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Geophysical study on Lake Abhé geothermal prospect, Djibouti

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ABSTRACT

As part of the geothermal energy development program, a geophysical study was conducted on the Lake Abhé prospect which is considered a potential geothermal site. The objective of the geophysical study was to delineate the boundaries of the geothermal reservoir. This site is located in the south-west of the country, and has geological structures related to tectonic plates associated with the Arabian plate movement over the last 3.4 M.y. The area is mainly composed of stratospheric basalts bounded by EW faults. There are several hydrothermal surface manifestations around the lake, fumaroles and a rich variety of hot springs and many travertine constructions. In 2012, a geophysical campaign conducted by the CERD team carried out 86 gravity stations, 34 Magnetotelluric (MT) soundings and 35 time domain electromagnetic soundings (TDEM). A second campaign conducted by ODDEG including 66 gravity stations, 39 MT and 17 TDEM soundings were conducted in 2015.

The residual Bouguer gravity map shows increasing gravity toward the northeast, presumably reflecting thinning of the sediments covering the basement. A high gravity is observed within the graben area, oriented in a SW-NE direction. Distinct gravity highs are seen in the graben. Some of the faults are present trending in an E-W direction, lineaments and the geothermal surface manifestations. The resistivity model shows a low resistivity layer, less than 5 Ωm thick, approximately 300-400 m thick, which corresponds to the thickness of conductive sediments in the western part of the study area and thins at East. Below this layer, we have another layer of low resistivity below 10 Ωm that would correspond to permeable stratoid

basalts and coincides with geothermal surface manifestations related to geothermal fluid or geothermal alteration. This structure is also imaged by the Bouguer residual anomaly and corresponds to the negative anomaly surrounding the strong positive anomaly in the central part of the study area.

1. Introduction

Lake Abhé is located in the southwest of Republic of Djibouti (figure 1). It is considered as a potential geothermal field (Jalludin, 2014) due to the surface hydrothermal manifestation expressed around the Lake, fumaroles hot spring and travertine. In order to evaluate the Lake Abhé geothermal system, two phase of surface studies have been undertaken by two national institutions CERD and ODDEG respectively in 2012 and 2015.

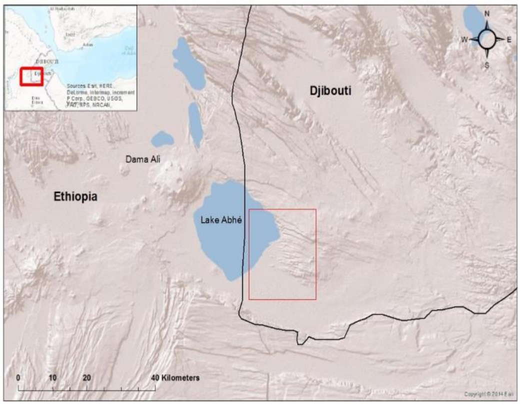

Figure 1: Lake Abhé prospect area and the red square show the study area.

During these exploration studies several disciples geoscientifics including geology, geophysics, geochemistry, and hydrogeology were carried out in the site.

But in this paper the discussion is specifically based on the geophysical surveys including gravity and resistivity surveys conducted during the two campaigns of 2012 and 2015.

In 2012, geophysical surveys were conducted by CERD and consisted MT/TDEM and gravity survey. In total 34 MT sounding 35 TDEM and 86 gravity station were measured in this survey. The quality of some of MT data was not good, because the data was collected from metronix system which has not been calibrated since 2010s and the acquisition was done without a remote reference which could improve the processing data. The location of gravity stations of 2012s are not much accurate. In addition, following 2012s the lake Abhe is moved back to the west and some surface manifestation appeared and the area survey is extended to the west.

Therefore, in 2015 a second campaign of geothermal exploration was conducted by new national institution ODDEG under support of ISOR. The main objectives are to fulfill and to improve the previous study done by CERD, to create a conceptual model of the geothermal field based on both CERD and ODDEG studies.

The results indicate a low enthalpy geothermal system with reservoir temperatures within a range of 110-150°C. it was suggested that this range of temperature may be used for electricity production using binary technique but the cooling potential of the brine within the power plant is also limiting the chance of feasible power production. Water within this temperature range has potential for direct use, such as drying of wood and food products cooling and even freezing (ODDEG, 2015)

1.2 Previous studies

Lake Abhe region has known three phase of geothermal explorations conducted by different institutions and in differents periods.

The first phase, in 1970s consisted of geological, geochemical and geophysical surveys conducted by the French Geological Survey (BRGM) in order to locate and evaluate an eventual reservoir. During this phase two geophysical techniques were carried out in the area, electrical method and magnetic method . However the information resulting from these techniques were insufficient and provided many hypothesis. That could be due to the limite of investigation of electrical method.

In 2012, a second phase of geothermal exploration has been undertaken by the national institution CERD. Several disciplines studies including geology, geochemistry, geophysics and hydrogeology were conducted by CERD Survey team. In comparison with BRGM, CERD Survey team used the perform and modern technique of measurements and analysis to investigate the area. The geochemical analysis indicated a maximum temperature of 150°C and two categories of water related to the sedimentary rock and volcanic rock (CERD, 2010). The geophysical surveys consisted MT/TEM sounding, and gravity survey confirmed these two aquifer and suggested a geothermal reservoir around 700-800m.

In 2014, a survey team of the Japan International Cooperation Agency (JICA) carried out a data collection survey to collect and analyze geological and geochemical information of thirteen geothermal sites in order to evaluate the development of geothermal sites.

In lake Abhe, the result of data collection suggested a geochemical temperature of 150°C which is in accordance with the result of CERD. From these geochemical analysis JICA Survey team considered that lake Abhe as lower priority of geothermal exploration.

2. Geological setting

Lake Abhé is located in the Tendaho-Gobaad graben and it is highlighted by recent and current volcanism in the NE, including the Dama Ale volcano on the other side of the lake, in Ethiopia. Gobaad is purely tectonic, with significant sedimentary accumulation since the Late Pliocene (more than 2Ma). The basaltic stratum series (3.5 to 2 Ma) affected by normal WNW-ESE and NW-SE trend faults (with SW dominant at the northern boundary of the graben). There are numerous thermal events (fumaroles and hot springs, between 71 and 99.7 ° C) on faults NW-SE to WNW-ESE. Hydrothermal system active for some years with spectacular chimneys and travertine deposits, aligned on the same tectonic directions formed while the level of the lake was 30m higher.

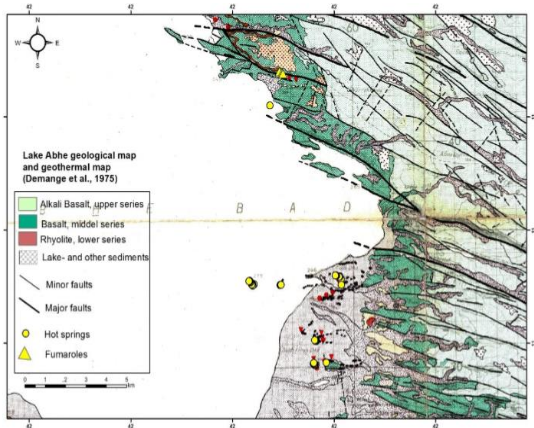

Figure 2: Lake Abhé geological map and geothermal map.

3. Geophysical surveys

3.1 Gravity survey

The Gravity method is non destructive geophysical techniques that measure the variation of the gravitational attraction by the earth at specific location. This technique is useful and powerful in geothermal energy investigation in order to define the lateral density variation in the subsurface which will be related to basement depth variations, rim of caldera, intrusive, rock alteration, sediments, porosity variations, faults or dykes.

3.1.1 Data acquisition

Two gravity surveys were conducted in the Lake Abhe prospect, previously by CERD (2012) and recently by ODDEG and ISOR in 2015. A total of 156 gravity stations were measured in both the 2012 and 2015 survey using the same equipment Scintrex CG-5 gravimeter. Figure 3 shows the location of all the gravity stations that have been measured at Lake Abhé.

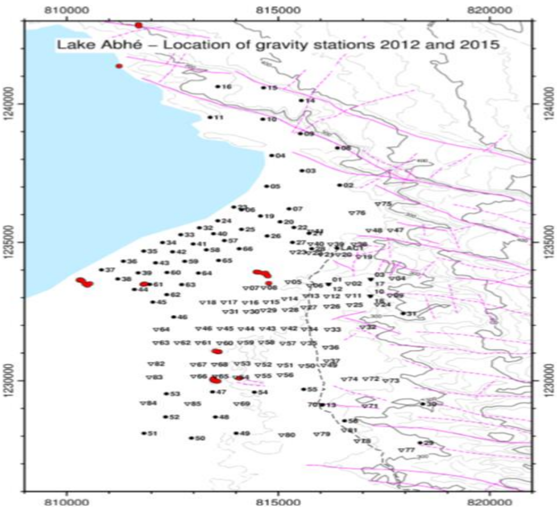

Figure 3: Location of gravity stations in the Lake Abhe prospect; small triangles are the 86 station from 2012 and small black dots denote the 66 sites from 2015.

Since the required elevation accuracy for detailed surveys is between 0.004 and 0.2 m, the position of stations from 2012 surveys have been measured using an electronic distance meter (theodolite) and the stations from 2015 have been measured using a differential global positioning system (DGPS). In order to tie the station from 2012 to the survey in 2015 a gravity observation were made at four of the old gravity stations.

3.1.2 Processing and interpretation

The observed gravity reading obtained from the gravity survey reflects the gravitational field due to all masses in the earth and the effect of the earth's rotation. In order to remove all these effects, several corrections have to be applied to the field gravity readings. All gravity readings in Lake Abhé prospect were processed in a conventional manner (see.eg Keary et al., 2002) to reach the Bouguer anomaly at each point using a density of 2.6 g/cm 3 for the Bouguer and terrain correction. Terrain correction was done from 50.3 m to 21.9 km assuming a flat area within the nearest 50 m and elevation model in a 30 m x 30 m DTEM grid. Figure 4 shows the Bouguer gravity map of the Lake Abhé prospect. It shows an increasing of gravity value from southwest to northeast, reflecting the decreasing thickness of the sediment.

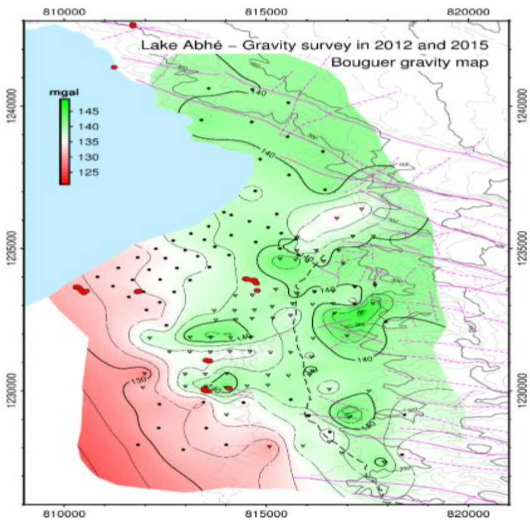

Figure 4: Bouguer gravity map of the Lake Abhe prospect.

A second order polynomial (in x and y; 6 parameter approximation) was fitted to the Bouguer values shown in Figure 4. By subtracting the calculated polynomial from the Bouguer values a residual Bouguer map is found as seen in Figure 5. It indicates the more local (residual or regional) anomalies of the prospect. The map shows a low gravity values covering the higher gravity toward the northeast.

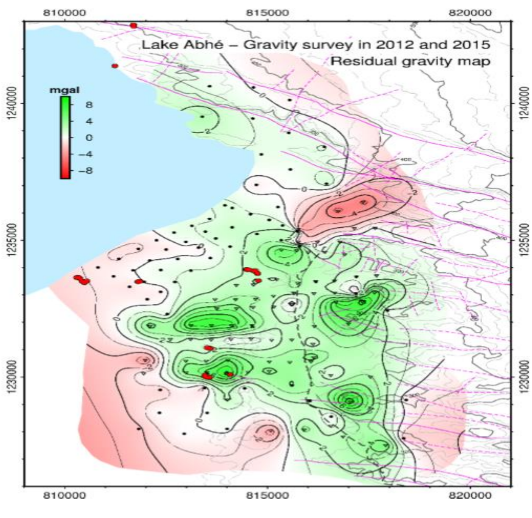

Figure 5: residual Bouguer gravity anomaly map.

3.2 Resistivity survey

A resistivity survey is one of the powerful geophysical tools in geothermal energy investigation due to the direct correlation between electrical resistivity of the rock and the fluid salinity, temperature and alteration caused by geothermal activity. Usually, in a high temperature geothermal systems the near surface is characterized by unaltered zone and the conduction is mainly pore fluid conduction. Since the temperature increases at greater depth and a high content of mineral alteration appear as smectides-zeolites. In this case the conduction mechanism is dominated by mineral or surface conduction which reflects in general low resistivity. At high temperature (above 230°C) the resistivity increases due to disappear of smectites and formation of high temperature secondary alteration minerals like chlorite and epidote and here the conduction is dominated by surface and pore fluid conduction. Figure 6 shows a summary of the alteration mineralogy in high temperature system as a function of temperature (Árnason et al., 2000; Flóvenz et al., 2012).

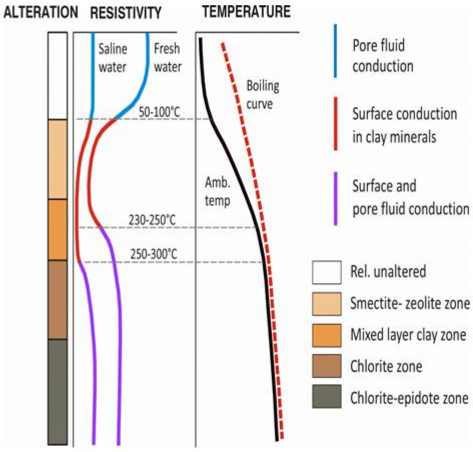

Figure 6: resistivity variations in a high temperature geothermal system with alteration and temperature.

3.2.1 MT and TEM methods

Magneto-Telluric (MT) and Transient Electro-Magnetics (TEM) also called TDEM (Time Domain Electro-Magnetics) are two geophysical methods revealing a physical parameter, the electrical resistivity. There exists several methods for measuring the electrical resistivity of the subsurface. These methods can be classified into two categories, galvanic (DC) and Electro-Magnetic (EM) methods. DC methods mainly Vertical Electrical Soundings (VES) were widely used during the past decades for probing the subsurface. Those methods present some difficulties in the field where it may prove to be difficult to inject current into the ground. These methods have a poor depth of investigation, a penetration depth of only a few hundred meters. Nowadays, in geothermal exploration EM methods are mainly used.

The MT method is based on measuring currents induced in the ground by time variations of the Earth’s magnetic field. The fundamental theory was first developed by Cagniard (1953) and Tikhonov (1986). The time varying magnetic field and the associated electric field generated in the subsurface are measured simultaneously. The electric field is measured in two perpendicular horizontal directions and the magnetic field in the same horizontal directions besides the vertical direction. The measured time series are Fourier transformed into harmonic components for different periods. The harmonic components of the electric field are related to the magnetic field by the so-called impedance tensor, which depends on the subsurface resistivity. For short periods the tensor is mainly dependent on shallow resistivity structures, but for long periods it is mainly dependent on the deep lying resistivity structures. The MT method has the greatest depth of exploration of the available EM methods (several and even up to a few tens of 7ilometers) and is practically the only available method for studying deep resistivity structures particularly in volcanic medium.

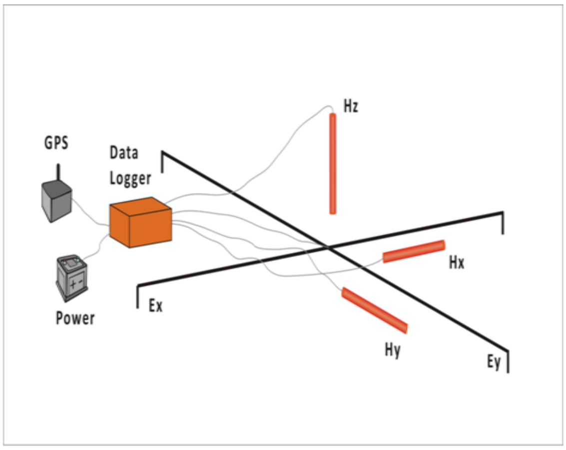

Figure 7: The field setup of MT sounding: Ex and Ey are the two orthogonal electric fields while Hx and Hy are magnetic channels. The Hz channel is used for strike analysis Flóvenz et al., (2012).

The TEM method has a depth of investigation from about 100 to 1,000 m according to the size of the transmitting loop and provides a geoelectrical model with a good resolution. The fundamental principles of the method were developed by Kaufman (1983) and Decloîtres (1998). The technique also makes it possible to correct for the static shift which affects the apparent resistivity of the MT soundings. The principle of the method consists of injecting an electric current into a loop of wire (transmitting loop). The electric current induces a magnetic field in the subsurface. The current is then turned off abruptly and an electromotive force is created which generates electric currents called eddy currents in the subsurface. These currents induce a secondary magnetic field in the subsurface which is measured by another loop of wire (receiver loop) on the ground. The decaying magnetic field depends on the resistivity of the subsurface.

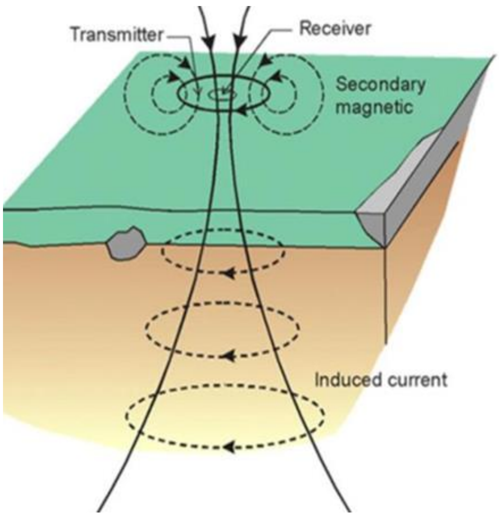

Figure 8: The central loop TEM configuration showing transient current flow in the ground, Hersir and Björnsson (1991).

3.2.2 Data acquisition

Two campaigns combining magneto-telluric and transitient electro-magnetic were carried out in the Lake abhe prospect in the southwest of the Republic of Djibouti, the first campaign is conducted in 2012 by the applied geophysics laboratory of the study and research center of (CERD). In this survey 34 MT soundings and 35 TDEM stations were measured. The MT time series were acquired with one Metronix system. The TEM data were collected using terraTEM equipment.

The second campaign was conducted jointly by ÍSOR geophysical team and ODDEG geophysical team in 2015. Two different acquisition systems were used in the fieldwork for the MT and TEM data collection. The ÍSOR team carried out MT soundings at 21 new locations plus repeating 8 of the soundings from 2011 using two Phoenix equipment. During the MT recording, an MT remote Phoenix station was operating simultaneously at a distance of approximately 10 km from the survey area. The ÍSOR team also carried out four good quality TEM soundings, using a central loop configuration and a 135 m x 135 m transmitter loop, before having a trouble with the Zonge instrument. At the same time the ODDEG team carried out 29 MT soundings (thereof, 5 of the sounding from 2011 were repeated and 4 were made at the same location as Phoenix stations) using two Metronix equipment. After the departure of the Icelandic experts, the ODDEG team performed 17 TEM soundings using the terraTEM equipment at the same location as the MT stations were performed, using the Phoenix equipment, and two at the 2015 Metronix sites. The 17 TEM soundings had a coincident loop, 100 m x 100 m for the transmitter and 100 m x 100 m for the receiver.

A total of 92 MT soundings (at 73 different locations) and 55 TEM soundings were performed in the Lake Abhé prospect during these two field campaigns. Most of their location is shown in Figure 25 (some of the repetitions are skipped). Each MT station was kept running overnight, for a total of about 18 to 20 hours. The quality of the MT data was good in the range of 800 Hz to about 300 seconds. Unfortunately, a big error bar on the MT impedance tensor is observed for the soundings from the Metronix system. These big error bars might well be due to the processing phase.

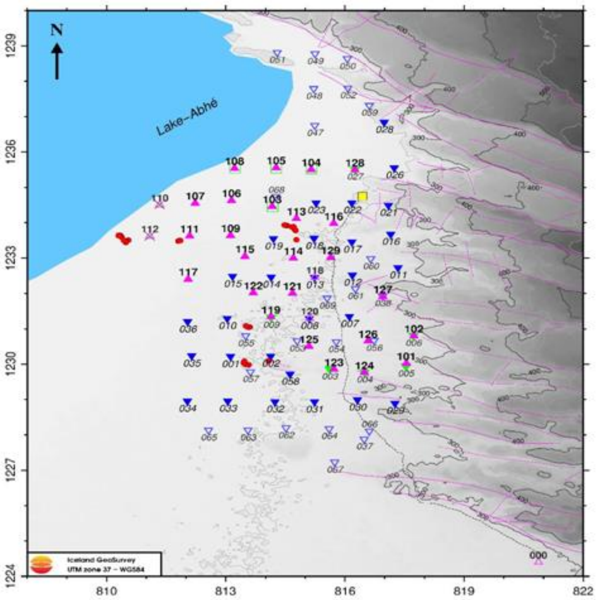

Figure 9: location of the MT and TEM soundings using Metronix equipment (blue triangle) Phonix

equipment (purple triangle) and using both in the same place (green square).

3.2.3 Processing and inversion Data

The raw TEM data from both the terraTEM and Zonge equipment were processed using the TemxUSF program (Árnason, 2006b). The program calculates averages and standard deviations of repeated transient voltage measurements and calculates late time apparent resistivity as a function of time after the current turn off. The MT data from Phoenix instruments were processed using the SSMT2000 and MTeditor program from Phoenix Geophysics (figure 10b) while the MT data from Metronix were processed using the ProcMT program from Metronix (figure 10a). The Phoenix MT data were processed using a remote reference station.

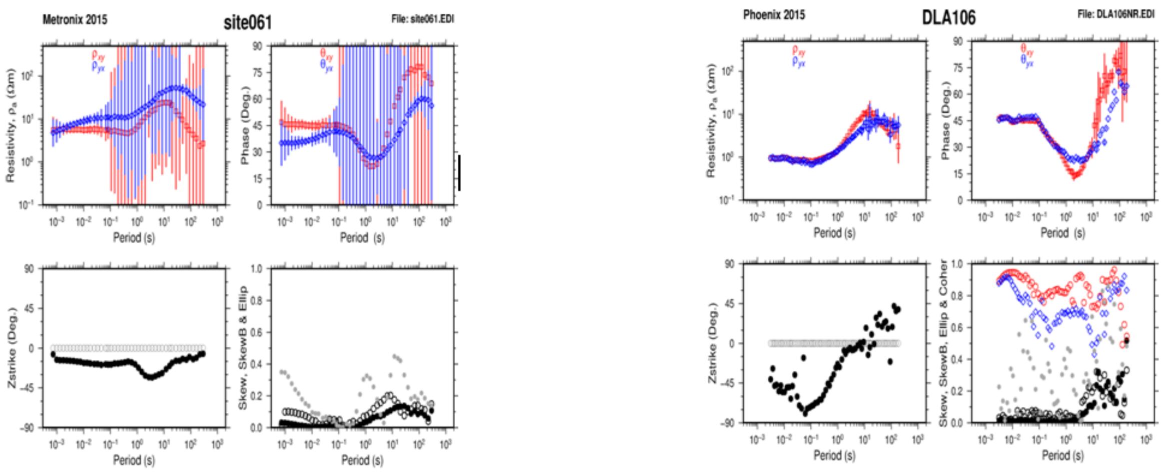

Figure 10: a) processing of MT data using ProcMT from Metronix b) processing of MT data using MT editor from Phoenix.

Following the processing work, the MT and TEM data from the same location are one-dimensionally (1D) jointly inverted to create a 1D resistivity model below each sounding site. In the joint inversion the MT data are corrected for the static shift that affects the MT apparent resistivity (see e.g. Árnason, 2015). There are 53 MT soundings that were measured close to the location of a TEM sounding. All of them are used performing the 1D joint inversion. The joint 1D inversion presented in this work is a so-called “minimum structure” or Occam inversion (Árnason, 2006a). It consists of fitting the apparent resistivity and phase data from each MT sounding and the TEM data from the corresponding TEM sounding with the response of a model of many layers with constant thicknesses, which increase exponentially with depth. The unknown parameters that are to be determined (inverted for) in this procedure are the true resistivity of the different layers of the subsurface and the static shift parameter. Figure 26 shows an example of joint 1D inversion of a TEM and MT sounding.

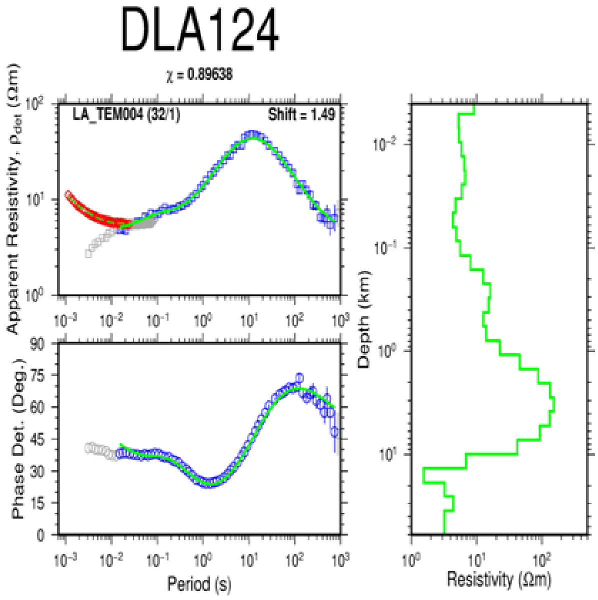

Figure 11: typical result of a joint 1D Occam inversion of TEM and MT data

3.2.4 Results and interpretation

In order to understand resistivity structure, the resistivity models resulting from 1D inversion of TEM/MT pairs are presented into 12 pseudo2D resistivity cross section and 21 depth slice from 100m to 7000m.

In this paper two resistivity pseudo 2D cross section and 5 depth slices are shown and discussed specifically to emphasize the main results of the 1D inversion.

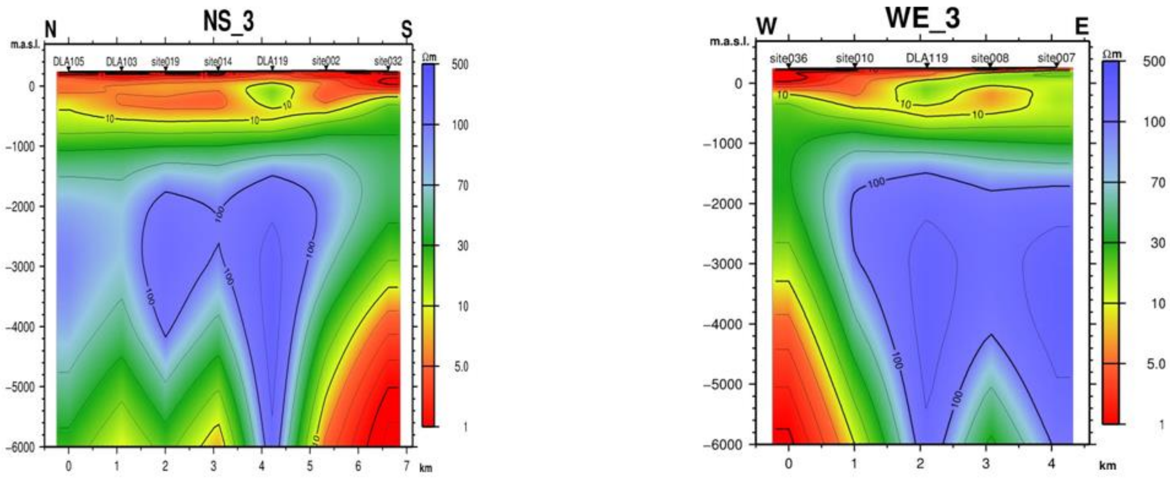

Figure 12: Resistivity cross sections NS_3 and WE_3 down to depth of 2000 and 6000 m bsl.

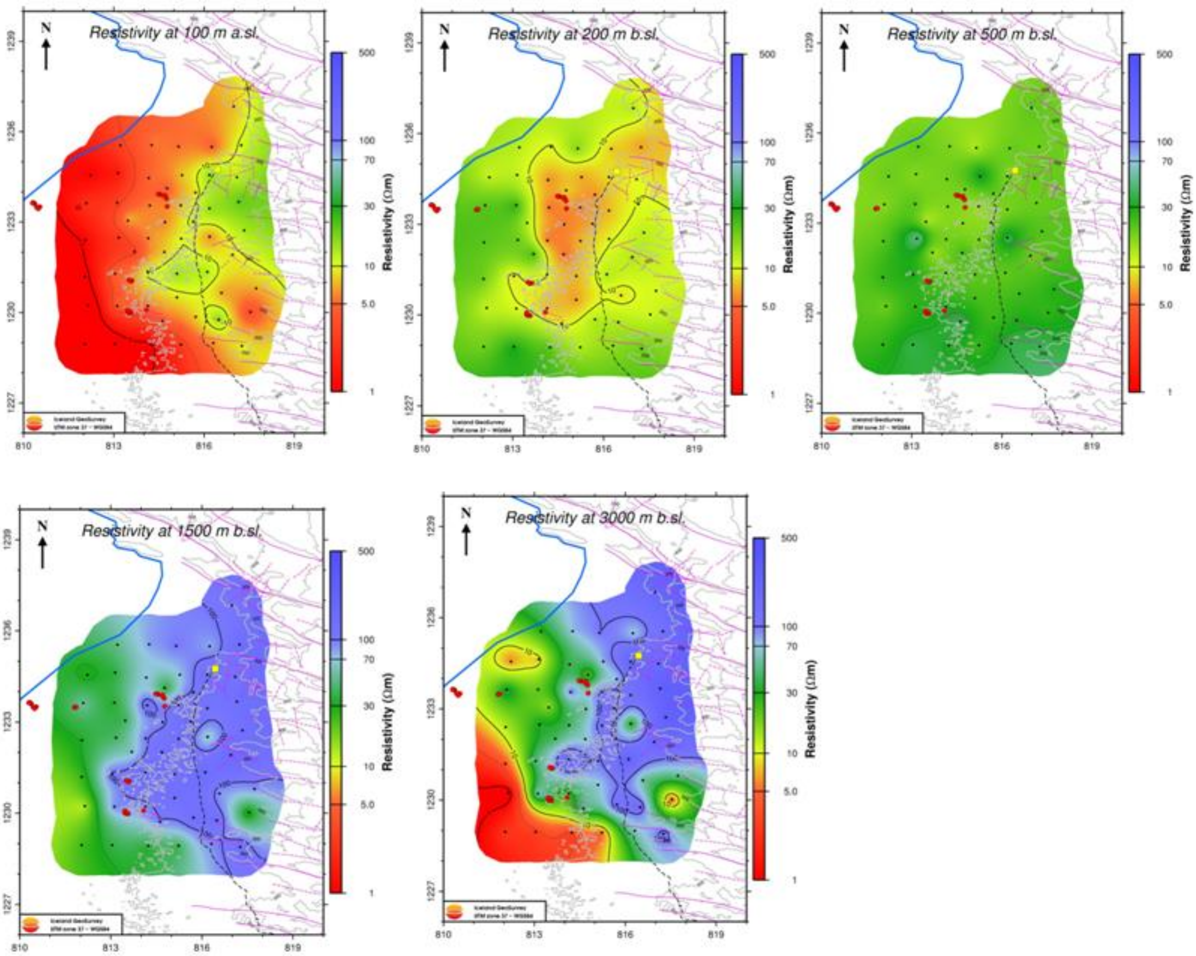

Figure 13: Resistivity depth slices at 100, 200, 500, 1500 and 3000 m bsl.

The WE2 lying cross section and NS lying cross section both show a low resistivity in the near surface. This conductive layer reflects the sediment conductive and covering the western in most part of the region with tickness about 200-300 m and becomes thinner to the east. At 200 m bsl specificaly at the centre of the survey area close to the surface manifestation another conductive formation is revealed. It was suggested that correspond to the permeable stratoid basalts connected to the geothermal fluid and/or geothermal alteration. An increasing of resistivity is seen below the conductive layer due to the less permeable stratoid basalts and rhyolitic formation. At greater deep, up to 2500 m bsl a low resistivity layer is shown in the westernmost part of region. The nature of this deep low resistivity is not clear. It is unlikely to be heat source, since the geothermal surface manifestations are mainly to the east of it.

4. Conclusion

Resistivity data and gravity data support a similar interpretation specifically in the central part of the survey. The conductive formation seen at 200 bsl caused by hydrothermal minerals-mineral densification correlates well with the high density revealed by the residual anomaly of Bouguer. About the conductive formation seen at great depth (more than 2500 m), some recommendations are suggested.

RECOMMENDATIONS

it is recommended to do forage exploration or to extend the exploration surface in the other side of Lake in Ethiopia to know exactly the nature of this conductive layer and its relation with the geothermal activity.

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