

Magneto-Telluric (MT) Survey in Tendaho Geothermal Prospect, Northeast Ethiopia.

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ABSTRACT

Magneto-Telluric (MT) survey was conducted in Tendaho geothermal prospect around Dubti and Allalobeda geothermal fields between December 29, 2012 and April 11, 2013 in an area bounded between the geographic coordinates (40°59'E, 11°47'59.4"N) and (41°14'50.7"E, 11°37'2.91"N). The major objectives of the study were to define the assumed up flow zone of the geothermal fluid south-east of the major hydrothermal manifestations in the Dubti field and refine the proposed conceptual model, to study the subsurface resistivity structure of the geothermal system at the Allalobeda field, its relation to the geothermal field marked by fossil altered ground around Logya town situated north of it, and to outline possible geothermal reservoirs at an economical depth level around both fields.

Magnetotelluric survey in the frequency range between 320Hz and 0.001Hz was conducted over six profiles across the two fields and the data were analyzed. As a result the Swift strike analysis indicated the general NW-SE impedance strike direction coincident with the N155°E strike of the Tendaho rift axis. The dimensionality analysis revealed 1D conductivity structure up to 10 sec and 5 sec periods around the Dubti and Allaobeda fields and non-1D structure for the longer periods at the respective fields.

Combined results using 1D model obtained from the Occam procedure to the invariant mode of the impedance tensor and 2D inversion model using the joint TE+TM modes, revealed zones of conductive layers successively decreasing in magnitude with depth delineating possibly the cap rock, a horizon of low temperature alteration clay minerals in the zeolite-smectite zone, and the mixed layer zone followed by a zone of high temperature alteration product in epidote and chlorite clay minerals, adjacent to the structural discontinuities AD1, AD3 and AD4 in Allalobeda field and D0, D2, D3 and D4 in the Dubti field. Possible geothermal reservoirs inferred at both fields related to these resistivity structures. A well-defined low conductivity zone ($\approx 10 \text{ Ohm-m}$) in the south-eastern Dubti field delineates the up flow zone of the geothermal fluid and circulation of geothermal fluid was deduced to be related to the discontinuities D2/D3 whose northern extension of the inferred structures is the Dubti fault. The trend of high and low resistivity contour lines and the discontinuities (NW-SE alignment) indicated the possibility of the connection of the Allalobeda and Logya geothermal systems. Additional MT soundings towards Logya at Allalobeda field and south of TDO8 in the Dubti field and reinterpretation of result using TEM data were recommended for a better definition of the anomalies and to achieve the stated objectives.

INTRODUCTION

The prospect area is located within the Afar depression, an area of active extensional tectonics and volcanism where the Gulf of Eden, the Red sea and the Ethiopian rift systems (MER) join, Aquater (1996). The present study area is shown in Figure (1), located between 40°59'E and 41°14'50.7"E longitude and 11°37'2.91"N and 11°47'59.4"N latitude.

A number of detailed geo-scientific works had been made in Tendaho graben (TG) as a part of the study of the Ethiopian rift including GSE (1969), UNDP (1970-1972), joint Ethio-Italian work 1979-1996, and GSE (1997). Tendaho graben is part of the southern portion of Arta Ale-Manda Haro rift system, which extends the active tectonic of the Red sea to the south. The borders of the NW trending Tendaho rift are marked by the Afar Stratoid Series while the rift is filled with lacustrine, evaporite and alluvial deposits and with post Stratoid basalt overlain by recent volcanoes, Aquater (1997) and references therein. The prospect area consists of a couple of geothermal fields including the Dubti and Allalobeda fields. The geological map of TG is presented in Figure (2). In the studies it was indicated that the stratigraphic sequence underlying the sediment to include the Afar Stratoid basalt, the Dahla basalt followed by thick sediment and Mabla rhyolite .

METHODOLOGY

To meet the stated objectives a total of 37 MT stations were distributed along three profiles (TDO6, TDO8 and TDO10) and 27 stations were situated at Allalobeda along TDO20, TDO30 and TDO40, laid approximately perpendicular to the NW-SE Tendaho rift axis, as shown in Figure (1). The measured in the MT frequency range between 320 Hz and 0.001Hz. The data was processed and then the MT impedances and phase versus frequencies, apparent resistivity versus frequencies, standard deviations of apparent resistivity, the tipper magnitude and other MT parameters calculated and the result discussed and summarized below.

DISCUSSION OF RESULT

Directionality of the impedance tensors at different depth levels (frequencies) analyzed from the Swift's strike and tipper strike analysis and the majority of the stations appear to show a general NW-SE strike direction, coincident with the major trend of the Tendaho rift axis. As a result the geo-electrical strike angle N25°W was chosen for impedance tensor rotation.

The dimensionality analysis using the pseudo-sections of the apparent resistivity and phase of the TE and TM mode illustrates overall discrepancies in the resistivity distribution for the two modes and a demarcation horizon as 1D and non-1D conductivity

structure are around 10 sec period in the Dubti and around 5 sec at Allalobeda field as can be seen in Figure (3a) and (3b). The directionality of the data is also inferred from the differences between the sections from the two modes. The impedance skew and the tipper magnitude analyzed for different frequencies as shown in Figure (4a) and (4b) and the combined result is in agreement with the analysis made using the pseudo-sections. All analysis tools indicated the presence of the 3D conductivity structure for the long period records at the respective sites and from the combined analysis result of both 1D and 2D conductivity structures generalized and implementation of 1D and 2D inversion modeling justified in the interpretation.

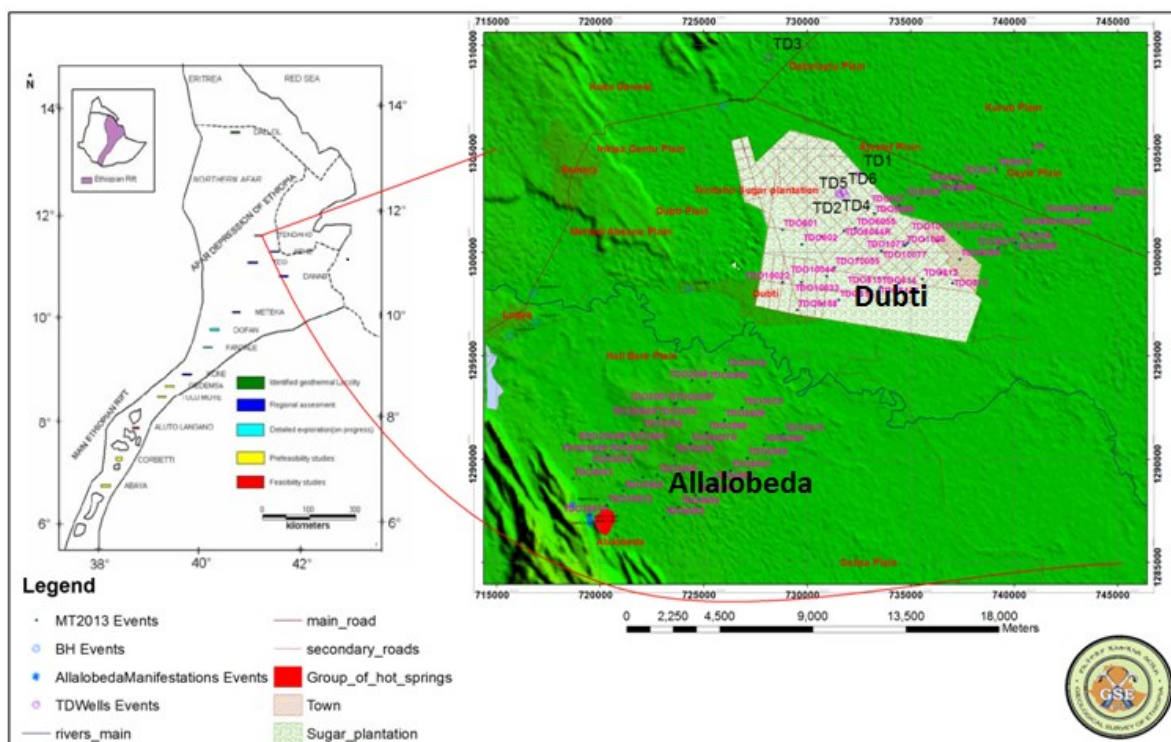


Figure (1) Location map Dubti and Allalobeda geothermal fields, and the MT soundings, Tendaho graben.

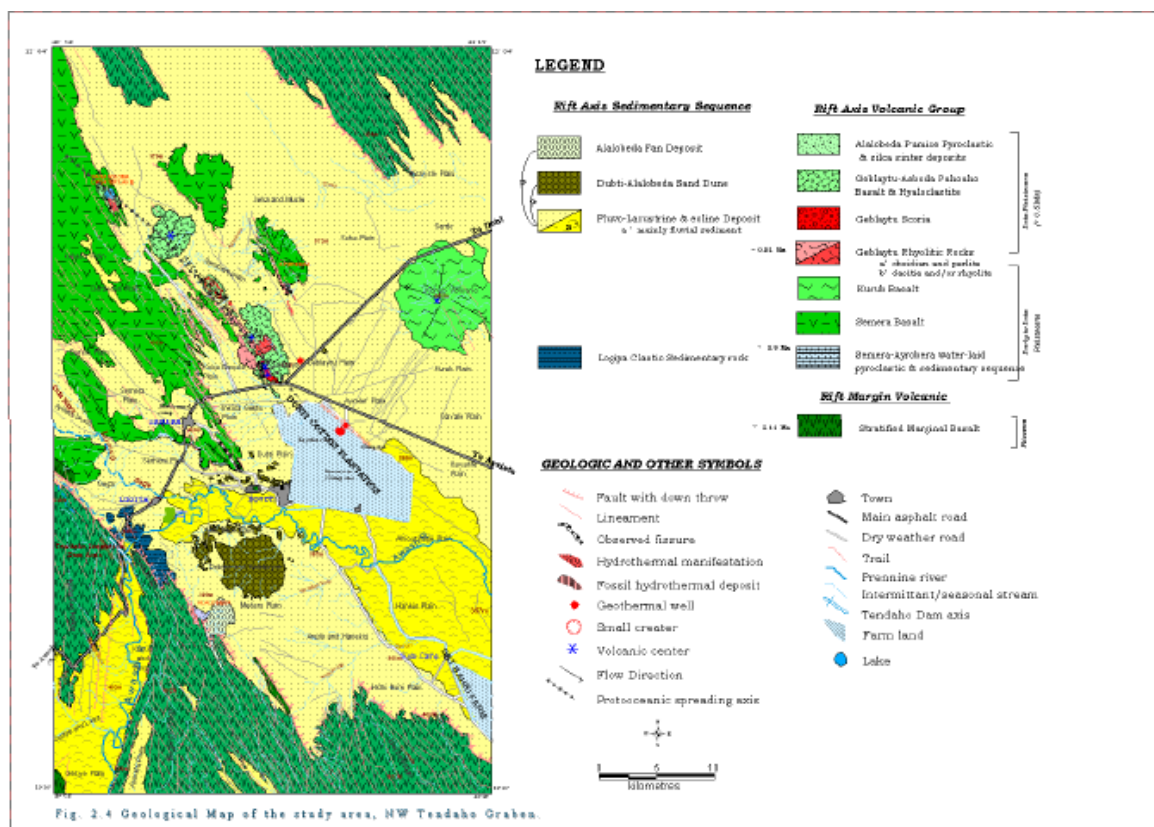


Figure (2): Geological map of Tendaho graben, after Megersa, G. et al., 2006.

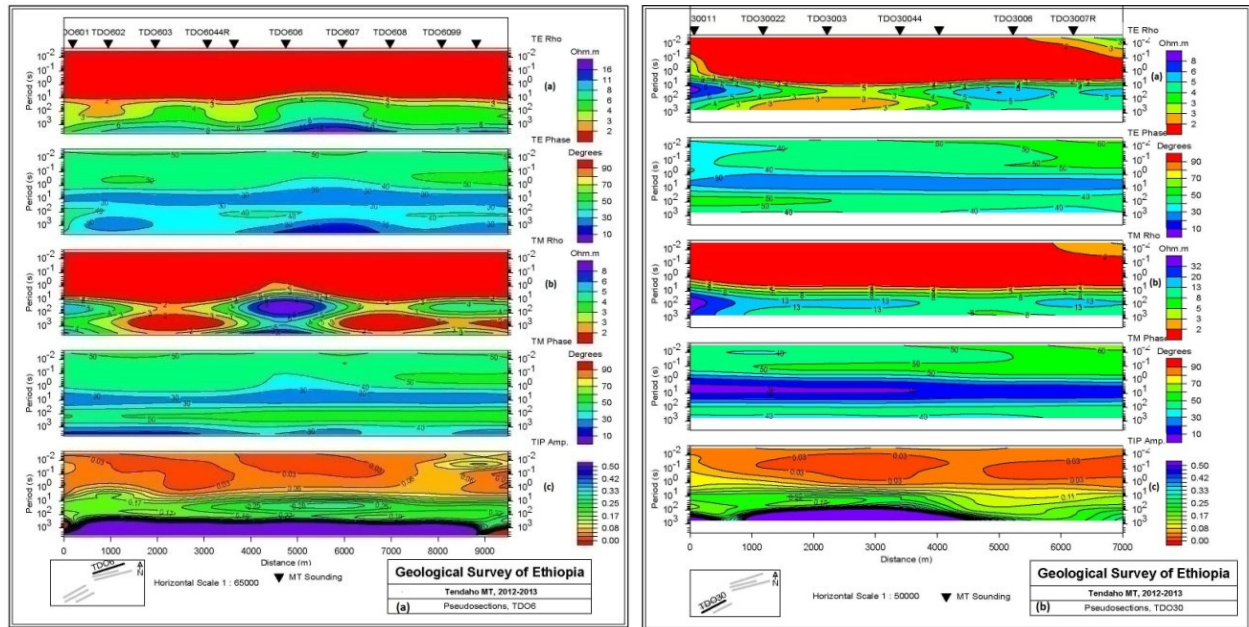


Figure (3). Pseudo-section plots of TE and TM modes of the apparent resistivity, phase and tipper magnitude from Dubti (a) and Allalobeda (b) fields showing directionality and dimensionality of MT data from both areas.

In MT measurement, small isolated conductivity anomalies, near surface inhomogeneities, and rough topography distort the apparent resistivity curve and introduce error in the magnitude of the resistivity by the shifting factor and the depth by the square root of the factor. The galvanic distortion effect is due to an electric field generated from the boundary charges on near surface inhomogeneities and persists throughout the MT recording stage independent of the frequency Pellerin and Hohmann, 1990. The static shift should be fixed prior to the MT data modeling and inversion using data from a resistivity method that is less sensitive to near surface inhomogeneities acquired at the same location like TEM (Sternberg et al., 1988; Pellerin and Hohmann, 1990; Arnasson, (2008) after Teklessenbet, K. (2012). Nevertheless, no such correction was made to the present data due to no TEM soundings available in the study, but the presence of the shift problem was noted and examples are presented in Figure (4a) and (4b) below.

Note the presence of static shift problem on both fields, impedance strike almost stable around N25°W in Dubti field except for high frequencies and show variation between 0.1 and 10 Hz for Allalobeda field. The tipper magnitude reflect non-1D conductivity structure generally for the period greater than 10 sec in Dubti while the Allalobeda field starts at a lower period ≈ 3 sec.

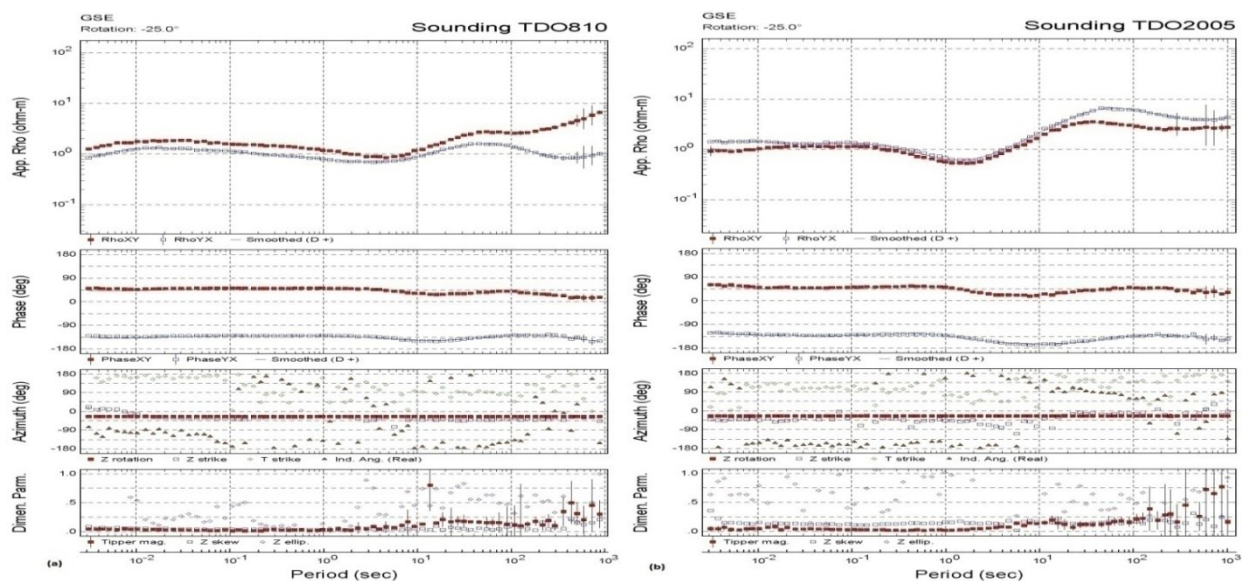


Figure (4). Representative MT soundings with interpretational parameters from Dubti TDO810 (4a) and Allalobeda TDO2005 (4b) fields.

1D inversion modeling using the Occam procedure to the invariant mode (the geometric mean of TE and TM modes) and joint 2D inversion of the TE+TM mode was obtained. The cross-sections from both indicated three similar geo-electrical layers at Dubti and Allalobeda fields with an additional fourth layer in the Dubti field as can be seen on Figure (5a) and Figure (5b) and Figure (6a) and

Figure (6b) from the respective areas. The 1D cross-section at both fields depicts the vertical and horizontal resistivity distribution in a better detail while the 2D inversion models show smooth resistivity variation within and across the layer boundaries. In general the top three layers are almost similar with the good conducting top layer with resistivity of less than $4 \Omega\text{-m}$ and with an average thickness of 780m at Dubti and 725m in Allalobeda fields. This layer is correlated to the thick fluvo-lacustrine and alluvial sediment with intercalated post stratoid basalt and portion of highly fractured/ altered Afar Stratoid Basalt. The second layer, the resistive layer with average thickness of 2850m is correlated to portion of the Afar stratoid basalt and the Dalha Basalt, the unit hosting the geothermal brine in Asal4, Djibouti, Varete, J. 1978. The third is a conductive layer that is correlated to the magmatic melt and its thickness in Dubti is about 3940m. A fourth layer slightly resistive is only mapped at the Dubti field, and correlated to the Mabla rhyolite. The average thicknesses are obtained from the 1D sections since the 2D section generally gave a bit exaggerated results. Comparison of the resistivity values of the two fields indicate an overall increase in magnitude at the Allalobeda field and is accounted to the possibility of steam dominated geothermal fluid, relatively higher abundance of high temperature alteration products and relatively lower content of dissolved minerals and infiltration of cold fresh water from the nearby Awash river.

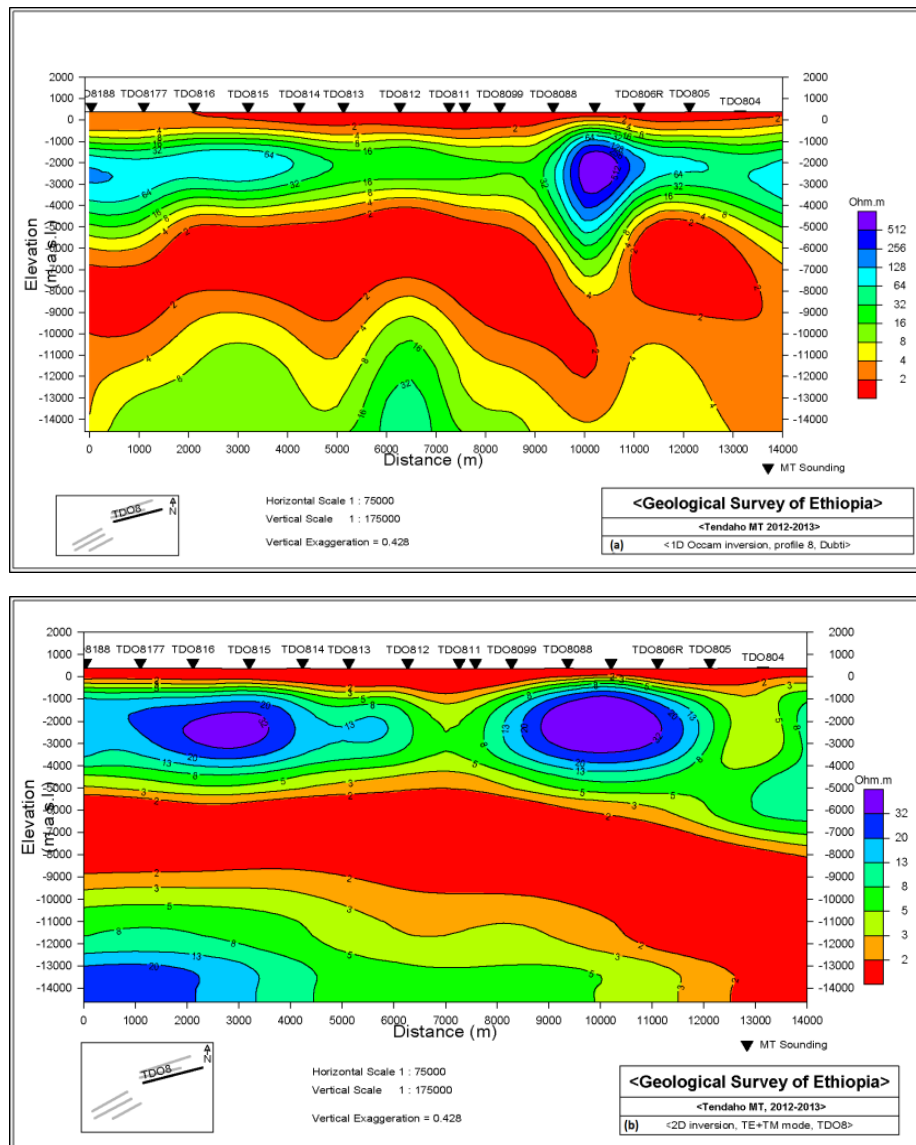


Figure (5): (a) 1D and (b) 2D geo-electric cross-sections along profile TDO8 of the Dubti field.

Major target zones that pertain to a geothermal reservoir, a conductive top layer followed by a layer of slightly increased resistivity marking the zone of high temperature alteration mineralogy and the resistivity discontinuities are assumed to be inferred from the iso-resistivity maps at fixed elevation from 1D and 2D inversion results.

1D slice maps up to sea level, Figure (7), reveal that the two areas generally characterized by resistivity less than $3 \Omega\text{-m}$ with a NW-SE oriented slightly higher resistivity zone aligned along the south-western border fault of the graben in the south-western periphery of Allalobeda field. Subsequent depth maps up to 500m b.m.s., presented in Figure (8), show a general increase in resistivity magnitude. The high resistivity zone is observed to widen and displaced towards east, truncated and distorted forming sharp gradient to the conductive zones to the west and east of it. Traces of discontinuities related to the NE-SW trending structure AD4, and NW-SE structures AD1 and AD2 are inferred at Allalobeda field in association with intensive manifestations in the

western zone located around the intersection of the discontinuities. The resistivity of the zones east of AD2 and west of AD1 increases from lower than 22 Ω -m to less than 76 Ω -m. Typical shallow geothermal reservoir to a depth of more than 900m from the surface could be inferred around the western periphery Allalobeda marked by low resistivity of less than 22 Ω -m that could be related to low temperature alteration product in the zeolite and smectite minerals delineating the cap rock followed by an increased resistivity that could be related to a zone of high temperature alteration minerals/ mixed layer zone epidote near the inferred discontinuity AD1.

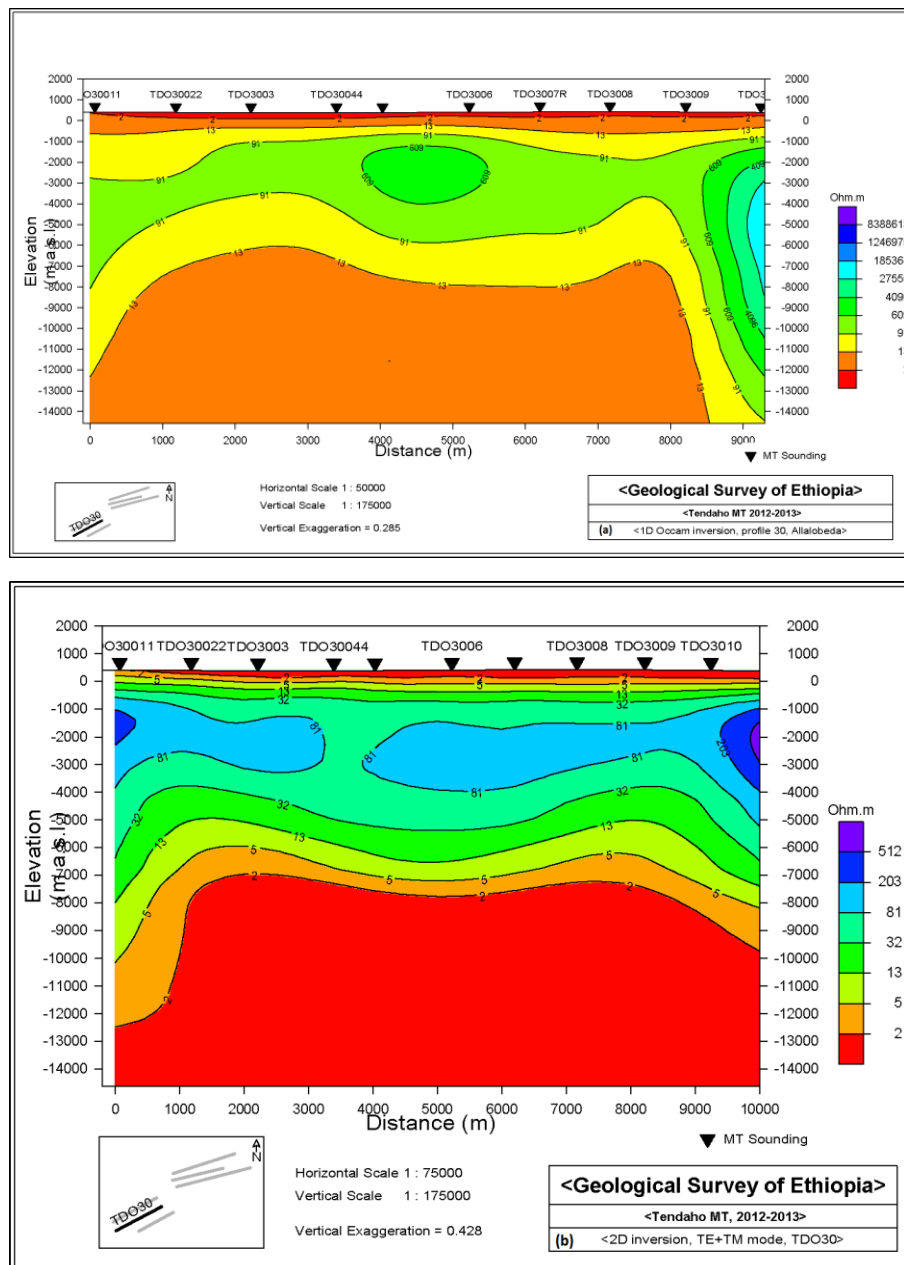


Figure (6): (a) 1D and (b) 2D geo-electric cross-sections along profile TDO30, Allalobeda field.

Most parts of the Dubti field up to 500m b.m.s.l are characterized by high conductivity less than 10 Ω -m that is a typical response of the thick sediment and the conductive clay mineral (\approx 1100m thick). The gross low resistivity in the two areas is an attribute of the thick fluvo-lacustrine deposit that consist of siltstone, sandstone and finer deposit mudstone and alteration products with intercalated basalt observed in the deep TG wells in Dubti. Though shallow, at Logya similar lithologic unit logged in a borehole (GBH9) can be extrapolated to cover the underlying formation between Logya and Allalobeda where it attains a thickness of about 750 m (as seen on the depth slice map at 300 m b.m.s.l, not shown here).

The majority of the 1D and 2D depth maps reflect the resistivity distribution of the Dubti field in a similar way to a depth of 750m, the level where discrepancies start to show up. Also noted was the 2D result shows a little bit exaggerated in the resistivity magnitude. In the depth slice maps at 1000 m and 1200 m b.m.s.l presented in Figure (9) and Figure (10), the low resistivity distribution which is less than 10 Ω -m in the Dubti field grows to moderately low resistivity (< 28 Ω -m) zones generally occupying the central and western peripheries of the surveyed area bounded by the high resistivity blocks. This growth in magnitude with depth may signify the change in the alteration zone from the high conductive zeolite-smectite and the mixed layer zone to the zone

of high temperature alteration minerals. Two resistivity discontinuities DD1 and DD2 are inferred in Dubti geothermal field bounding the NW-SE trending high resistivity zone. The active thermal manifestation in Dubti and the productive Tendaho wells TD2, TD4, TD5 and TD6 drilled in the area are aligned in the direction of the discontinuity DD2 showing the south ward extension of the Dubti fault beyond 2 km. Analogous to the inferred shallow reservoir at Allalobeda field, geothermal reservoir at intermediate depth ($\approx 1500\text{m}$) could be intersected around the peripheries of DD2 in the area marked by the low resistivity.

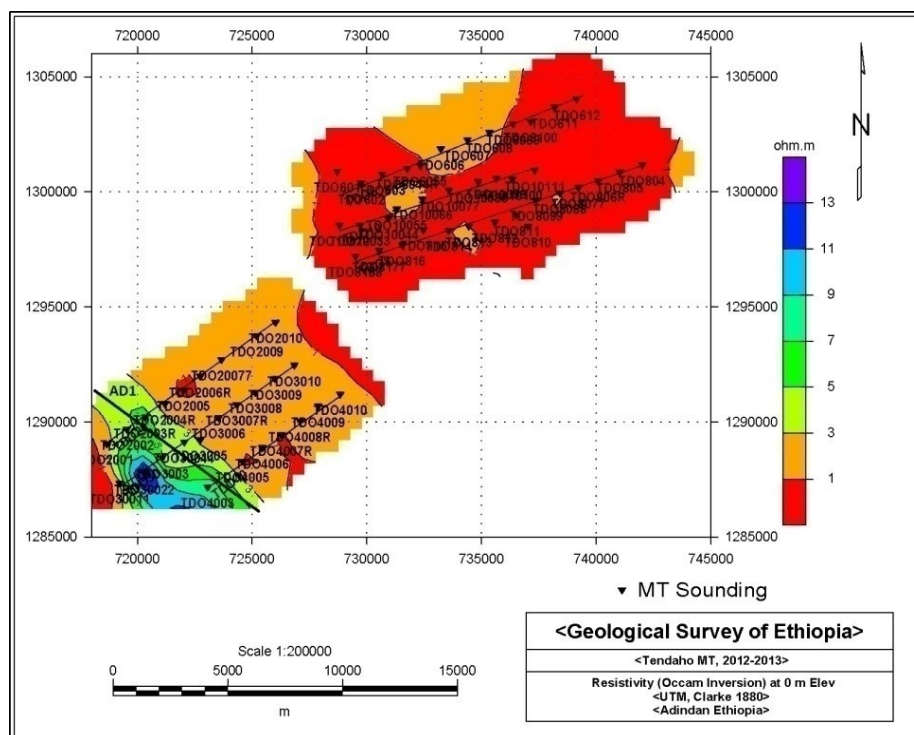


Figure (7). 1D Iso-resistivity map at sea level, Dubti and Allalobeda geothermal fields.

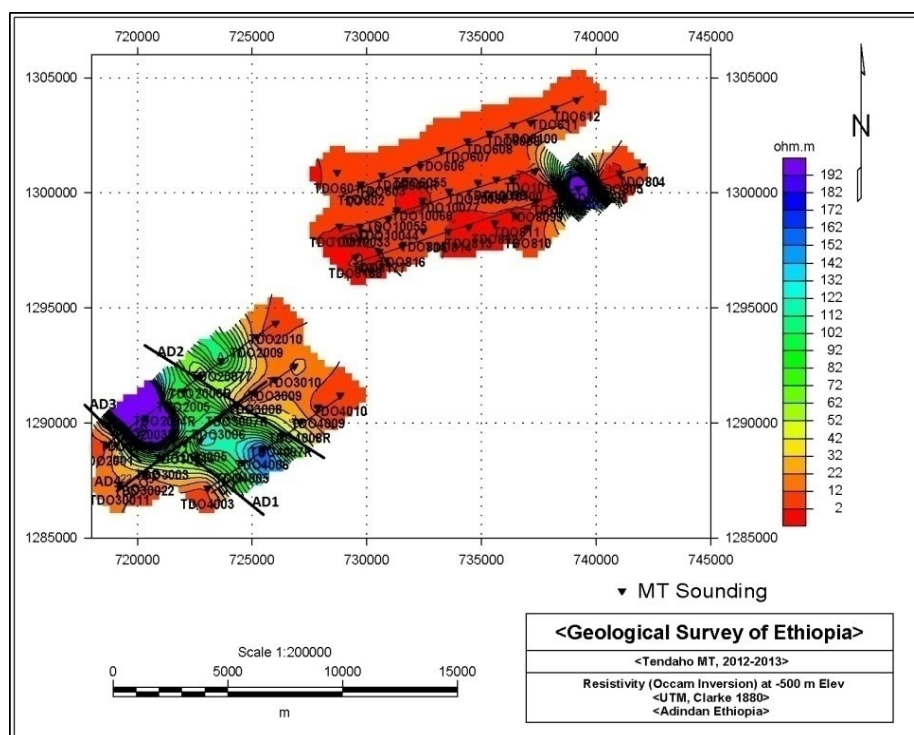


Figure (8). 1D Iso-resistivity map at 500m b.m.s.l, Dubti and Allalobeda geothermal fields.

For the greater depth interpretation result from the 2D inversion was used, keeping in mind the observed exaggerated resistivity magnitude on the 2D model. The resistivity distribution at 2000 m, 2500 m and 4000 m b.m.s.l Figure (11), Figure (12), and Figure

(13) reveal a decrease in the low resistivity values reaching as low as $4 \Omega\text{-m}$ in Dubti. In addition various resistivity discontinuities NE-SW DD0 and NW-SE, DD1, DD2, DD3 and DD4 were inferred around Dubti. The low resistivity anomaly which was detected by previous studies (Lema Y. et al., 2012) in south-east of the Dubti wells and manifestations along the Dubti fault is now refined and bounded by the discontinuities DD0, DD2 and DD3 opening farther towards south-east. The up flow of the geothermal fluid could be the well defined central low resistivity zone in Dubti field and deep geothermal reservoir within an exploitation depth could be associated around the peripheries of the central low resistivity zone adjacent to the inferred structures. The central conductive zone here persistently increase in its conductivity to about $2 \Omega\text{-m}$ and widens over a large with depth indicating a conductive magmatic melt heating the area as can be seen in Figure (14). Referring to Figure (11), Figure (12) and Figure (13) the well defined low resistivity zone east of DD4 may suggest the presence of a different geothermal system (blind geothermal system) in the Dubti field.

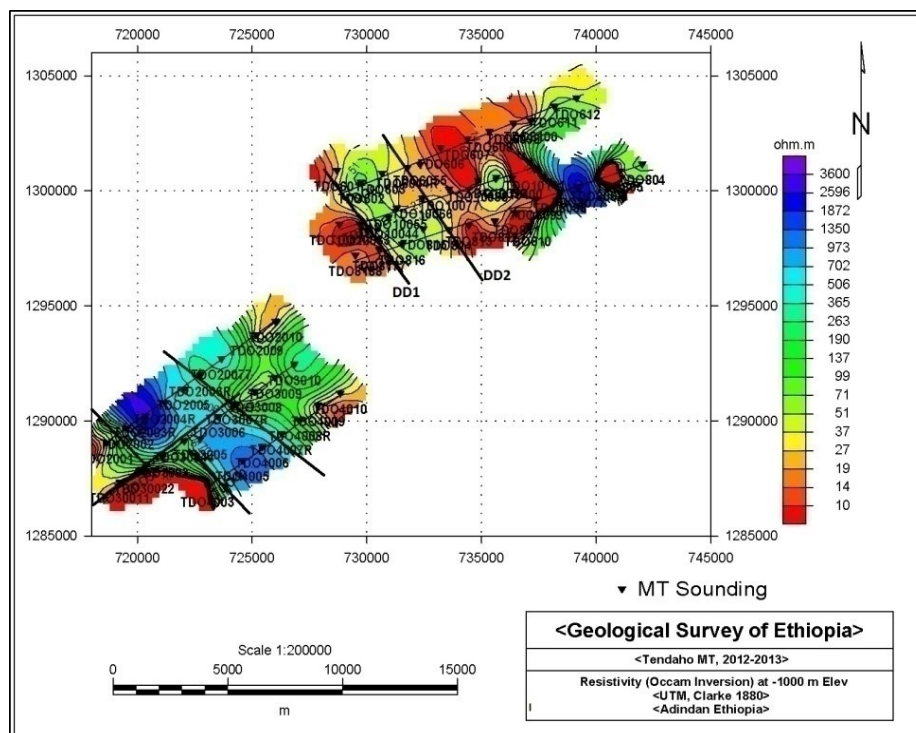


Figure (9). 1D Iso-resistivity map at 1000m b.m.s.l, Dubti and Allalobeda geothermal fields.

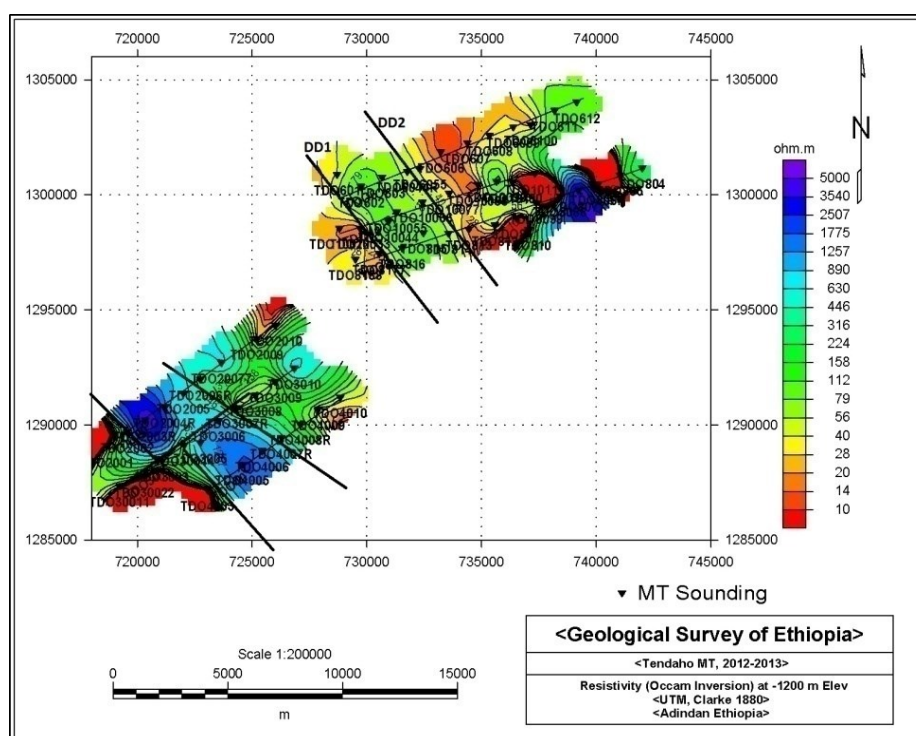


Figure (10). 1D Iso-resistivity map at 1200m b.m.s.l, Dubti and Allalobeda geothermal fields.

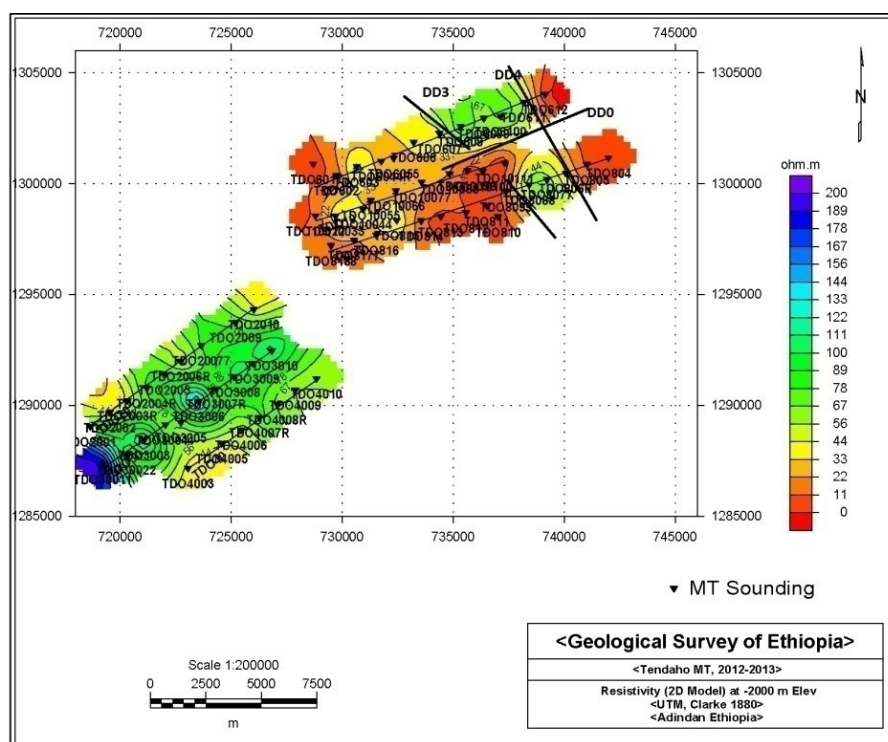


Figure (11). 2D Iso-resistivity map at 2000m b.m.s.l, Dubti and Allalobeda geothermal fields.

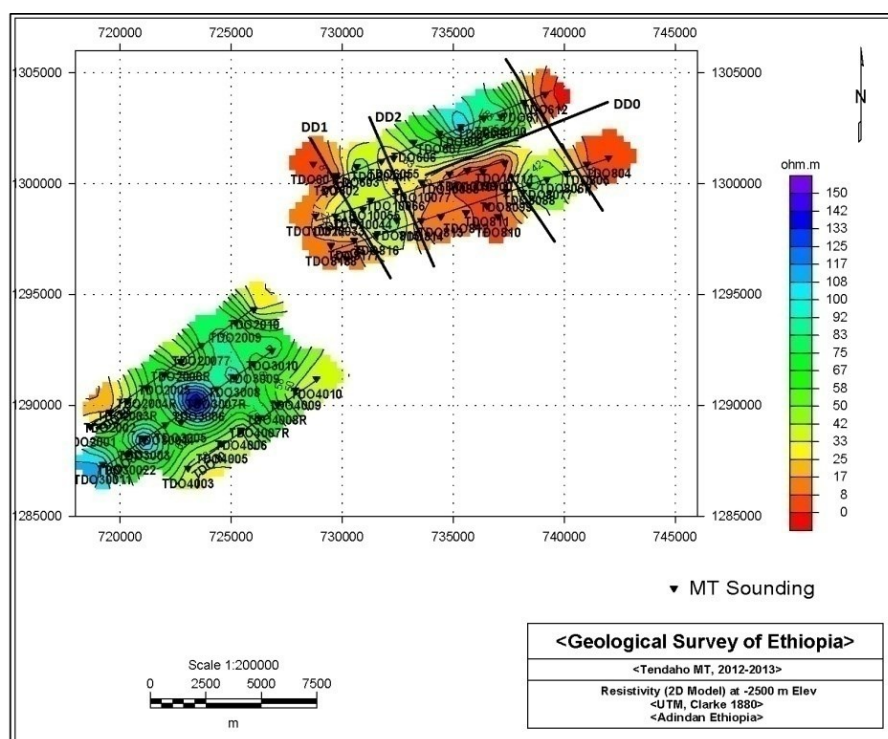


Figure (12). 2D Iso-resistivity map at 2500m b.m.s.l, Dubti and Allalobeda geothermal fields.

Structural complexity of the Allalobeda field can be witnessed from sporadic nature of the contour lines for different depth levels which could be due to faults and fractures of different orientations. Even the major NW-SE high resistivity contour lines are disrupted and offset by a possible NE-SW structure (AD4). This may reflect the area to be intersected by the two major fault systems related to the north-west tectonic trend of the Tendaho graben and the north-east trending the Main Ethiopian Rift (MER). Also noted to the field is the relatively higher magnitude of the resistivity value compared to the Dubti field and this is accounted to the relatively higher abundance of high temperature alteration minerals, relatively fresh basaltic rock, possible infiltration of cold water from Awash river, lesser content of dissolved chemicals in the geothermal fluid and the possibility of steam dominated fluid in the system.

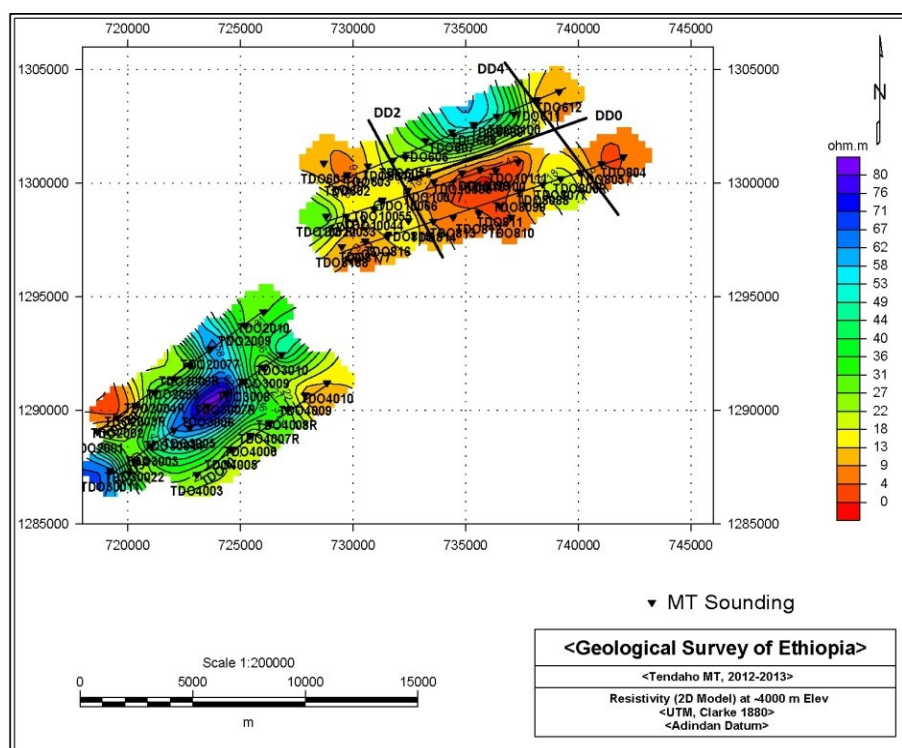


Figure (13). 2D Iso-resistivity map at 4000m b.m.s.l, Dubti and Allalobeda geothermal fields.

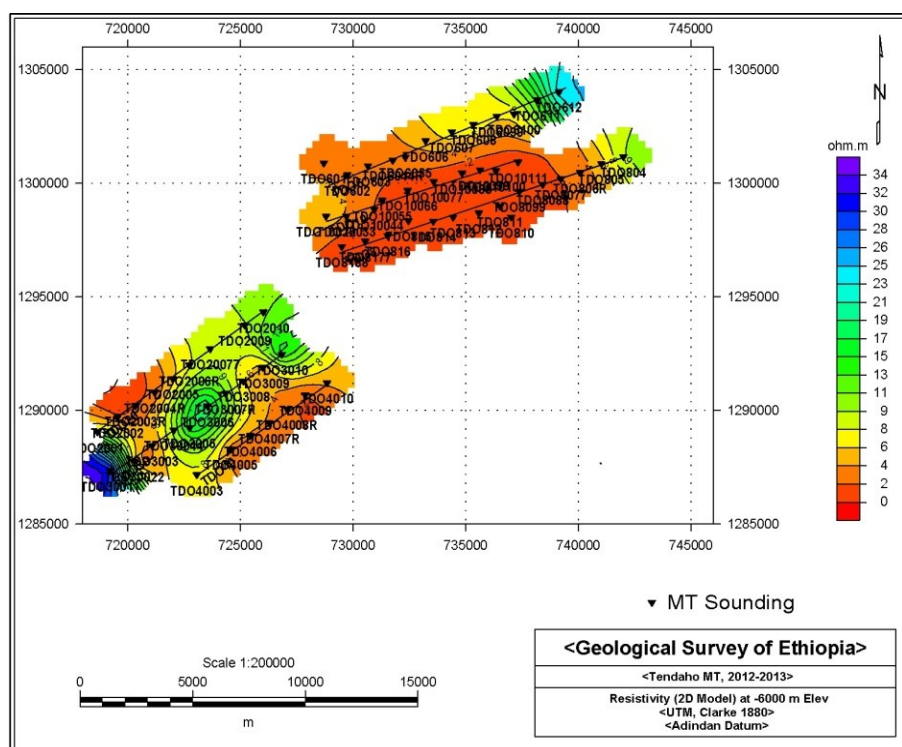


Figure (14). 2D Iso-resisitivity map at 6000m b.m.s.l, Dubti and Allalobeda geothermal fields.

CONCLUSION

- The Swift's impedance strike and tipper strike analysis at different depth levels (frequencies) indicated that the majority of the stations show a general NW-SE strike direction coincident with the major trend of the Tendaho rift axis N25°W.
- The dimensionality analysis parameters, the Swift skew, the tipper magnitude, and the polar plots at different frequencies indicated non-1D conductivity structure for the longer period beyond 10 sec and around 5 sec at Dubti at Allalobeda field respectively.

- Cross-sections from 1D and 2D inversion models revealed similar resistivity layers: a good conducting top layer correlated to fluvo-lacustrine and alluvial sediment with intercalated post stratoid basalt together with the portion of highly fractured/ altered Afar Stratoid Basalt underlain by a resistive layer correlated to portion of the Afar stratoid basalt and the Dalha Basalt, and the third conductive layer correlated to the magmatic melt. A fourth layer only mapped at the Dubti field may be correlated to the Mabla rhyolite.
- Conductive reservoir environments are inferred from 3D view using iso-resistivity maps from 1D and 2D inversion models. From the 1D model, a shallow geothermal reservoir can be found to a depth of about 900m around the western periphery of Allalobeda marked by a moderately higher resistivity zone (22-76 Ω -m) associated to the surface intensive manifestations in the western zone around the intersections of the NE-SW trending structure AD4, and NW-SE structures AD1 and AD3. While in Dubti geothermal reservoir at an intermediate depth (\approx 1500m) could be intersected around the peripheries of DD2 in the area delineated by a moderately low resistivity ($\rho < 28 \Omega$ -m) in the central area.
- The resistivity structure beyond 2000m b.m.s.l is better defined from the 2D slice maps: a widely distributed low resistivity horizon of the deepest horizon emerge to the depth of 2000m b.m.s.l, narrowing as a well defined central low resistivity zone ($\rho < 4 \Omega$ -m) in the south-eastern central Dubti field bounded by the NE-SW discontinuity D0 and NW-SE lineaments DD0, DD2 and DD3 delineating the up flow zone in the field. Geothermal fluid at depth emerges to shallow level along these structures, flowing laterally and enriching the shallow permeable formation and vertically as the thermal manifestations in the field.
- Despite limited MT soundings at Allalobeda, the general NW-SE trend of resistivity contour lines that open in the direction of Logya may suggest the possibility of connection of the two systems.
- The sporadic nature of the orientation of the resistivity contour lines for different depth levels suggest that the Allalobeda field is structurally complex, which is diagnostic to the presence of different faults and fractures of 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).
- The presence of a different deep geothermal system (blind geothermal system) in the Dubti field is inferred from a well defined low resistivity zone mapped east of DD4.

RECOMMENDATIONS

- Since the presence of a static shift is noted in the MT data of the present study, Transient Electromagnetic (TEM) sounding should be made around the present MT stations. Reprocessing of the data is recommended before taking any drilling action around the suggested promising sites by this study.
- Further MT soundings are advised towards north and south of the Allalobeda field to persuade the open resistivity structures, additional MT profiles should be made south of profile TDO8 to pursue the open low conductive zone of the central Dubti anomaly. The profiles TDO10, TDO6 as well as TDO8 should be extended towards east to further investigate the conductive zone mapped east of DD4 towards the respective directions. In addition 3D inversion modelling is recommended to better map the conductivity structure of the subsurface in the two fields.

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