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Magnetotelluric Data Inversion at Tendaho-Allalobeda Geothermal Field, North east Ethiopia

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ABSTRACT

The main role in geothermal exploration through the use of magnetotelluric (MT) method is to detect and delineate geothermal resources and locate exploitable reservoirs. Tendaho geothermal field is located in the Afar depression, Ethiopia, a structural feature with high-standing fault scarps between the axial depression and marginal area. It is one of several geothermal fields in the Ethiopian rift valley which has been identified as a high temperature geothermal field containing Ayrobera, Dubti and Allalobeda areas. MT survey was carried out in Tendaho-Allalobeda geothermal field by Geological Survey of Ethiopia and Electro consultant (ELC) in 2014 and 2015.

The surface of the Allalobeda area has low resistivity with less than 10 Ωm. Most of the depressions with depth of greater than 600 m, are correlated with alluvial sediment and geothermal fluids or zeolite smectite clay mineral zone as cap rock. The volcanic rocks at the graben shoulder shows high to low resistivity and low resistivity of less than 10 Ωm underneath, possibly a shallow reservoir in the Tendaho-Allalobeda area, which is common in the Tendaho geothermal field from test wells. The high resistivity of basaltic lava flows of Afar stratoid series serves as a deep reservoir underneath the top surface low resistivity structure which showed the existence of two geothermal reservoirs confirmed by drilling well in the Tendaho geothermal field, and the resistivity getting low deeper than 8 km, possibly the partial melt in the magma chamber of Tendaho-Allalobeda geothermal field as a heat source of the geothermal.

The fractured volcanic rocks filled with hydrothermal fluid or an up-flow zone of the geothermal system with low resistivity of less than 10 Ωm connected with the partial melt. Directional drilling is suggested following the fractured up-flow zone or fault in Thendaho geothermal field which will possibly increase permeability of the deep reservoir of Afar stratoid basalt. The Bouguer anomaly and the 3-D density difference maps also show relatively low anomaly (surrounded by high anomaly) in the same place as up-flow in agreement with the resistivity map. Hence, the inferred presence of a fracture zone and shallow partial melt magma reservoir suggest that there is exploitable potential at Tendaho-Allalobeda for conventional hydrothermal energy development.

1. Introduction

Geothermal energy is utilized for electrical power generation or for direct heat applications. The advantage of electrical power generation from geothermal energy is evident when connected to the electrical grid or on remote locations with insufficient power supply with a high energy demand or areas where other energy sources are scarce or expensive. Science Ethiopia is developing country; energy is the main economical accelerator for the development of the country. Tendaho geothermal field is one of better geothermal resource for the country. Tendaho geothermal field is located in the Afar depression, an area of active extensional tectonics and volcanism where the Gulf of Eden, the Red sea and the Main Ethiopian Rift systems join (Aquater, 1995; Abbate et al., 1995). Tendaho geothermal field in Afar consists of a NW-SE elongated broad plain which is Tendaho graben, mainly filled by alluvial and lacustrine deposits (Aquater, 1996a, b). It has three interesting geothermal areas, Tendaho-Ayrobera, Tendaho-Dubti and Tendaho-Allalobeda with variant geothermal manifestations (UNDP, 1973; Barberi et al., 1972) (Fig.1).

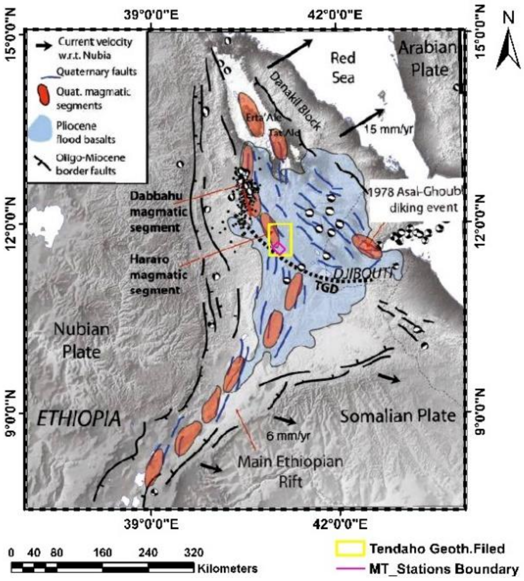


Figure 1. Location map of Tendaho geothermal field and MT station boundary of the study area, which is located at the SSE end of the Hararo and Dabbahu magmatic segments (after Ebinger et al., 2006).

The study area is located at the SSE end of the Hararo and Dabbahu magmatic segments. The magmatic segments are aligned along the Ethiopian rift system. Tendaho-Gobaad Discontinuity (TGD) is a position of the Africa-Arabia plate boundary indicating the existence of the multiple plate boundaries in the Afar Depression (after Ebinger et al., 2006). The yellow and purple rectangles show Tehndaho geothermal field and the boundary of the study area respectively (Fig.1). The Manda Hararo magmatic segment (MHMS) within Tendaho graben, is an area of increasing interest for high-temperature geothermal exploration and development as confirmed by shallow and deep exploratory drilling, with a thick sedimentary basin (Aquater, 1996a; Battistelli et al., 2002).

The study area has surface thermal manifestations such as geysers, hot springs, hot water pools and high-temperature fumaroles (near or at boiling point) (Aquater, 1996a, b; UNDP, 1973). The study area covers approximately 200 km^2 and 101 MT data were collected by Geological Survey of Ethiopia and Electro consultant (ELC) in 2014 and 2015 to propose a conceptual model of the study area to delineate the subsurface geological structure and geothermal reservoir using MT data. The study area is located near or on the fault escarpment of the southern rift margin complex and Such geothermal manifestations are aligned along the NW-SE and NNE-SSW trending normal faults that exist within the inner rift floor and the intersections (Fig.2) (Megersa and Getaneh, 2006; Di Paola, 1970).

The MT method is an electromagnetic exploration method which can image the electrical resistivity distribution of the deep subsurface (Chave and Jones, 2012). MT method has advantage to detect both directional and depth information about the subsurface resistivity structure.

In this study 3-D inversion models of the rotationally invariant of impedance tensor of MT data was done using ModEM program (Egbert and Kelbert, 2012). The results of MT and Transient Electromagnetic (TEM) adjacent to the study area reveal three main resistivity structures at different depths. The first structure is surface conductive sediment together with geothermal fluids or a hydrothermally altered clay cap (≤ 10 Ωm and > 1 km thickness). The second structure is a high resistivity structure in the Afar Stratiod basalt associated with the deep geothermal reservoir. The last structure is a highly conductive structure at a depth of greater than 5 km across the whole of the Tendaho geothermal field, inferring the partial melt (heat source) of the geothermal system. Moreover, the fracture zone (up-flow zone) in the Afar Stratoid basalts at the Tendaho-Dubti area has been used as a pathway for geothermal fluids (Didana et al., 2014; Didana et al., 2015; Lemma, 2007; Kalberkamp, 2010).

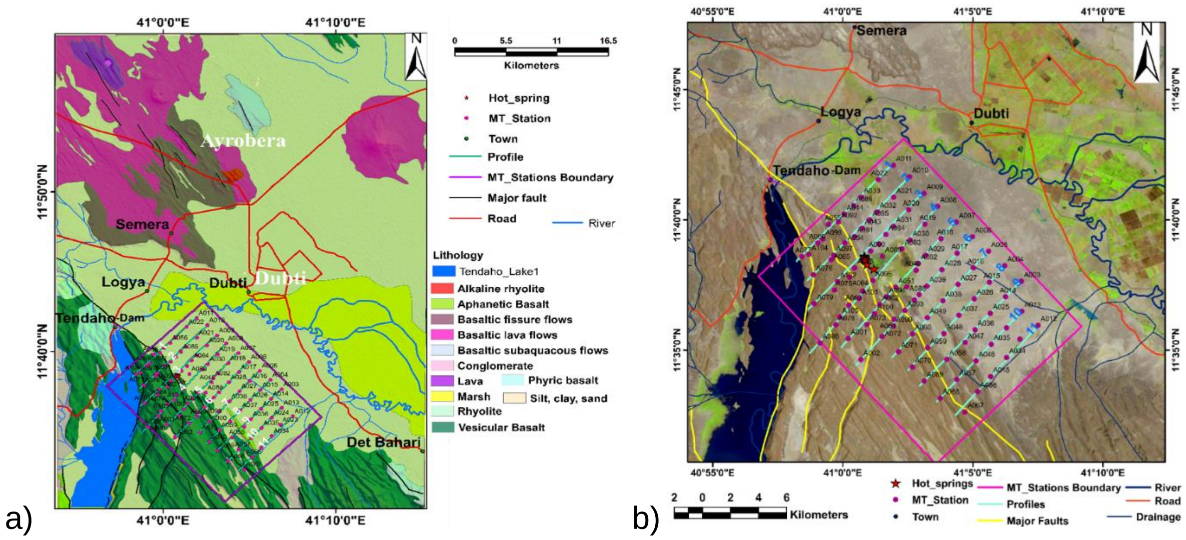


Figure 2. a) Geological map of the Tendaho geothermal field; b) The locations of Tendaho-Alalobeda MT sites and MT profiles.

2. GEOLOGIC AND TECTONIC SETTING

Based on the morphology, the geological structures of the Tendaho geothermal field are classified into two morph-structural complexes: the rift margin and the rift axis (UNDP, 1973; Abbate et al., 1995; Aquater, 1996a, b). A geological map of the Tendaho geothermal field is shown in Figure 2a. The oldest volcanic products in the area are lava pile outcropping on the graben edges (Afar stratoid series), a Pliocene to early Pleistocene formation consisting mostly of basalts of fissural origin, with minor rhyolitic bodies in its upper part. Whereas the most recent activity is concentrated within the graben, which is the axial part. The complex mosaic of horsts and grabens form localized sedimentary basins (UNDP, 1973; Aquater, 1995,1996a, b; Megersa and Getaneh, 2006). The rift margin complex is found in the southern and northeastern part of the graben. The southern sector which is Tendaho-Allalobeda area is a highly dissected and rugged plateau with the highest elevation of the whole area. It is dissected by the NW-SE and the NNE-SSW trending normal faults, which coincide with the structural trend of the Red Sea and Main Ethiopian rift systems (UNDP, 1973; Abbate et al., 1995; Aquater, 1996a, b; Barberi, 1972).
The rift axis complex covers half of the survey area and is characterized by flat depressed land. Volcanic activity of this complex area is characterized by the linear-fissured basaltic eruption overlaying the basin-filling sedimentary sequence and then the eruption through structurally controlled vents, which produced recent basaltic, scoraceous, hyaloclastitic and rhyolitic rocks. Sedimentation of fluvial, lacustrine and eoline have been simultaneously carried with the axial volcanic activity, mainly in the graben area. Eolian deposit is the dominant surface sedimentary unit at present (UNDP, 1973; Abbate et al., 1995; Aquater, 1996a, b; Megersa and Getaneh, 2006). The MT data was collected in the southern marginal sector (Tendaho-Allalobeda area)

of the mapped area, i.e. on the connection of the rift margin complex and the Rift Axis complex (NW-SE trending structure) shown in Figure 2b.

3. Dimensionality and Directionality Analysis

The MT transfer functions allow the analysis of the dimensional and directional properties of the subsurface resistivity of the research area. The information of the dimensionality of the area confirms selection of proper tools to invert and interpret the MT data. The MT data of Tendaho-Allalobeda geothermal field dimensionality and directionality was determined using Swift skew (Swift, 1967), Bahr skew (Bahr, 1991 and 1988) and induction arrow (Wiese, 1962; Parkinson, 1959).
Swift skew κ is a skew of the impedance matrix (Swift, 1967; Vozoff, 1972), which is a rotationally invariant parameter indicating the dimensionality of the subsurface structure defined by:

$$\kappa = \left|\frac{Z_{xx}+Z_{yy}}{Z_{xy}-Z_{yz}}\right|. \tag{1}$$

Where κ is Swift skew, z is the impedance tensor in the *xx*, *yy*, *xy*, and *yx*.

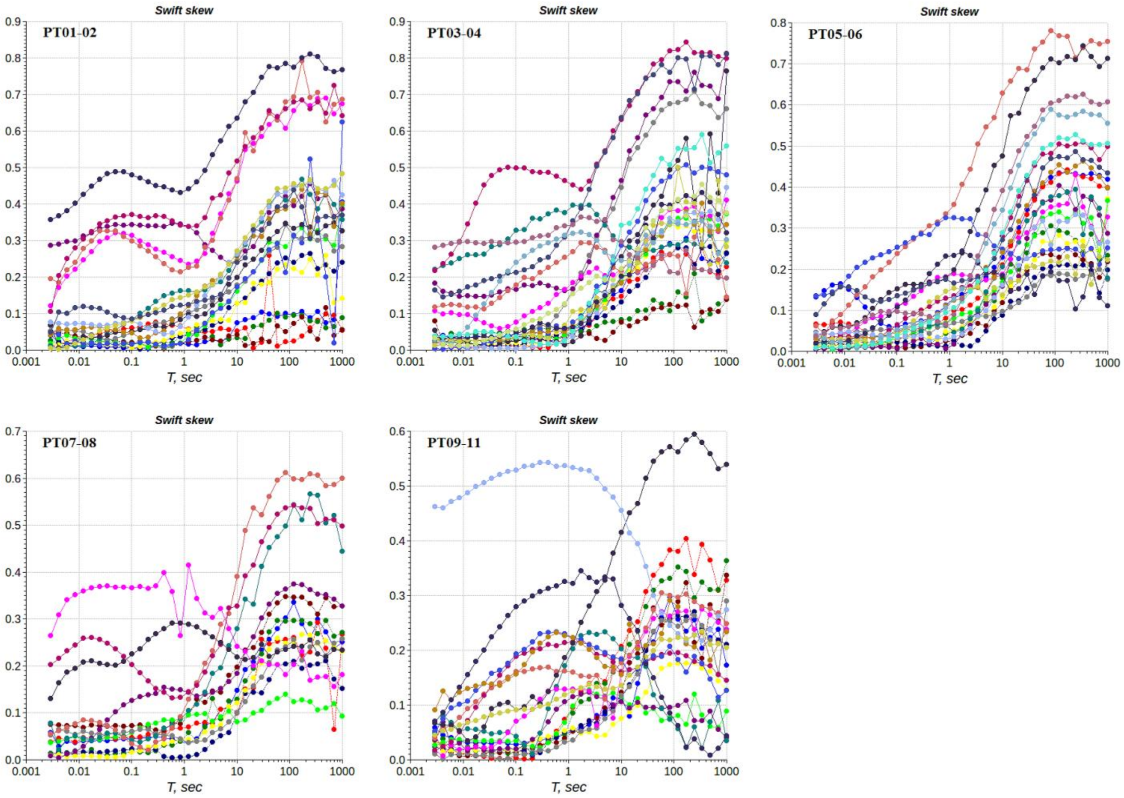


Figure 3 Swift skew results of the study area for all sites (from profile 1 to 11) and periods providing the rotational invariant misfit parameter of MT data. Higher skew values indicate the complex subsurface structures of the sites.

This indicator is independent of rotation of the tensor matrix and the values generally range from 0 to 1 for real data, indicating deviation from 1-D/2-D structure (Swift, 1967). The

threshold values are less than 0.2 for 1-D and 2-D structures (Swift, 1967). Higher skew values indicate a greater deviation from one or two dimensions (Berdichevsky et al., 1999).
Figure 3 shows the Swift skews at all profile lines from PT01 to PT11. Most of the Tendaho-Allalobeda MT data analysis of Swift skew show that after 10 s the values were greater than 0.2, probably indicating a 3-D structure (Berdichevsky et al., 1999) and less than 0.2 for 1-D/2-D structures according to Swift (1967).
Bahr skew (BS) is a measure of the local 3-D distortion of regional 2-D fields based on impedance phase, rather than on impedance magnitudes, which is the conventional definition of skew (Vozoff, 1972). It is a measure of the skew of the phase of impedance tensor and defined by:

$$\eta = \frac{\sqrt{|(Re(D_1)Im(S_2)-Re(S_2)Im(D_1))-(Re(S_1)Im(D_2)-Re(D_2)Im(S_1))|}}{|D_2|}, \qquad (2)$$

where $D_1 = Z_{xx} - Z_{yy}$, $D_2 = Z_{xy} - Z_{yx}$, $S_1 = Z_{xx} + Z_{yy}$ and $S_2 = Z_{xy} + Z_{yx}$.

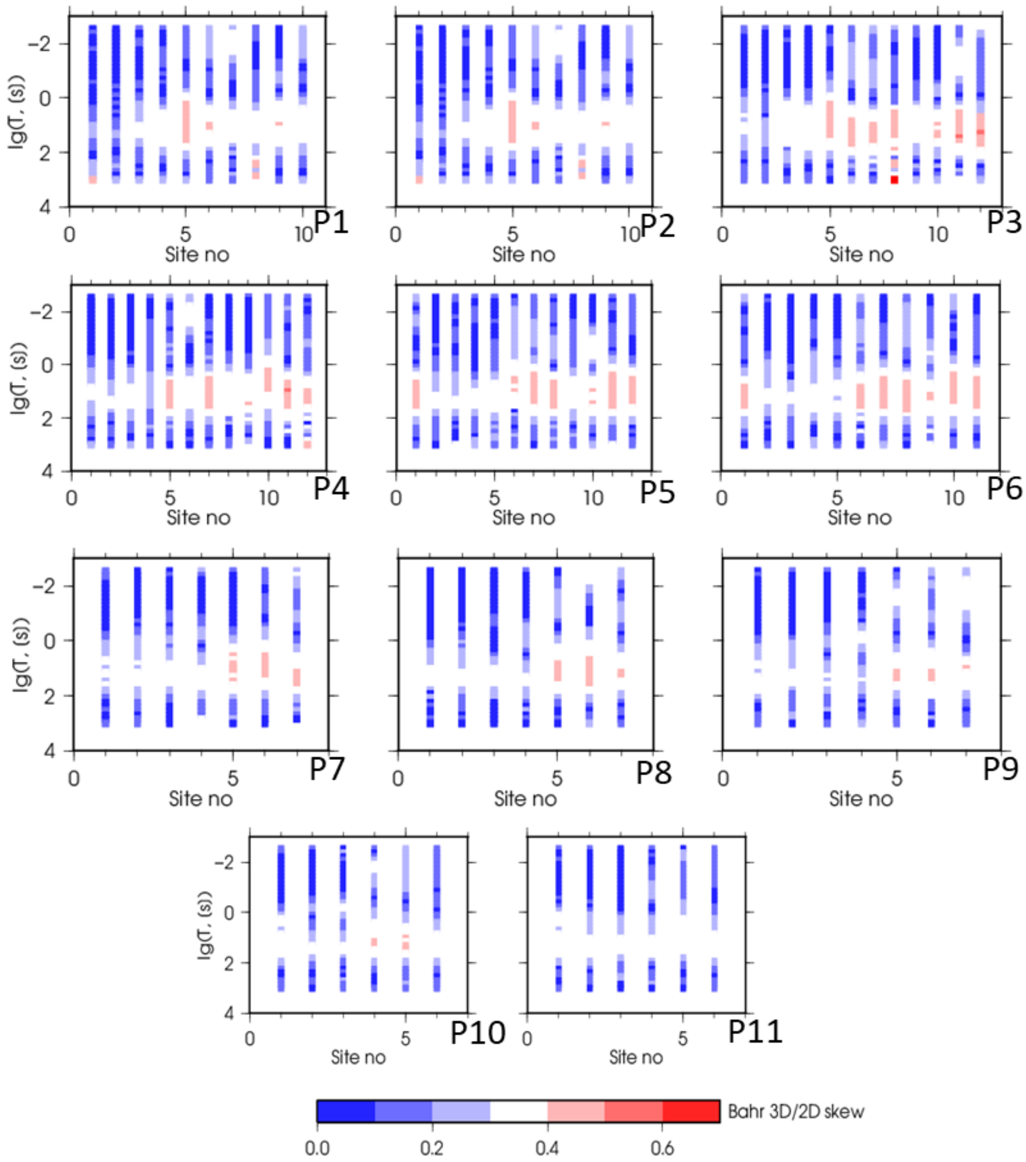


Figure 1 Bahr 3-D/2-D skew values for all sites and all periods which are insensitive to galvanic distortion.

According to Bahr’s (1988) recommendation, the regional 2-D indicator (3-D/2-D skew) should be below 0.3 for regional 2-D structures. Figure 4 shows the Bahr skews at all profiles from PT01 to PT11. Most of the skew values are smaller than 0.3, showing 2-D/1-D structure (Bahr, 1988). The 3-D effect can be clearly seen around the period of 10 s. In the study area of Tendaho-Alalobeda, the 3-D/2-D BS is mostly below the limit of the 3-D regional structure but all profiles show greater than 0.3 around the period of 10 s. This is probably a 3-D effect (Berdichevsky et al., 1999; Bahr, 1988) or noise and/or dead band with naturally low energy stretch in the low frequency band.
Strike direction can be found by making strike direction analysis of the MT data (Zhang et al., 1987). All the invariants of the MT data (azimuth of phase tensor (Caldwell et al., 2004), induction arrow (Wiese, 1962; Parkinson, 1959) and strike of impedance tensor) show that the regional strike direction is around N 100^{o} E direction (Fig. 5). Before doing 3-D inversion, it is better to do rotation of MT data to geoelectric strike direction if some of the resistivity structure is 2-D in nature (Tietze and Ritter, 2013). Hence, the MT data was rotated by -10^{o} before modelling.

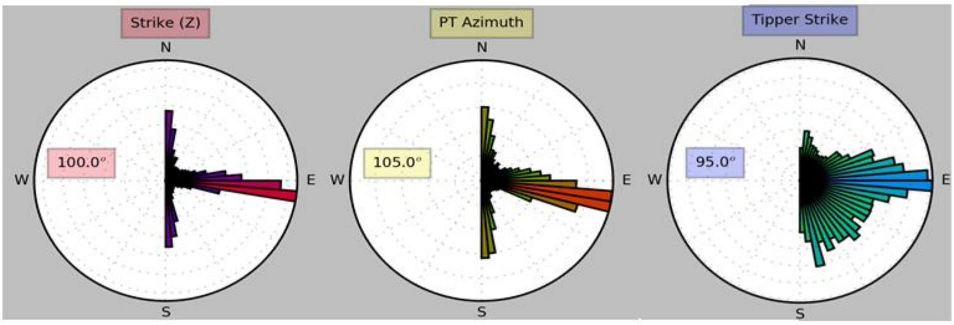


Figure 5 Rose diagram of strike angles showing strike estimated from the invariants of the impedance tensor (Z) (Weaver et al., 2000), azimuth of phase tensor (PT) (Caldwell et al., 2004) and tipper vector or induction arrow (Wiese, 1962 and Parkinson, 1959).

4. Results and Discussion of 3-D Inversion

Most of predicted and measured curves are good fitted showing the inversion result is well displayed the resistivity structures and model Fig.6. The 3-D resistivity distribution of Tendaho-Allalobeda geothermal field is shown in Fig. 7 to 8. The shallow subsurface has a low resistivity of less than 10 Ωm and thickness of greater than 600 m. Most of the axial depression (north-eastern part) correlated with the thick fluvo-lacustrine, alluvial sediment and geothermal fluids or zeolite smectite clay alteration mineral zone together with the cap rock (Aquater, 1996a; Didana et al., 2014; Battistelli et al., 2002). The low resistivity smectite clay zone of Tendaho geothermal field indicates, there is a high enthalpy reservoir at greater depth (Didana et al., 2015; Árnason et al., 2010).

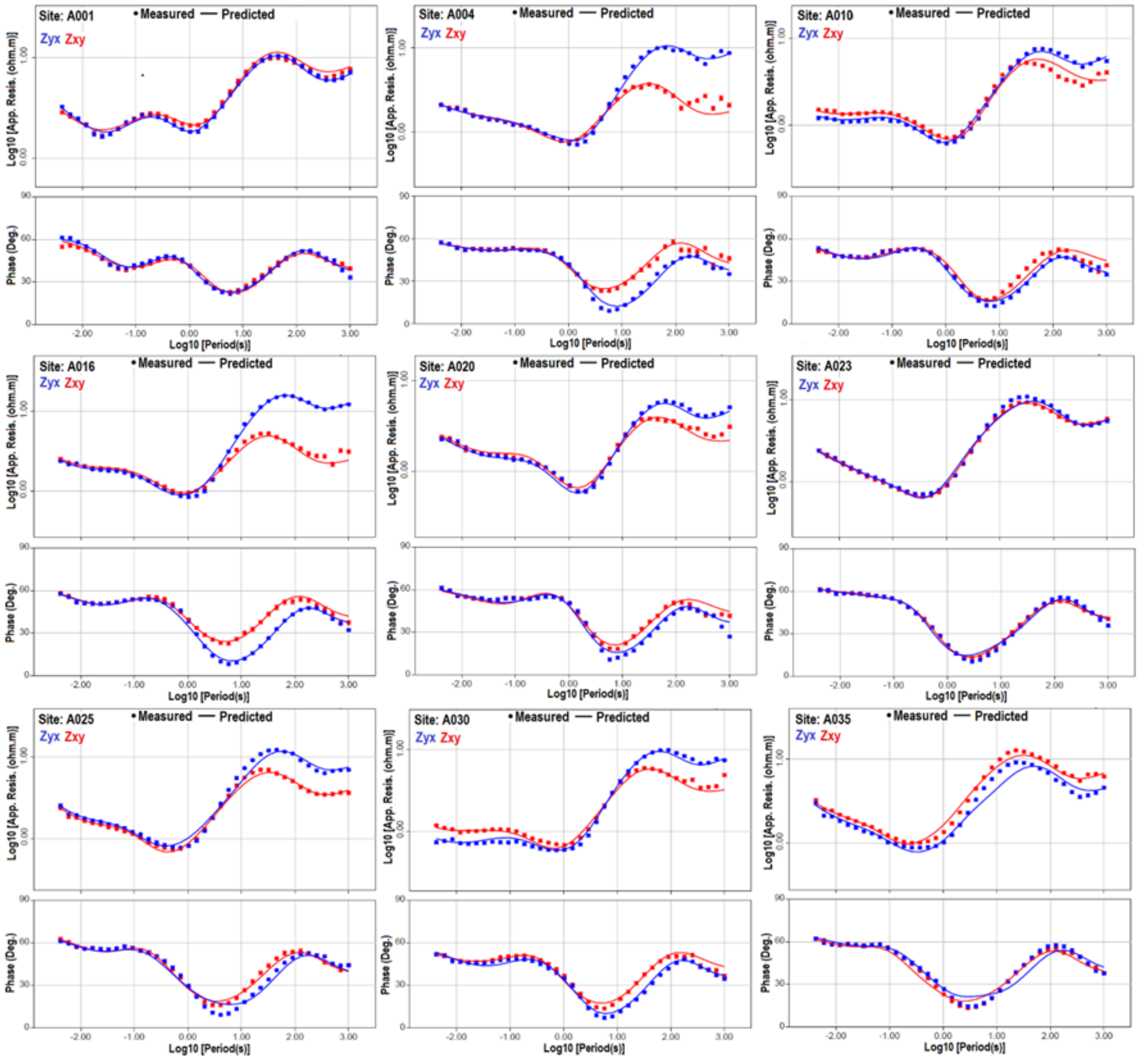


Figure 6. The curve fitness of selected sites of the MT data. The dotted lines show the measured and the solid lines show the calculated apparent resistivity and phase. Red represents TE mode and blue represents TM mode.

The top marginal part (graben shoulder) shows low to high resistivity with a range from 2 to 100 Ωm interpreted as volcanic rocks with low resistivity less than 10 Ωm underneath, possibly fractured volcanic rocks that continue till 1 km depth as a shallow reservoir which is proven in Tendaho geothermal field from shallow wells of Dubti (Aquater, 1996a; Amdeberhan, 1998; Battistelli et al., 2002).

The high resistivity zone starts around 1.5 km depth with a resistivity of greater than 100 Ωm and continues to a depth greater than 8 km in the north part of the study area, which correlates with the basaltic lava flows of the Afar stratoid series and serves as a deep reservoir. The resistivity decreases below 8 km depth (Fig. 7 to 8), possibly a part of partial melt in the magma chamber (C3) of the geothermal field as a heat source of the geothermal system (Didana et al., 2014; Didana et al., 2015; Aquater, 1996a, b; Battistelli et al., 2002; Desissa et al., 2013). The drilling of Dubti shallow and deep wells showed the existence of two geothermal reservoirs in the Tendaho geothermal field (Aquater, 1996a, b; Amdeberhan, 1998; Battistelli et al., 2002).

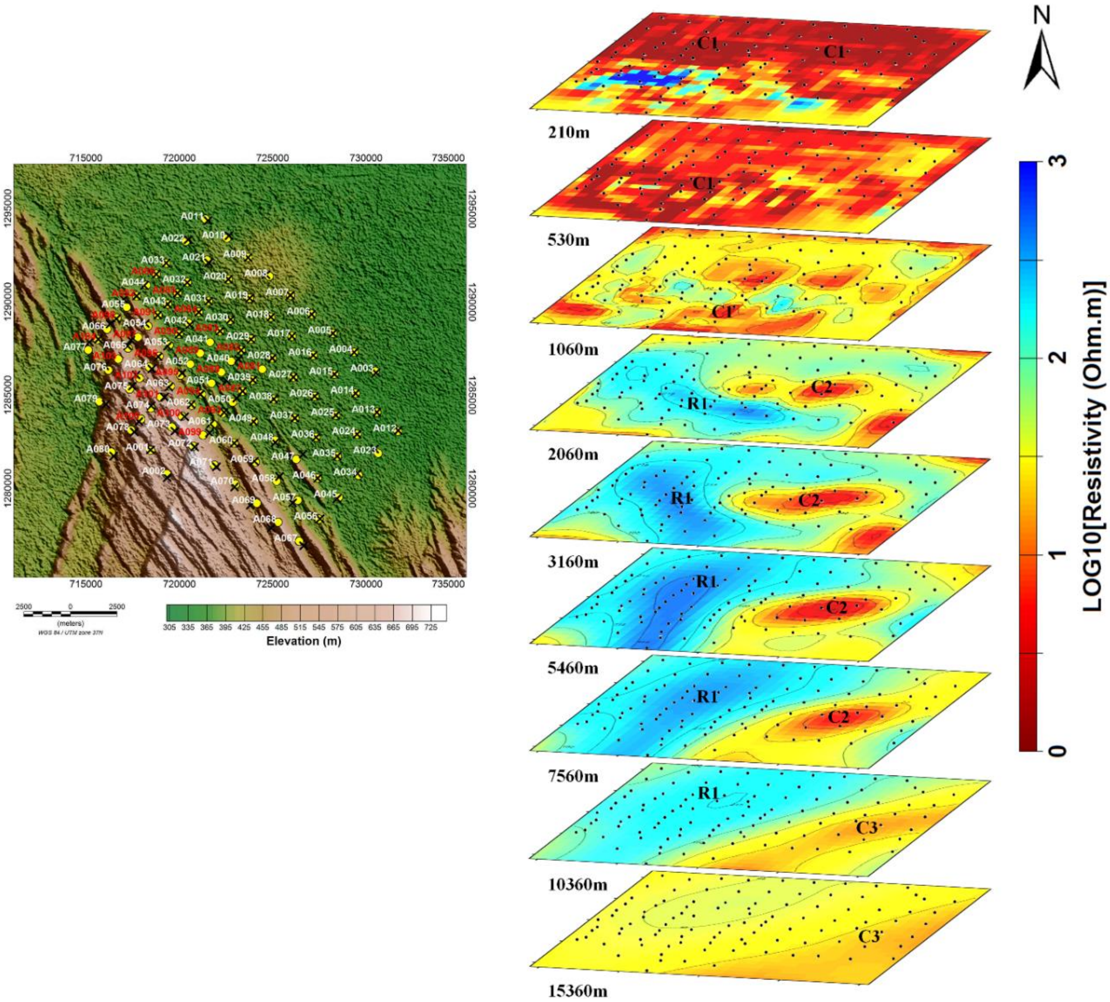


Figure 7 The horizontal resistivity distribution mapped at different depths starting from 210 to 15,360 m after 3-D inversion. The black dots show the horizontal location of MT stations and the digital elevation map shows the data location on the graben shoulder and depression.

The top sediment accumulation in the axial and volcanic rocks of the marginal area of profile 6th – 10th underline low resistivity of less than 10 Ωm. This is interpreted as fractured volcanic rocks filled with hydrothermal fluid or an up-flow zone (C2) of the geothermal system, continuing through depth and connecting with the partial melt (C3) (Didana et al., 2015; Aquater, 1996a; Battistelli et al., 2002) in Figure 7 to 9.

The deep reservoir in the Tendaho geothermal field has low permeability according to Aquater (1996a, b), Amdeberhan (1998) and Battistelli et al. (2002), so that directional drilling is recommended targeting the fracture up-flow zone or fault (C2) in the Afar Stratoid Series basalts.

Groundwater aquifers of the geothermal system include coarse sedimentary and fractured volcanic units (Aquater, 1996a; Battistelli et al., 2002). The 3-D resistivity structures of Tendaho-Allalobeda, Dubti and Ayerobera have similar structures of fractured volcanic rocks. The water at depth in the geothermal system are of sodium chloride type (Aquater, 1996a; Battistelli et al., 2002; Aquater, 1991). The deep recharge to the system originates in the western escarpment and plateau at elevations above 2,000 – 3,000 m a.s.l. (Aquater, 1996a; Battistelli et al., 2002). The main hot springs at Tendaho-Allalobeda have similar isotopic compositions to those of water from the Dubti wells, suggesting a hydrological connection (Aquater, 1991; Aquater, 1996a; Battistelli et al., 2002).

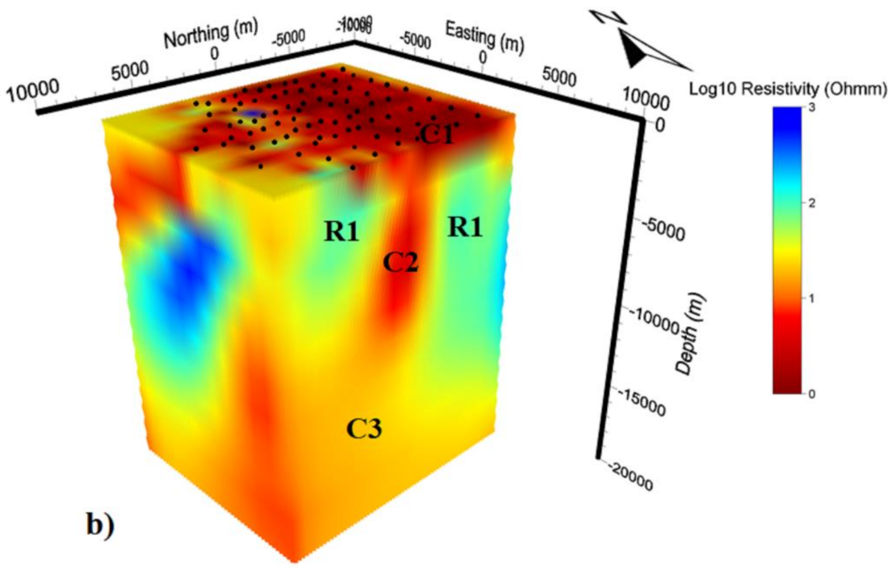


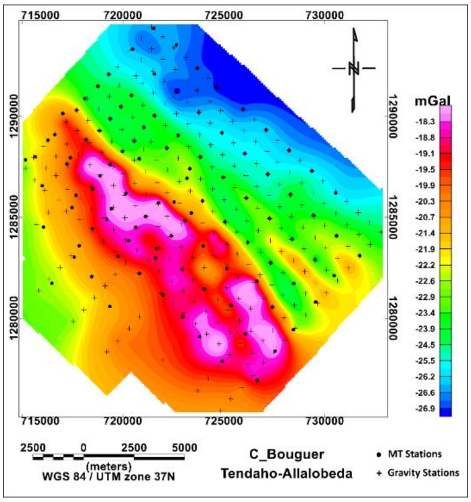
Figure 8. Three-dimensional resistivity distribution of Thendaho-Allalobeda, looking southwest into the preferred resistivity distribution showing the conductive and resistive anomalies of C1, C2, C3, and R1 and the distribution was cut around profile 8 to show the up-flow zone (C2). The black dots represent MT stations.

5. Conclusion

The 3-D resistivity distribution of Thendaho-Allalobeda geothermal field model was created by all MT data. Generally, the study area has the top axial low resistivity structure, the top marginal volcanic rocks with high to low resistivity structure, low resistivity as shallow depth reservoir underneath the axial and marginal area, high resistivity Afar basaltic stratoid series, low resistivity fractured volcanic rocks (up-flow) and the partial melt.

The top layer of the graben depression part of the study area has a strongly conductive structure with less than 10 Ωm. This structure is correlated to fluvo-lacustrine and alluvial sediment containing geothermal fluids or a zeolite smectite clay alteration mineral zone (> 600 m thickness), acts both as cap rock and a shallow geothermal reservoir. The top marginal area of low to high resistivity volcanic rocks underline the shallow depth reservoir with low resistivity interpreted as altered volcanic rocks in Fig. 7 to 8. The low resistivity on the subsurface including the cap rock and the shallow reservoir has been seen in the inversion results. The clay alteration minerals often form an impermeable clay cap covering the geothermal reservoir with high resistivity.

The 3-D result shows highly resistive structure with greater than 100 Ωm correlated with a portion of the Afar stratoid basalt or chlorite–epidote alteration mineralogy as a deep less permeable reservoir through depth (Aquater, 1996a, b). The low resistivity that connects the top layer sediment accumulation and the partial melt of the geothermal system correlated with an up-flow zone (fractured volcanic rocks) (Aquater, 1996a; Battistelli et al., 2002; Amdeberhan, 1998). The high anomaly of the Bouguer map, the up flow zone filled with hydrothermal fluid (C2 which is shown in Fig. 8) can be seen with decreased value comparing the surrounding high anomaly and also in the 3-D gravity contrast, the up flow zone shown by low density contrast (Fig. 9). Due to low permeability of Afar stratoid basalt directional drilling is advisable following the up-flow zone to increase the production (Aquater, 1996a; Battistelli et al., 2002, Didana et al., 2015).

a) 

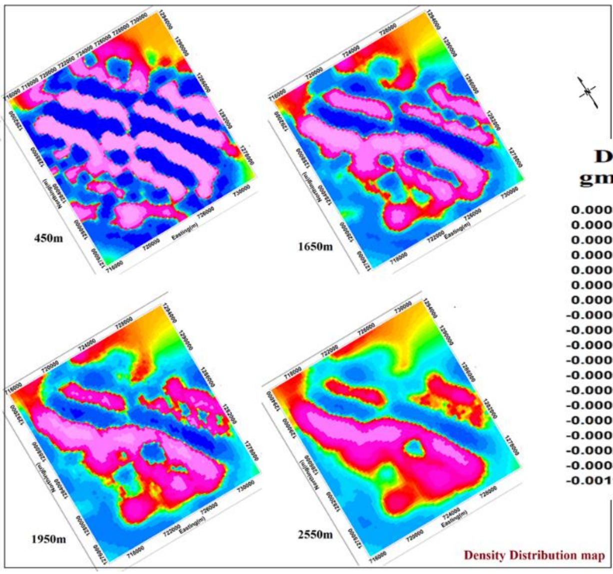
b) 

Figure 9. A total of 300 gravity data was collected to study the subsurface density distribution of Tendaho-Allalobeda geothermal field; a, Complete Bougure anomaly map. b, Resistivity map of the 3-D inversion result at 530 m, 1,660 m 2,060 m and 2,560 m of Tendaho-Allalobeda geothermal field.

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