

MAGNETO TELLURIC METHODS IN GEOTHERMAL EXPLORATION AT ALUTO-LANGANO, ETHIOPIA

Weldeyohannes Hadush

Ethiopia Electric Power: Geothermal Sector Development Program

weldeyohannesh@yahoo.com

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ABSTRACT

Aluto–Langano geothermal field is one of the high-temperature geothermal fields in the middle Ethiopia rift valley. In order to explore the geothermal potential of the area, 166 MT and TEM soundings were performed during the last few years. This paper presents the results of data from two profile lines consisting of 17 MT and 17 TEM soundings. The joint 1-D inversion of the TEM and MT data was done in order to correct the static shift affecting the MT soundings.

The results of 1-D joint inversion are presented as cross-sections of the resistivity down to different depths using the WIN RESIST (IPI2 WEN) software and the leapfrog software. The 1-D inversion of TEM soundings alone reveals the subsurface resistivity down to a depth of less than 1 km, while the joint inversion of the TEM and the MT data reveals the subsurface resistivity down to a depth of several km. According to the joint inversion resistivity cross-section, the permeable zones are presumably located below 700 to 1300m and below 1700m. The depth dimensions of the reservoir have been quite well defined by cross-sections based on MT soundings and correlated with geological and reservoir data of the existing wells in the field. Based on this interpretation, two favorable potential areas have been identified as target areas for geothermal resource exploration in the Aluto - Langano field one of which has not been drilled as yet.

1. Introduction

Magnetotelluric (MT) and Transient Electromagnetic (TEM) methods are widely used in geothermal exploration (Hersir and Björnsson, 1991). The MT method is an important exploration technique for investigation of deep resistivity structures within the earth (Swift, 1967; Vozoff, 1991; Berdichevsky, 1999). Near-surface resistivity bodies can also severely distort MT apparent resistivity data at arbitrary frequencies Pellerin and Hohmann, (1990). This distortion, known as the MT static shift, is due to an electric field generated from boundary charges on near-surface resistivity in homogeneities. TEM soundings are more correct in the subsurface since they do not measure the electric field, only the decay of the magnetic field. The overall objective of this work was to perform a joint 1-D inversion of both MT and TEM soundings, to remove the effect of the MT static shift.

A total of 166 MT and TEM sites have been acquired in Aluto-Langano field (Fig.1) between 2009 and 2015 and 1-D inversion done (Eysteinnsson, 1999 and 2001; Hersir et al., 2010). These

data were used in the current study and subsurface resistivity distributions were correlated with the existing well data to assess the geothermal resources of the area.

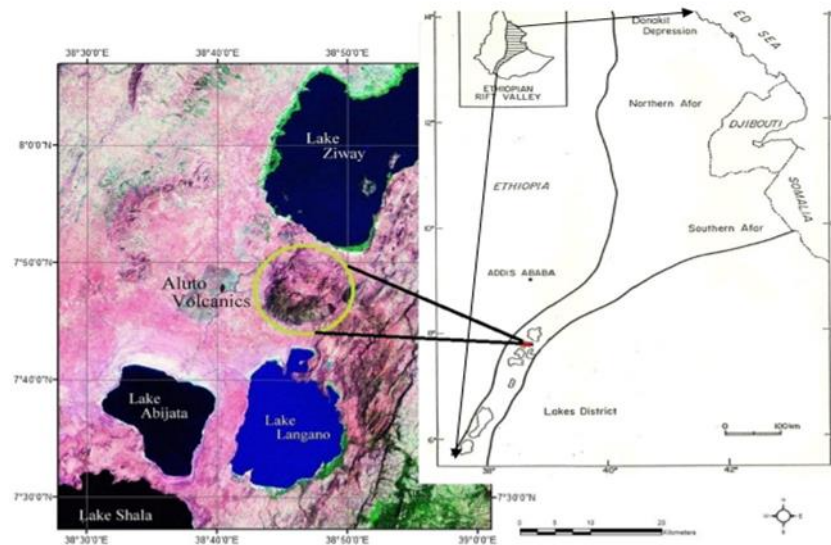


Figure 1: Location map of the study area

This work is divided into four parts. The first describes the generalities of the two methods used, MT and TEM. A discussion about the technical work, the data acquisition, how to record the data, process the data and make the joint inversion of the two data sets follows. The next step was to analyze the results from the joint inversion and interpret them to access the geothermal reservoir area and identify favorable locations for exploration.

2. Geophysical Exploration Methods for Geothermal Resources

According to Hersir and Björnsson (1991) Geophysical exploration methods for geothermal resources are divided in to direct and indirect/ structural methods based on the parameters to be measured or investigated; the following overview is mainly based on Hersir and Björnsson (1991).

2.1 Magneto Telluric (MT)

The MT method was proposed by Tikhonov in the 1950s and later by Cagniard (1953), although the principle was recognized much earlier. In its forms (MT, AMT and CSAMT), the method is now used in a broad variety of applications, from very deep and large scale studies of the crust and upper mantle, through a wide range of exploration applications, geothermal and petroleum exploration, to the shallow problems of epithermal gold, 'deep' base metals and groundwater. In many of these applications, MT provides a kind of information which can be obtained in no other way.

The magneto telluric (MT) method uses time variations of the Earth's natural electromagnetic field to determine the electrical conductivity of the Earth. The solar system ejects charged particles called solar wind. These particles are mainly protons and electrons interacting with the Earth's magnetosphere and producing electromagnetic fields. The charges in the ionosphere cause displacement currents and conduction currents to produce lightning and thunderstorms. The flow of charged particles in ionospheric zones or magneto spheric layers, as hydro magnetic waves or plasma, generates electrical and magnetic fields that propagate towards the

Earth Vozoff, (1991). The strength of the electromagnetic fields depends on time and position (in latitude) due to the relationship between the Sun and the Earth in rotation and the ejection of the Earth's magnetic field. The magnetic field of the Earth varies from the equator to the poles. The interactions of solar particles and the Earth's magnetic fields result in electromagnetic waves of various frequencies.

The geomagnetic fluctuations range between periods of 10^{-3} s and 10^5 s depending on their origin Vozoff, (1991). When reaching the ground, the electromagnetic waves penetrate to great depths and interact with subsurface layers that produce secondary electromagnetic fields that are measured by MT instruments.

Between 0.5 and 5 Hz lies the dead band at which natural EM fluctuation has a low intensity. MT measurements in this frequency range usually suffer from poor data quality. Magnetotelluric measurements presented throughout this work have a band width of 10^{-2} to 10^3 s. The period ranges between 1 and 10^3 s is due to interactions between solar particles, wind, the Earth's magnetosphere and the ionosphere.

2.2 Transient Electromagnetic Method (TEM)

In the transient electromagnetic method (TEM), an electrical current is induced in the ground and a magnetic field created is measured at the surface, from which the resistance of the underground rocks is determined. The current in the ground is generated by a time varying magnetic field. Yet, unlike MT-soundings, the magnetic field is not the randomly varying natural field but a field of controlled magnitude generated by a source loop. 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 (Fig.2). The decaying magnetic field induces electrical current in the ground. The current distribution in the ground induces a secondary magnetic field decaying with time. The decay rate of the secondary magnetic field is monitored by measuring the voltage induced in a receiver coil (or a small loop) at the center of the transmitter loop. (a) Shows the current in the transmitter loop; (b) is the induced electromotive force in the ground; and (c) is the secondary magnetic field measured in the receiver coil. For the graphs of the induced electromotive force and the secondary magnetic field, it is assumed that the receiver coil is located in the center of the transmitter loop (Christensen et al., 2006)

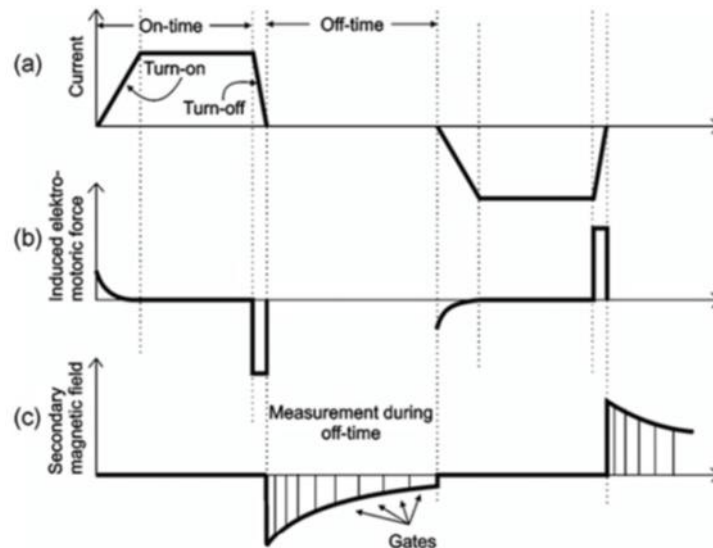


Figure 2: Basic nomenclature and principles of the TEM method (Christensen et al., 2006)

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. The depth of penetration in the central loop TEM-sounding is dependent on how long the induction in the receiver coil can be traced in time before it is drowned in noise.

The depth of penetration of the EM wave into the earth is inversely proportional to rock conductivity. In a uniform earth, E and H decay exponentially with depth, the more conductive the earth, the less is the penetration.

At the depth δ (T), called the skin depth, EM wave attenuated to e^{-1} of their amplitudes at the surface of the earth. Hence, in MT studies, one electromagnetic skin depth generally equated with the penetration depth of electromagnetic wave into the earth. In MT studies of the earth, μ is usually the free space value $\mu_0 = 4\pi \times 10^{-7}$ H/m and the skin depth is written as;

$$\Delta(T) = 500\sqrt{T\rho_a} \text{ (m)}$$

Where,

$\Delta(T)$ = Electromagnetic skin depth in m for a given period T (s); and

ρ_a = Apparent resistivity or the average resistivity of an equivalent uniform half space.

From the above equation, we can conclude that for a given period, the depth achieved by the EM wave will be dictated by the average conductivity of the overlying earth that is penetrated (Simpson and Bahr, 2005).

MT Phoenix equipment acquires data in the frequency range from 400 to 0.0000129 Hz. AMT acquires data in the frequency range of about 100-10,000 Hz (roughly the range of human hearing, hence the audio designation). Therefore, MT is used for deeper and AMT for shallow investigation. The MT method depends on the penetration of electromagnetic energy into the earth. The measurements are absolute and the apparent resistivity calculations from MT measurements are accurate for the true resistivity values. Their interpretation gives true

resistivity values and true depths, not just anomalies. Depth interpretation based on MT data is therefore much more definitive than interpretation of gravity or magnetic data (Vozoff, 1972).

The MT method is one of the very few geophysical techniques that can provide information about rock units deeper than about 1,000 meters. This makes it useful for geothermal exploration, where target depths are typically in the range of 1,000 to 3,000 meters for convection-dominated geothermal systems and even deeper for conduction dominated systems. The MT method is particularly useful for convection-dominated plays because it can potentially image low resistivity and low permeability involving clay units that often cap high enthalpy geothermal reservoirs (Melosh et al., 2010). For this reason, the MT method is often used to reduce uncertainties about reservoir depth, geometry, and areal extent.

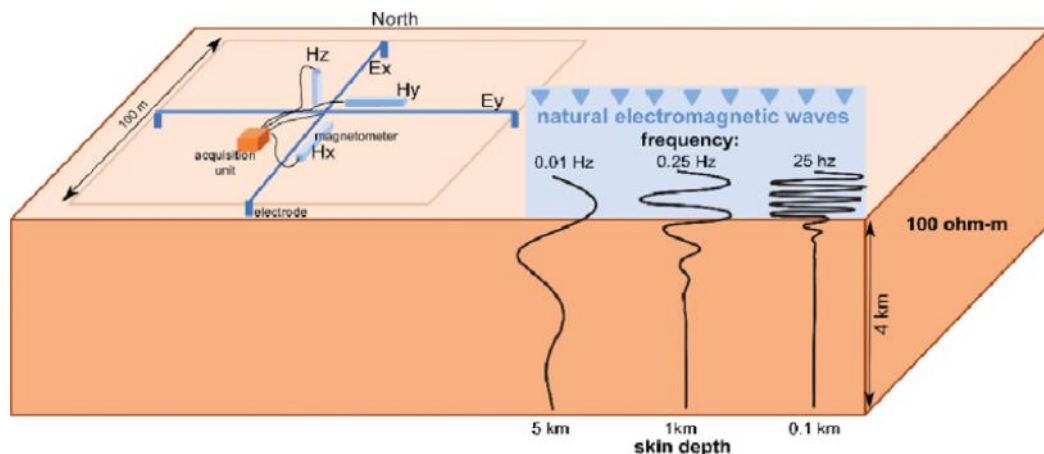


Figure 3: MT survey station layout and skin depths for natural electromagnetic waves depending on frequency. Note: Low frequencies respond to deep structures while high frequencies respond to shallow structures.

3. Acquisition of Data and Instrumentation

Instruments used for the survey consists of resistivity meter Phoenix V5 System 2000 software components called MTU-5A(Figure 5). It consists of 2 Electric and 3 magnetic field measuring channels which is powered by sources of 12 Volt battery. The average space between the sounding stations is 1km, but depends on the local topographic accessibility of the area.

The Phoenix V5 System 2000 has also other components (SSMT2000,MTplot,syncTSV and MT editor) to edit the survey data and WIN RESIST(IPI2 WEN) is used for 1D inversion modelling. The software is also used to construct the pseudo section and Geoelectric sections and to show the distribution of different lithological unit in vertical direction and finally to construct the 1D module. The leapfrog and GIS soft wares were used for the geological map and also for constructing geological, geophysical and temperature cross sections. As mentioned previously 166 MT and TEM survey pointes were conducted in the area but only 17 MT (in 2 profiles) data which were close to the existing drilled wells used for this study in order to correlate with the geological and reservoir data. The data was obtained from the Ethiopian Electric power (EEP), Geological Survey of Ethiopia (GSE

4. Data Processing, Discussion and Presentation

4.1 Well completion test of LA-10D

This is the first well from the new wells drilled from 2013 to 2015 in the Aluto –Langano field. From the pressure, spinner and temperature test of the well, the main permeable zone is 800m to 1300m, which is indicated by change of spinner rotation and the temperature increase below 1200m as shown in Figure 4 below. The well exceeds 260 °C at depth greater than 1800m.

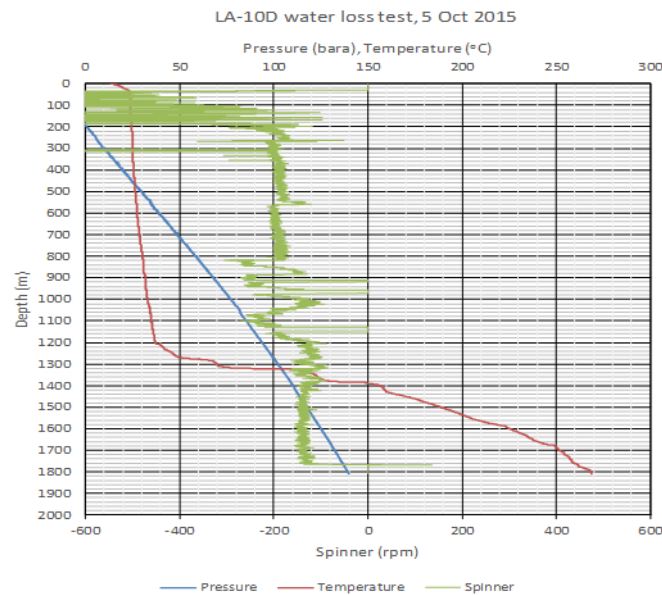


Figure 4: pressure, temperature and spinner profile test of LA-10D.

4.2 Lithological Cross Section (leapfrog software) using the available well data

The stratigraphic sequence of the subsurface lithological E-W cross section of the study area along the center through the wells (Fig. 5) constructed from well logs can be described as follows:

1. The Aluto Volcanics, which covers the upper parts of the study area. The extent of this formation decreases eastwards.
2. The second layer is the younger silicic formation. It also decreases eastward
3. The third layer is the Bofa basalt, which thickens towards the west.
4. The bottom layer of the lithological cross section is the tuff ignimbrite. This layer is the thickest in the well field.

From the well data that were, drill in this cross section all the productive wells were drill in the bofa basalt and tuff ignimbrite. In addition to this, these productive wells were drill near to the NNE-SSW fault structures. Therefore, the bottom of the bofa basalt and the tuff ignimbrites are the sources of the geothermal resources. Whereas the non-productive well LA-1 and LA-2 were drill in the upper two sections and far away from the fault structures and these sections does not promote for the geothermal reservoir resources.

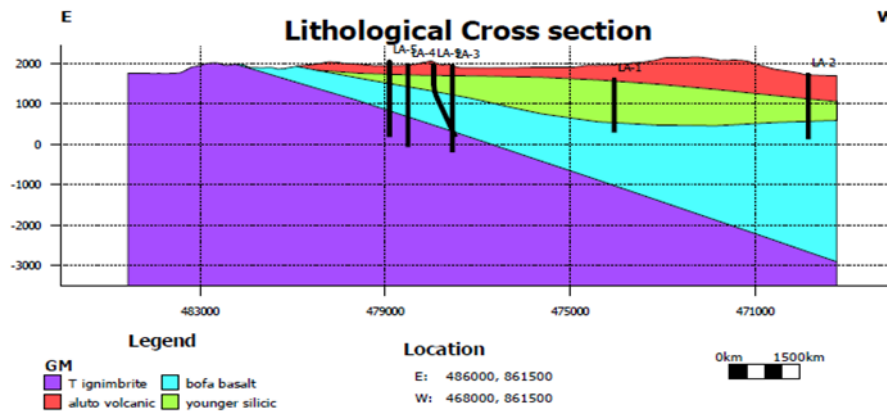


Figure 5: E-W Lithological cross section

4.3. Temperature Cross Section (Using Leapfrog Software)

Figure 6 shows E-W temperature cross section. The temperature cross section show that in the central part of the caldera the temperature is high exceeding 300°C and relatively extends towards east. The productive wells LA-4 and LA-9D were drilled along this profile and near the Jaw fault and Wonji belt fault. In contrast the non-productive well LA-2 ($< 150^{\circ}\text{C}$) was drilled far away from these faults. This is also proven by the other productive well LA-3, LA-6 and LA10D which were drilled near these structural faults and they are the best productive wells in the well field their temperature and there permeable zone with temperature $290\text{--}335^{\circ}\text{C}$ at depths $700\text{--}2200\text{m}$. Therefore based on these high temperature values, Aluto-Langano field can be characterized as a high temperature geothermal field.

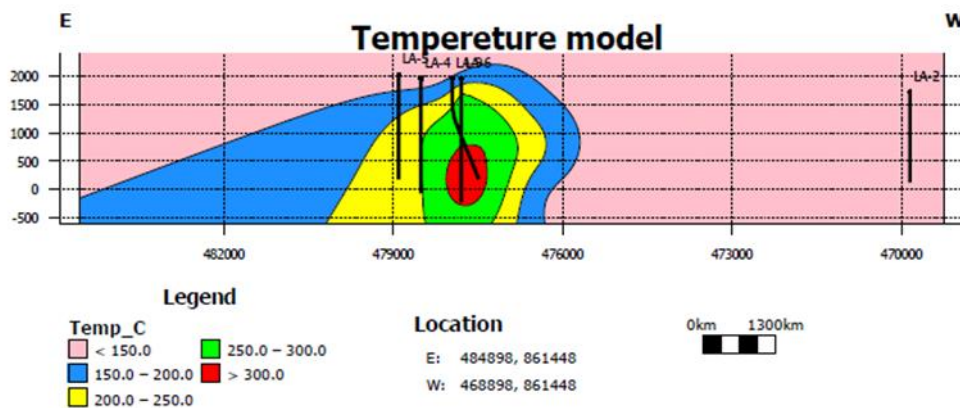


Figure 6: E-W temperature cross section

4.4 MT Survey Data

The MT survey data collected in the fieldwork was edited using the SSMT2000 software from Phoenix V5 system and transformed to EDI files which are suitable for IPI2win inversion software. The inversion is used to model the thickness and electrical resistivity of the possible layers that fit the MT data. The lithological units from the existing wells were used as initial model in the WIN RESIST inversion software and when modelling the MT sounding data. The depth, thickness, and resistivity parameters acquired by the mentioned software program were used to construct geoelectric sections for each MT profile. Available lithological logs from the existing wells in proximity of the surveyed traverses have been used for calibration

and further refining of the results. Most of the MT profiles were made along the east-west direction.

4.4.1. Resistivity Cross Section (Using Leapfrog Software)

Figure 9 shows the resistivity cross section in the central part of the caldera using Leapfrog software. The Jaw fault and Wonji belt fault are characterized by the low resistivity values. The resistive surface layer with >60 Ohm meter is characterized by the shallow pre-caldera pumice, recent rhyolites and young lava flows. High resistivity is also associated with a deep and thick basalts and ignimbrites. The 30-60 Ohm meter is attributed to Bofa basalts which are weathered and slightly altered while 15-30 Ohm meter are the same basalts but highly altered and fractured. The <15 Ohm meter layer is interpreted to present a clay layer of tuff ignimbrites forming the cap rock of the geothermal system.

From the resistivity cross section of Figure 7 the 30 - 60 Ohm meter, value extends towards the east into undrilled area but separated by a zone of . 60ohm meter. This eastern sector is a new area which is thought to be promising area for the geothermal resources (Bobesa). The productive wells LA-4, LA-6 and LA-9D were drill along this profile and near the Jawe fault and wenji belt fault whereas the non-productive well LA-2 was drill far away to the west from these faults. This is also proved by the productive well LA-3, LA-6, LA-10D, which were drilled near these structural faults, and they are the best productive wells in the well field with temperatures 322 °C 335 °C and 290 °C respectively.

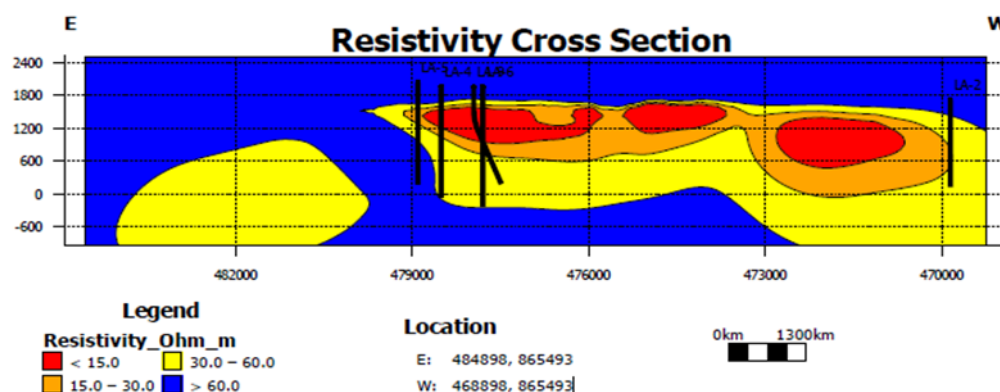


Figure 7: Resistivity cross section model

4.4.2. Apparent resistivity Pseudo Section and Geoelectric Sections along the Selected Lines (Using IPI2Win)

The program IPI2 Win (MT) V.2.0, which was developed at in Russia by Bachew (2002) was used to create two resistivity cross-sections based on the joint1D inversion models of the MT data plotted to a depth of 4,000 m. The plots for Traverse Line 3 is given as Figure 8 and for Traverse Line 4 is given as Figure 9. . The two cross sections used 17 MT soundings and almost run E-W perpendicular to the tectonic structure (Wonji Belt Fault) at the central volcanic)

4.4.3 Traverse Line-3

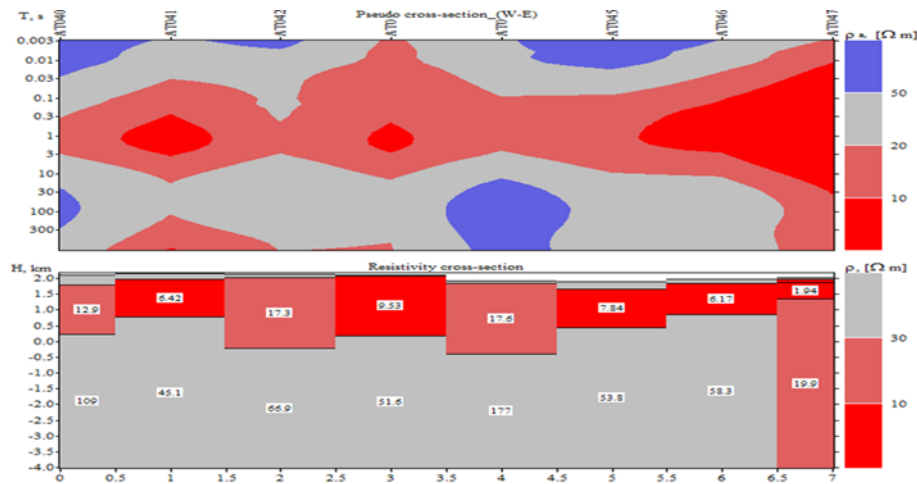


Figure 8: Pseudo cross -section and resistivity cross-section along E-W Travers Line 3

This line is the survey line on the central part of the surveyed area inside the Aluto caldera passing through LA-7 and is oriented east- west. The line has a total length of about 7 km constructed from 8 MT soundings (MT soundings AT040 to AT047) with an average MT spacing of about 1 km.

The pseudo section of this profile (Fig. 10) Shows are a relatively clear resistivity profile. The vast portion of the section is covered by low resistivity zone of 1.9 -19 Ωm which it is interpreted to relate to the highly altered and mixed layer of clay forming a cap. This is especially the case in the eastern part of the low resistivity of the profile which is highly affected by the geological fault structures (Wonji Belt Fault and Jaw faults). The rest of the profile has $>45 \Omega m$ resistivity value at the surface and at deeper levels, which is correlated with the recent Aluto pyroclastics sediments and alluvium and caldera pumiceous (near the surface), early Pleistocene Basalts and early Pliocene Ignimbrites (at the bottom). This resistivity profile is passing through nearby wells and its resistivity section is correlated with the Litho-stratigraphic section (lithological cross section) in the central parts of the study area (LA-6, LA-9D and LA-4) shown in Figure 7 above.

4.4.4 Traverse Line-4

This line is located in the central part of the surveyed area inside the Aluto caldera and passing through Jaw fault and some 500m north of LA-6 and is oriented in east to west direction running almost parallel to Line-3. The line has a total length of about 8 km using 8MT soundings (MT soundings AT048 to AT056) with an average MT spacing of about 1 km. The representative pseudo and geoelectric sections for the Line are shown as Figure 9.

This profile line has no clear resistivity profile. However, the shallow resistive patterns of the cross sections and deep at station AT049-52 related to the pre-caldera pumiceous and recent Aluto rhyolites (52.2 to 56.7 Ωm), and massive basalts and tuff ignimbrites probably characterized by the high temperature alteration minerals like chlorite and epidote ($>100 \Omega m$) respectively. The conductive layer is not continuous and is characterized by variable thickness. The resistivity value range between 1.02 and 9.9 Ωm . However, on the eastern side

of the profile (beneath station AT054 to AT056) the layer appears thicker than in the eastern part (stations AT048 to AT049).

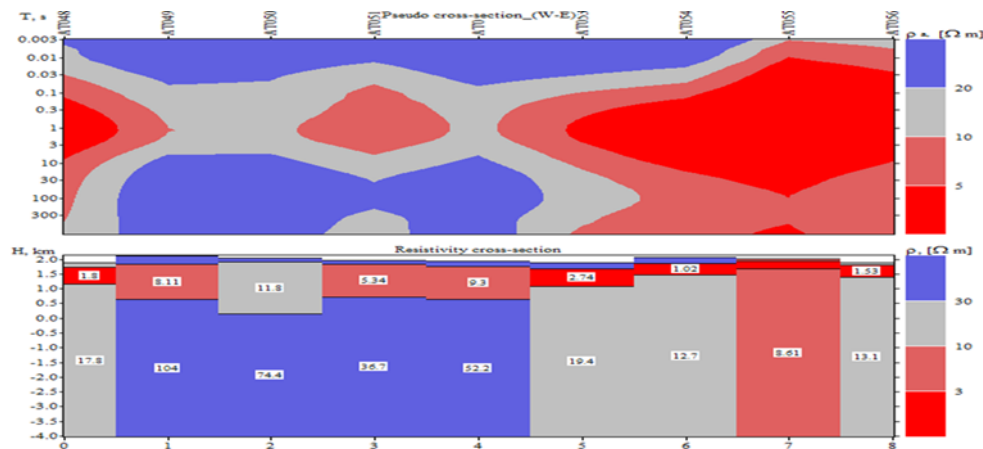


Figure 9: Pseudo cross -section and resistivity cross-section along E-W Travers Line -4.

4.5 Discussions

Generally, the resistivity structure seen in the cross-sections is not uniform presumably due to the complex and localized rocks and structures of the area. However, four main resistivity layers can be identified. In most cases the top is covered by a thin high resistivity layer (30-60 Ωm) which can be correlated with shallow pre-caldera pumice, recent rhyolites and young lava flows.. Below that (500 to 700m), there is a relatively thin intermediate resistivity formation or semi conductive layer (15-30 Ωm), which correlates with the silicic tuff, breccia and lake sediments (low temperature alteration minerals such as smectite and zeolite. The third layer (700 to 1300m) is a conductive layer (<15 Ωm) related to the high temperature alteration clay cap and geothermal heat sources.

Below the conductive layer, the resistivity increases considerably and reaches values of about >60 Ωm at a depth of >1300 m. This layer is associated with the massive basalt and tuff ignimbrite possibly also influenced by the high temperature alteration minerals such as chlorite and epidote is considering as the reservoir of the system.

5. Conclusion and Recommendation

5.1 Conclusion

Based on the result discussion and interpretation, the following conclusions have been drawn using the data of the well data and MT data presentation approaches, the result of the joint 1D inversion of 17 MT and TEM and well data, the resistivity structure in general reveals four main resistivity layers seen in the cross-sections presented.

Generally, the resistivity structure seen in the cross-sections is not quite similar due to the complex and localized structures of the area. However, four main layers have been identified.

Even though the resistivity values varies depending on the profile, in most cases at shallow depths down to about 500 m is a thin high resistivity layer (30-60 Ωm) which can be correlated to Aluto Volcanics (pre-caldera pumiceous, recent rhyolites, new lava flows).

Below that (500 to 700m), there is relatively thin section resistivity formation or semi conductive layer (15-30 Ω m), which correlates with the silicic tuff, breccia and lake sediments with low temperature alteration minerals such as smectite and zeolite.

The third layer 700- 1300m is a conductive layer (<15 Ω m) related to the high temperature alteration clay cap and geothermal heat sources.

Below the conductive layer, the resistivity increases considerably and reaches values of about >60 Ω m at a depth of >1300 m b.s.l. This layer is associated with the massive basalt and tuff ignimbrite possibly also influenced by the high temperature alteration minerals such as chlorite and epidote.

From temperature of the drilled wells,, the area is characterized as high geothermal field (>290 °C) from all the well in the field, and the subsurface geological formations are identified as the Aluto Volcanics, younger silicic formation, the Bofa basalts underlain by the tuff ignimbrites.

From the two appraisal drilled wells and the temperature intersected, the permeable and feed zone of the wells is from 900m to 1200 m. for LA-9D and 700 to 1100 m for LA10D and the temperature of the wells is almost the same 290 °C at the bottom of each well. The temperature of the wells indicate that this is a high temperature field.

Therefore, MT survey method is the best geophysical method for the identifying and mapping the subsurface lithology of the earth and is best when it is correlated with the existing borehole data.

5.2 Recommendation

According to the interpretation of the MT results, borehole data and geological structures, two promising areas have been identified for geothermal energy resources development in the Aluto Langano area. One is in the central part of the Aluto caldera following the NNE-SSW geological structure of Wonji belt fault and Jaw fault (along traverse Line-3 and 4) and with the relative depth of >2000m. The second area is the Bobesa area located 3km east of the first one but inside the Aluto caldera.

Due to lack of borehole data in the Bobesa area identified from the MT survey, exploration drilling is recommended to confirm the present finds and to obtain subsurface geological information which can be used to constrain and refine the resistivity modelling

The MT data used in modelling the two lines in this study has used geological and temperature data from wells in order to interpret the structures considered producing steam. It is therefore recommended that in order to identify and evaluate the geothermal reservoir extent and minimize the risk before drilling, multidisciplinary use of geological, geophysical and geochemical information must be employed and integrated rather than relying on 1D resistivity modelling alone.

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