the Tendaho area.* Completed for UNEP and the Geological Survey of Ethiopia, 83 pp

Teclu, A., and Mekonen, M., 2013: *Preliminaryradon soil geochemical survey at Alallobeda geothermal prospect (Tendaho geothermal field).*GSE, GREAD, Addis Ababa,unpubl. report 55 pp..

UNDP, 1973: *Geology, geochemistry and hydrology of hot springs of the East African Rift System within Ethiopia*. UNDP, December report DD/SF/ON/11, NY.