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Integrated Geophysical Surveys to Characterize Tendaho Geothermal Field in North Eastern Ethiopia

Yohannes Lemma[1], Aklilu Hailu[2], Mohammednur Desissa[3] , Ulrich Kalberkamp[4]

[1,2,3] Geological survey of Ethiopia, P.O.BOX 2302, Addis Ababa, Ethiopia

[4] Geological survey of Germany, GEOTHERM Programme, Stilleweg 2, 30655 Hannover, Germany

yohanesle207@gmail.com or yohlema@yahoo.com

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ABSTRACT

Tendaho geothermal field is a high temperature geothermal resource in Afar regional state North Eastern Ethiopia. Gravity, magnetic, transient electromagnetic and magneto-telluric survey were carried out. The objective of the geophysical survey was to delineate the boundaries of the geothermal reservoir and geological structures that control flow of geothermal fluids.

The complete Bouguer anomaly map has reveled two distinct broad high (in NW sector) and low (in SE sector) Bouguer anomalies. These contrasting Bouguer anomalies may indicate the presence of ENE-WSW trending regional crustal discontinuity (fault). The Tendaho graben is mapped as a NW-SE trending prominent magnetic low feature and corresponding high residual gravity anomaly. The geothermal manifestations at Tendaho geothermal field lie on NW-SE trending fault system on magnetic and gravity surveys.

TEM data from the same site was used to correct for static shift in MT data. MT data were analysed and modelled using 1D Occam inversion of the determinant of the impedance tensor. In the MT cross sections, the low resistivity at shallow depth is interpreted as a sedimentary formation, lateral flow of geothermal fluids or a fracture zone. The high resistivity below the low resistivity can be associated to less permeable Afar stratoid series basalts. A low-resistivity zone bounded between high resistivity is interpreted as a fracture zone in the Afar stratoid basalts which may give rise to higher permeability and higher temperature and may indicate upflow of geothermal fluid. The fracture zones inferred from MT correlate with NW-SE trending structures from gravity and magnetic surveys and the surface geothermal manifestations in the area. The fracture zones are not well resolved because of large MT station spacing..

1. INTRODUCTION

The Dubti (Tendaho) geothermal field is located in the central part of Afar Depression about 600 kilometers from Addis Ababa in the northeastern part of Ethiopia (Figure 1). Structurally the area is part of the Tendaho graben, which is about 50 km wide, 100 km long and oriented in the NE-SW direction. Gravity and magenetics surveys were conducted to study the geological structures and dimension of subsurface lithology of Tendaho geothermal field. The gravity survey was conducted using a Lacoste and Romberg model 819G gravimeter having a reading accuracy of 0.01mGal. The position and elevation of the survey stations were obtained using the Magellan 315 GPS and Barometric Altimeter. The Scintrex made portable proton precession magnetometer MP-2 was used to measure the total magnetic field.

Magnetotelluric (MT) and Transient Electromagnetic(TEM) surveys were conducted by joint collaboration of experts from BGR (German geological survey) and Ethiopian Geological Survey from January 23 – February 23, 2007. A total of 51 MT soundings were measured using ADU-06 Metronix MT units.

2. REVIEW OF PREVIOUS WORK

2.1 Geologic and Tectonic Setting

Tendaho graben is trending in a NW direction as a southern portion of the Erta-Manda Hararo rift system in the Afar region (Aquater, 1995). The rift joins the Ethiopian rift close to volcano Dama Ale, west of Lake Abhe. The Tendaho rift, however does not merely swerve into the Main Ethiopian rift, but is prolonged east of the latter by Gobaad structure (Aquater, 1996).

The borders of the Tendaho rift are constituted by the Afar Stratoid Series and the rift is filled with lacustrine and alluvial deposits and with post stratiod basalt flows. This filling is topped by recent volcanoes, including the historically active Kurub and Damal Ale volcanoes (Aquater, 1996). The Tendaho graben is bounded by Logya fault to the west and Gamare fault to the East. In the Tendaho region NW and NNE trending faults predominate (UNDP, 1973).

NNE trending faults may have played only a minor role in the evolution of the Tendaho graben, where the dominant structural element is NW (UNDP, 1973). The intersection of these two faults trend appears to be a controlling factor governing the locations of current hydrothermal activity (UNDP, 1973).

Inside the Tendaho Rift, lacustrine and alluvial plains alternate with zones where basalts crop out as NW-oriented elongated fault blocks. Evidence for active NW-striking faults includes aligned steaming grounds, fumaroles and hydrothermal deposits in the sediments within the Dubti plantation (Aquater, 1995).

According to the stratigraphy under the graben floor (revealed by geophysics), the rock units are grouped into:

- Upper unit: thick sedimentary sequence consisting of fine to medium grained sandstone, siltstone and clay probably intercalated by basaltic lava sheets; and
- Lower unit: basaltic lava flows of the Afar stratoid series.

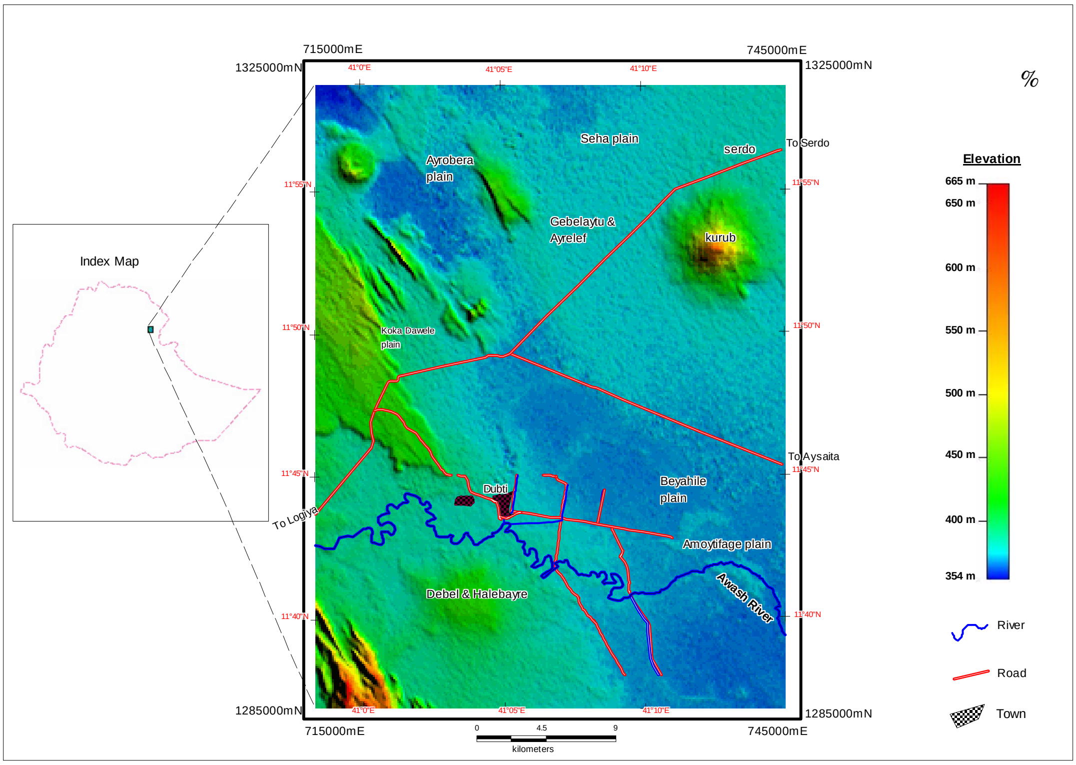

Figure 1: Location map of the study area

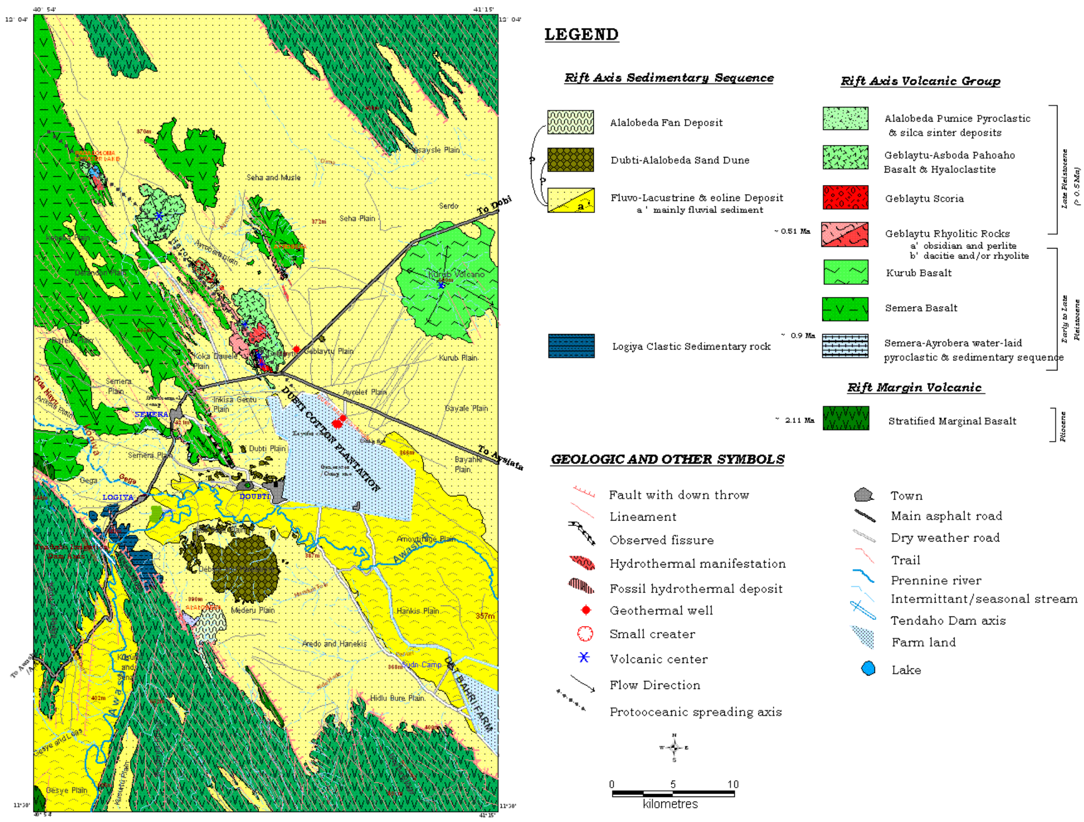

Figure 2: Geological map of Tendaho Graben (After Megersa and Getaneh, 2006)

The geology of Dubti-Semera area was mapped at a scale of 1:50,000 and the following units were identified (Megersa and Getaneh, 2006) and (Figure 2). The Rift margin complex of the study area represented by Stratified Rift Margin Basalt and the Rift Axis complex comprises of volcanic and sedimentary sequences. The Rift Axis Volcanic Group of the study area, found in the axial range of Tendaho rift, includes: Ayrobera-Semera Water-laid Pyroclastic and Sedimentary Sequence, Semera Basalt, Kurub Basalt, Geblaytu Rhyolitic Rocks, Geblaytu Scoria and Geblaytu-Asboda fresh Pahoehoe Basalt and Hyaloclastite. 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. The measured surface temperatures in geothermal manifestations mainly fall in the ranges from 65 to 100.3ºC (Megersa and Getaneh, 2006).

In Tendaho geothermal field six wells were drilled from 1993-98. Wells TD1, TD2 and TD3 are deep wells with depth of 1550, 1881 and 1989 m respectively. Wells TD4, TD5, and TD6 are shallow wells with depth of 466, 516 and 505 m respectively. Wells TD2, TD4, TD5 and TD6 are productive.

2.2 Previous Geophysical Work

Regional and semi-detailed geophysical studies have been carried out in the Afar Depression and Tendaho geothermal field, with the aim to investigate the deep structures and to delineate possible geothermal reservoir. The methods include Magneto-telluric (MT) (e.g. Berktold, 1975); Vertical Electrical Sounding (VES), Magnetics and Gravity survey (e.g. Aquater, 1980) among others.

In 1971 MT survey was carried out in the Afar region to investigate the deep electrical resistivity distribution (Berktold, 1975). The survey included measurement of the electric field in 36 temporary stations along three profiles for a total length of 900 km. Profile I of the MT survey which is trending East-West (Dessie-Bati-Serdo) intersect the study area. Results indicate that in the Afar Depression and the marginal parts of the Western plateau, the resistivity is decreasing from 200-500 Ohm-m in the uppermost kilometers to 10-50 Ohm-m at a depth of about 15 km (Berktold, 1975). The anomalously low resistivity beneath the Afar and the marginal parts of the Western plateau was interpreted as an anomalously high temperature of 800-1000˚C at a depth of about 15 km and a temperature gradient of about 60˚C/km (Berktold, 1975).

In 1972 five deep seismic refraction profiles 120-250 km long were run in the Afar lowland and on the western Ethiopian plateau (Berckhemer and Baier, 1975). In one profile, the crustal thickness is estimated beween 22 and 25 km with a 7.7 km/s mantle velocity; whereas in other profile the estimated crustal thickness is about 24 km and mantle velocity 7.6 km/s. According to Berckhemer et al., 1975, the interpretation suggests a crustal thinning and upwelling of hot upper-mantle material beneath Afar.

A gravity survey (between Tendaho, Serdo and Asayita) was conducted by Searle and Gouin (1971) in an area 1000 km². The authors produced a Bouguer anomaly map using an average crustal density of 2.67 Mg/m³. The main feature of the map is a decrease in Bouguer gravity from -40 mGal to the north to -55 mGal along the Awash River in the south, mainly caused by the accumulation of sediments in the Awash Basin. A few localized Bouguer gravity anomalies are observed along the southern edge of the surveyed area. A relative positive Bouguer anomaly is located near Tendaho village and a negative one near Dubti plantation.

An aeromagnetic map produced by Aquater (1979) showed a complex pattern of short positive and negative lineations. These were interpreted by Aquater (1979) being related to short spreading segment that have been active in the last four million years. One of such anomalies is located in the survey area along the Manda-Hararo Volcanic range.

In 1971 the Hunting Geology and Geophysics Ltd. conducted an airborne infrared survey of the geothermal prospects in Ethiopia including the Tendaho area. The infrared survey was able to detect hot grounds in Tendaho that were not recognized by previous ground surveys.

Vertical Electrical Sounding (VES) data was acquired by Aquater (1980). In this survey, depth of investigation reached only to a maximum of one km and the data lacked resolution in differentiating layers within the sedimentary and basaltic sequences. In addition, Aquater (1980) occupied 2086 gravity stations in the Tendaho area. The NW-SE trending gravity low near Tendaho plantation is related to a depression of the high-density substratum. A strong positive Bouguer gravity anomaly centred over the Ayrobera area may be due to a dense intrusive body in the fluvial-lacustrine sediment system (Aquater, 1980).

Aquater (1980) has also produced total field magnetic map that shows a general NW-SE magnetic anomaly. The anomaly extends from northwest to southeast following the Tendaho graben axis with minor anomaly interruptions attributed to near surface inhomogeneities.

Aquater (1980, 1994) drilled nine temperature gradient wells to map the subsurface temperature distribution in the Tendaho Graben and Logiya area. But, due to shallow depths of the boreholes (76.6-173.5 m) the reservoir temperature is masked by the thick sediment layers and the presence of hot or cold shallow aquifers. The micro seismic survey (Aquater, 1995) in the Tendaho graben has indicated that the hypocenters of the seismic events are distributed in a NW-SE direction and to a depth between 5 and 10 km.

A geophysical survey by Oluma et al. (1996) consist of Schlumberger traversing, Head-on resistivity profiling, vertical electrical sounding (VES) at three well sites (TD1,TD2,TD4) and 60 line km gravity surveys were conducted centring the active thermal manifestations of the Tendaho graben. The result of AB/2=500 m resistivity map indicated a prominent anomaly with its roots in the SE part**.** The result of resistivity map for AB/2=1000 m showed a narrow NE elongation of low resistivity zone. The dominant regional trend, i.e., NW and NE ones are the major structures controlling the flow of hot geothermal fluids.

Gravity survey by Lemma and Hailu (2006) indicated broad high Bouguer anomaly in Ayerobera area and low Bouguer anomaly in Dubti plantation area. These contrasting Bouguer anomalies may indicate the presence of ENE-WSW trending regional crustal discontinuity (fault).The high Bouguer and low total magnetic field anomalies at Ayrobera and Gebelaytu plains may indicate the presence of intrusive body or is associated with deposition of hydrothermal minerals on the volcanic rocks (Lemma and Hailu., 2006). The geothermal manifestations at Dubti plantation and Ayrobera areas lie on NW-SE trending fault system on magnetic and gravity anomaly maps (Lemma and Hailu, 2006).

Please include an Abstract, an Introduction, and Conclusion sections. Please check that you put the authors' names in the second and third page headers.

3. RESULTS

3.1. Bouguer Anomaly Gravity Map

Broad and relative positive Bouguer gravity anomalies (above -25 mGal) characterize the northwestern part (Ayrobera and Gebelaytu plain) of the study area (Figure 3). They are narrow and negative high on southwestern part of Debele plain and Serdo area. Strong negative Bouguer anomalies (less than -35 mGal) are observed on Beyahile and Amoytifage plain. Intermediate Bouguer anomalies of about -30 mGal separated the two Bouguer anomalies. Seha plain to the north is characterized by intermediate Bouguer value.

The low Bouguer anomalies of Beyahile plain are associated with sedimentary basin and apparently the thickness increases towards Amoytifage plain. The high positive Bouguer anomalies (greater than -29.8 mGal) of Ayrobera and Gebelaytu plain appear to be related to basaltic upper extrusive complexes. The most positive Bouguer anomaly, near Ayrobera plain geothermal manifestations is possibly associated with deposition of some hydrothermal minerals (hydrothermal alteration) on the volcanic rocks.

The narrow postive Bouger anomalies in the north east of Serdo and south west of Debel plain are associated to rhyolites and basalts (middle extrusive complexes). The area between Koka Dawele plain and Dubti is characterized by relatively low Bouguer gravity anomalies. This may indicate the area is covered by loose, low density sediment below, which probably a basaltic body exists (Aquater 1980). Broadly, the thickness of the sedimentary rocks decreases from southeast to northwest in the Tendaho rift, which is also observed from the Bouguer anomaly features (relative positive to the North West and a relative negative to the south east).

The geothermal manifestations at Ayrobera plain and Alelo bade area correlate to the north west- southeast trending fault systems (Figure 3).

The complete Bouguer anomaly map has revealed two distinct broad high (in the north western sector) and low (in the south eastern sector) Bouguer gravity anomalies. These two contrasting Bouguer anomaly features may indicate the presence of regional crustal discontinuity (fault) in between. The probable structure has ENE/WSW orientation. The low Bouguer anomaly in Beyahile plain is also separated from another high Bouguer anomaly over Debele plain by a probable NW-SE trending structure. The aforementioned high Bouguer zone is characterized by nearly circular contour of increasing magnitude towards the center. This may suggest the presence of high density volcanic up doming, which could be the reason for thin sediment deposit. Since the survey area is located in an area where lithosphere is thinned by stretching**,** an increased heat flow and doming **(**Berckhemer et al., 1975**)** are the consequences.

3.2. Total Field Magnetic Anomaly Map

High total magnetic field relief is observed in Koka Dawele plain, Dubti town, Kurub plain and Serdo area (Figure 4). Low magnetic relief characterizes the Ayrobera plain, Gebelaytu plain, Beyahile plain and Dubti plantation.

The high magnetic anomalies are related to upper extrusive complex and middle extrusive complex basalts and rhyolites. The low magnetic anomalies of Dubti plantation and Beyahile plain are associated to thick sedimentary rocks. The Tendaho graben is mapped as a NW-SE trending low magnetic feature and corresponding high residual gravity anomaly. Low magnetic anomaly near the geothermal manifestations in Ayrobera plain is interpreted as result from alteration effects on magnetic minerals (Aquater, 1980)

Possible lineaments inferred from the total field magnetic map is shown in Figure 4.

The manifestations are well correlated with the NW-SE trending structure (possible fault). The magnetic gradient at Dubti plantation (geothermal manifestation) could be interpreted as possible fault trending NW-SE. The Alalobeda thermal manifestations also lie on magnetic gradient SW of Debel plain, which is interpreted as fault.

Comparison of the Bouguer and total magnetic field anomaly maps (Figures 3 and 4), the total magnetic field anomaly is very low and the Bouguer anomaly is high at Ayrobera and Gebelaytu plain. . The high Bouguer anomaly indicates the presence of high density probably caused by deposition of hydrothermal minerals on basaltic body (e.g. Hochestein and Hunt, 1970). Consequently, the magnetic response of the basalt has to be high too (e.g. A. Manzella). But, the total magnetic field anomaly is low. This may show that the basaltic unit has lost its ferromagnetic nature due to high temperature underneath. This geophysical information help to infer the presence of heat source which could be one of the causes for the existence geothermal potential in the area.

3.3. MT Soundings Cross Section

MT cross section, L1, (Figure 5 and 6), runs from Dubti in the SW, passes the geothermal manifestations near shallow well TD4 and ends SE of Kurub volcano. A low resistivity of about 1 Ω m is observed across the cross section to a depth of 100 m a.s.l. This resistivity structure can be associated to sediments. On northeast part of the cross section a relatively high resistivity is observed from a depth of 0 to 200 m b.s.l. This is correlated to basalts intercalated in sediments. Another low resistivity of 1 Ω m is observed from 200 to 500 m b.s.l. This is associated to sediments or lateral flow of geothermal fluid or fracture zone. A high resistivity of anomaly > 100 Ω m is observed under TDO0106 from a depth of 1000 m. to 2000 m b.s.l. A similar anomaly is observed under TDO0103 and TDO0107 from 1200 m to 2000 m b.s.l. This high resistivity can be associated to the less permeable Afar stratoid basalts. Between these two high resistivity structures, there is a low-resistivity zone under soundings TDO0107 and TDO0108 at bottom part of the cross section. This can be due to presence of fracture zone in the basalts which may give rise to higher permeability and higher temperature and may indicate upflow of geothermal fluid into the system.

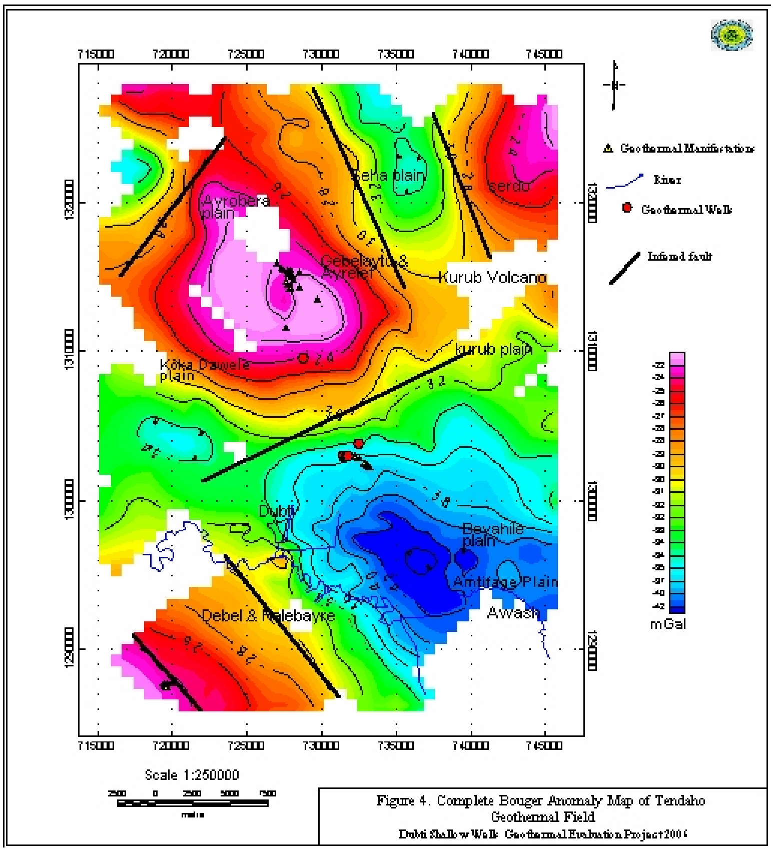

Figure 3: Bouguer Anomaly map of Tendaho Geothermal field

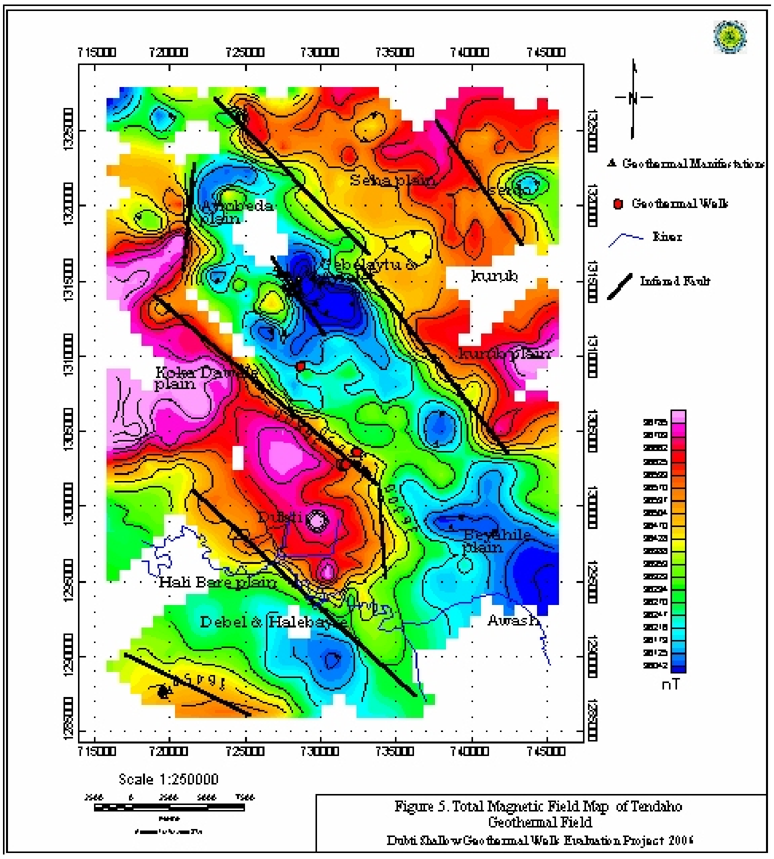

Figure 4: Total Field Magnetic Anomaly Map of Tendaho Geothermal Field

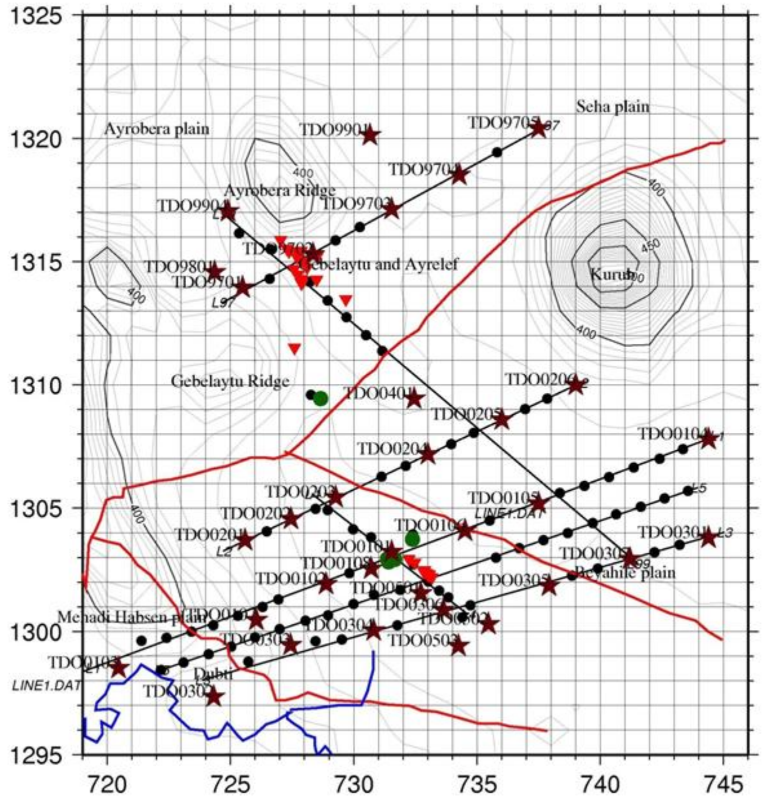

Figure 5: Location of MT and TEM soundings (UTM 37, datum: ADINDAN-Ethiopia, in km)

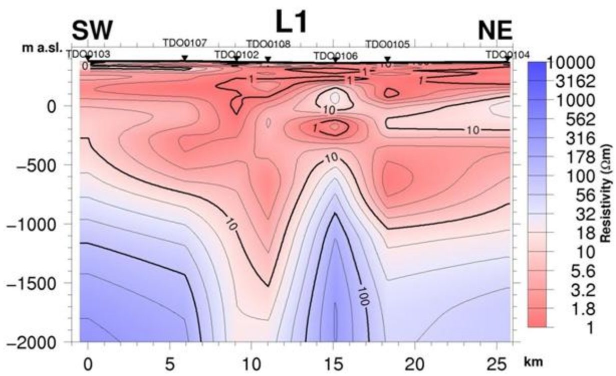

Figure 6: MT resistivity cross section L1

MT cross section L2, Figure 7, runs from Mehadi Habsen plain in SW to Kurub volcanic complex in the NE. A low resistivity ≤ 10 Ω m is observed along the whole cross section to depth of 0 m at sea level. This low resistivity extends to a depth of 1000 m b.sl at southwest section under sounding TDO0201 and TDO0202. The same resistivity structure extends to 800 m b.s.l at northeast part of the cross section under soundings TDO0205 and TDO0206. This low resistivity structure can be correlated to sediments. A broad high resistivity of ≥ 100 Ω m is observed along the cross section at an average depth of 1000 m b.s.l. This high resistivity is up doming near southwest sector of the section especially under TDO0203. The high resistivity at the bottom part of the cross section is associated with Afar stratoid series basalts.

MT cross section L3, Figure 8, runs from Dubti in SW to Behyahile plain in NE. A low resistivity ≤ 10 Ω m is observed to a depth of 0 m at sea level. A broad high resistivity of ≥ 100 Ω m is observed under the low resistivity to a depth of 2000 m b.s.l. The low resistivity can be associated with sediments and the high resistivity to Afar stratoid basalts.

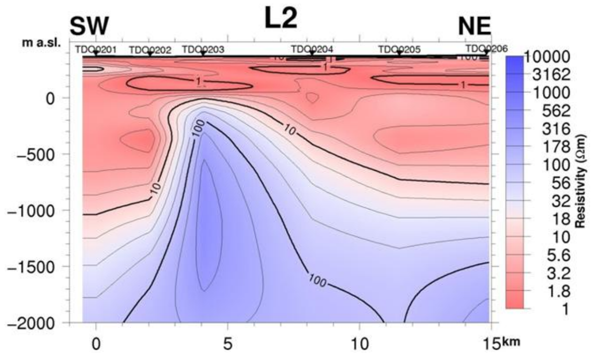

Figure 7: MT resistivity cross section L2

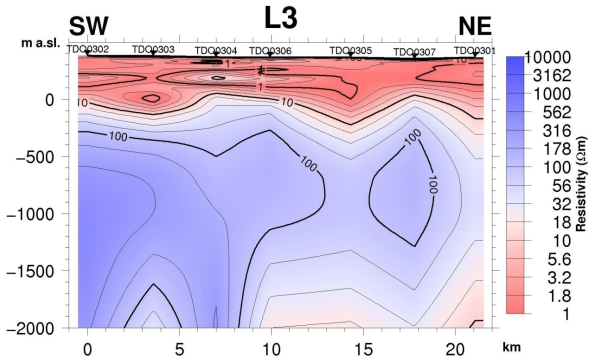

Figure 8: MT resistivity cross section L2

MT cross section L97, Figure 9, runs from Gebelaytu ridge in SW to Seha plain in the NE. A high resistivity anomaly ≥ 100 Ω m is observed at shallow depth of about 200 m a.s.l in the southwest part of the cross section under sounding TDO9712. A relatively high resistivity of ≥ 10 Ω m is observed on the northeast part of the cross section at the same depth. This high resistivity can be correlated to basalts in the area. The rest of the cross section is characterized by low resistivity ≤ 10 Ω m to a depth of 300 m b.s.l. This low resistivity is associated with sedimentary formation or geothermal fluid circulation in the formation. A high resistivity of anomaly > 100 Ω m is observed under TDO9712 from a depth of 400 m. to 2000 m b.s.l. A similar anomaly is observed under TDO9704 and TDO9705 from 500 m to 2000 m b.sl. This high resistivity is associated to less permeable Afar stratoid basalts. Between these two high resistivity structures, there is a low-resistivity zone under soundings TDO9702 and TDO9703 in the Afar stratoid basalts. This anomaly is interpreted as fracture zone in basalts where geothermal fluids circulate.

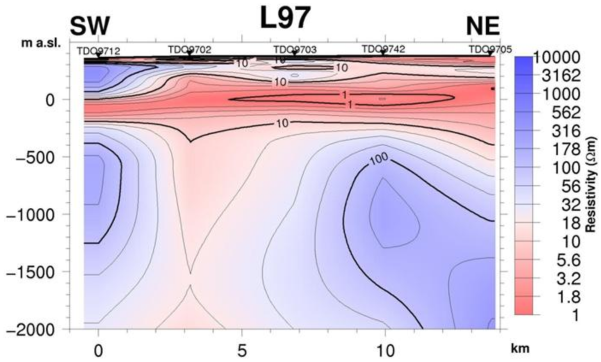

Figure 9: MT resistivity cross section L97

CONCLUSIONS

The geological structures controlling the flow of geothermal fluids are dominantly NW-SE trending regional system. The mapped geological structures are in line with Aquater, 1990. The density distribution of the Tendaho geothermal field is predominantly volcanics in NW sector and sedimentary in SE sector from gravity surveys.

Since both volcanic and sedimentary rocks cover the survey area, it is difficult to indicate the boundaries of geothermal reservoir by magnetic method. Even though the geothermal manifestations in Dubti, Ayrobera and Alelobade lie on a fault, it is not possible to infer that they are connected in anyway structurally because of data scarcity in some areas.

In MT cross sections L1 and L97, the low resistivity at shallow depth can be correlated to sedimentary formation (clay, siltstone and sand stone), lateral flow of geothermal fluid, fracture zone or alteration mineralization. The high resistivity at depth below the low resistivity can be associated to the less permeable Afar stratoid series basalts. A low-resistivity zone bounded between high resistivity in the basalts is interpreted as a fracture zone which gives rise to higher permeability and higher temperature and may indicate upflow of geothermal fluids. The fracture zone inferred from MT cross sections coincides with the surface geothermal manifestations in Dubti and Ayrobera area.

On MT cross section L1 the low-resistivity zone between MT soundings TDO0107 and TDO0106 may represent shallow sedimentary reservoir at depth of 200 m b.s.l and deep basaltic reservoir at 1000 m b.s.l which was also observed on well testing and reservoir engineering studies results of Tendaho geothermal field (Amdebrhan and Bjornsson, 2000).

The fracture zones interpreted from MT cross sections L1 and L97 (Figures 6 and 9) correlates to NW-SE trending structures inferred from the gravity and magnetic survey for the area (Figures 3 and 4). The fracture zone inferred from the MT cross sections also coincides with the surface geothermal manifestations in Dubti and Ayrobera area.

In MT cross sections L2 and L3, a low resistivity is underlain by high resistivity formation. The low resistivity can be correlated to sedimentary formation. The high resistivity can be associated to the Afar stratoid series basalts.

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