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Magnetotelluric Imaging at Tendaho High Temperature Geothermal Field in North East Ethiopia

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ABSTRACT

We report on a recent magnetotelluric (MT) survey across Tendaho geothermal field within the Tendaho graben in the Afar Depression in northeastern Ethiopia. Twenty-two broadband MT sites with ∼1 km station spacing were deployed along a profile with the recorded data covering a period range from0.003 s to1000 s. A two-dimensional (2-D) resistivity model reveals an upper crustal fracture zone (fault) and partial melt with resistivity of 1–10 Ωm at a depth of >1 km. The low resistivity surface layer is associated with sediments, geothermal fluids or zeolite-clay alteration zone. Below the conductive layer, a high resistivity zone that can be correlated to the back ground resistivity of Afar Stratoid basalts or epidote alteration zone. The inferred presence of a conductive fracture zone or fault with hydrothermal fluid and shallow heat sourcing magma reservoir makes the Tendaho graben a promising prospect for the development of conventional hydrothermal geothermal energy

1. INTRODUCTION

Magnetotelluric (MT) survey was conducted at Tendaho high temperature geothermal field to characterize the deep conductivity structure of the area. The Tendaho geothermal field is located in the central part of Afar Depression about 600 km from the capital city Addis Ababa in the north-eastern part of Ethiopia (Figure 1).

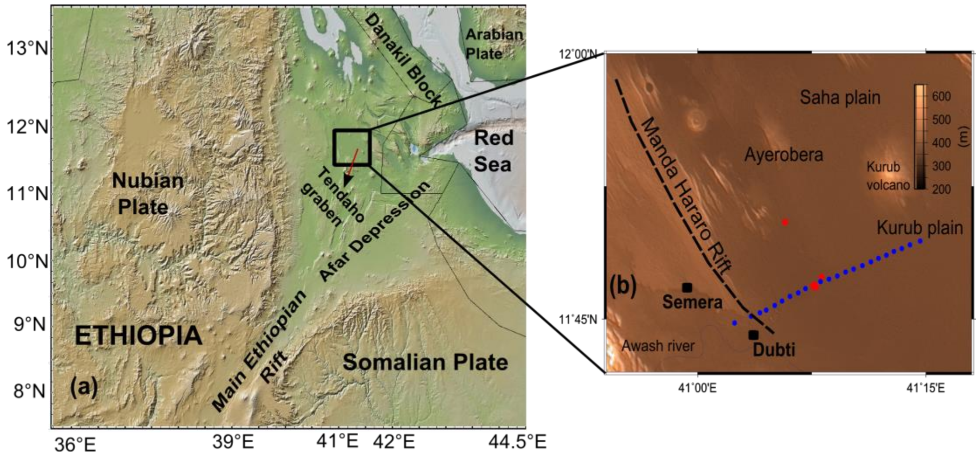

Figure 1: Location Map of the study area (a) the Afar Depression and Main Ethiopian Rift. The black square survey area is expanded in Figure 1b. (b) MT profile crossing the Tendaho geothermal field located within the Tendaho graben, blue dots are MT sites and red diamonds indicate geothermal wells.

Here we present results from magnetotelluric (MT) surveys conducted in the Tendaho graben along a SW-NE trending profile perpendicular to the graben's geological strike direction (Figure 2).

2. METHOD

Magnetotellurics is a passive electromagnetic method sensitive to electrical conductivity contrasts in the Earth's crust, caused particularly by conductive materials such as metallic minerals, graphite, molten rock (partial melts),and aqueous fluids (Chave and Jones, 2012; Muñoz, 2014). The MT technique involves measuring fluctuations in the natural electric (**E**) and magnetic (**B**) fields in orthogonal directions on the Earth's surface, as a means of determining its internal conductivity structure (Chave and Jones, 2012).

The depth to which electromagnetic waves penetrate into a uniform ground of resistivity (ρ) before becoming attenuated is characterized by the *skin depth* (δ). Skin depth is defined as the depth where the electromagnetic field has reduced to e^{-1}(or 37 percent) of its original value at the surface:

$$\delta \approx 500\sqrt{\rho T}\ (m)$$

where T is period in seconds

The impedance tensor (**Z**) describes the relation between the electric (**E**) and magnetic (**B**) fields which is given by **E**=**ZB** or in matrix form:

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix}$$

where Z_{xy}, Z_{yx} are the principal impedances while Z_{xx} , Z_{yy} are the supplementary ones (contributions from parallel components of the magnetic field).

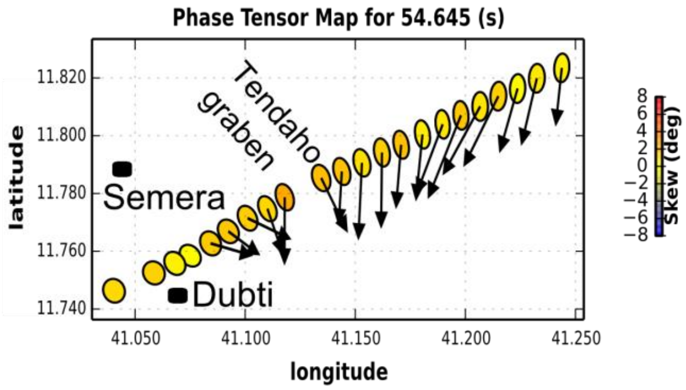

Figure 2: MT site locations crossing the Tendaho geothermal field located within the Tendaho graben. Ellipses indicate MT phase tensor plots at period of 55 s. The black arrows are the real part of the tipper which point to the possible upflow zone of the geothermal system.

A total of 22 MT stations were acquired by the Geological Survey of Ethiopia along the profile with station spacing of ∼1 km (Figure 2). Two five-channel MT data acquisition systems (MTU-5A, Phoenix Geophysics Ltd) were used to record the MT data. A sounding was produced at each site from a 24 h recording covering a period range from 0.003 s to 1000 s with a remote reference positioned 20 km from the survey area. The MT data were processed using the robust processing program SSMT2000 from Phoenix Geophysics Ltd. Dimensionality analysis was performed using the phase tensor approach (Caldwell et al., 2004). Skew angles are less than 3° for most sites, which is consistent with a 2-D regional conductivity structure beneath the survey area (Figure 2). This is further verified using the ellipticity criterion of MT data formulated by Becken and Burkhardt, 2004. Subsequently, the data are rotated to a geoelectric strike angle of x′=−25°. The x′y′ component of the MT data is assigned as the transverse electric (TE) mode and the y′x′ component is assigned as the transverse magnetic (TM) mode.

We invert the data using the 2-D Occam inversion code (de Groot-Hedlin and Constable, 1990) with a grid of 279 horizontal nodes and 100 vertical layers with layer thickness increasing logarithmically with depth. The model space used extends 600 km in the horizontal and 300 km in the vertical directions to avoid boundary effects. A total of 74 periods (0.003 s–1000 s) are used for the inversion. Many 2-D joint inversions of TE and TM modes with different starting models were carried out. A starting model of homogeneous half-space of 100 Ωm was used for the model presented here. Error floors of 10% for resistivity and 3% (equivalent to 1°) for phase were used for the joint inversion of TE and TM modes. The preferred model of the joint inversion achieved a minimum misfit of RMS ∼1.9 (Figure 3).

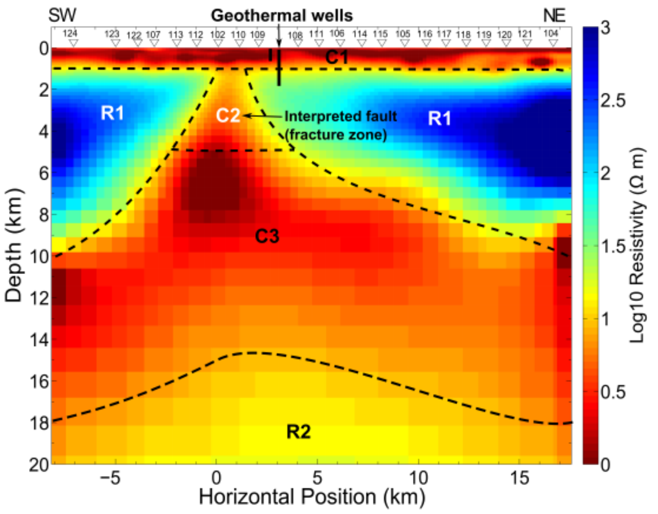

Figure 3: Preferred 2D resistivity model obtained by joint inversion of TE and TM modes along the profile (Didana et al., 2014).

3. RESULTS AND DISCUSSION

The 2-D inversion model reveals five main resistivity zones (Figure 3). The surface conductive zone (C1) is 1 km thick, with resistivity ≤10 Ωm, and spans the entire cross section. This conductive zone is associated with sediments, geothermal fluids, and smectite clay alteration (Aquater, 1996). The high-resistivity zone (R1) of >10 Ωm is inferred to be the background resistivity of the Afar Stratoid Series basalts or chlorite-epidote alteration mineralogy (Aquater, 1996). Values of R1 >1000 Ωm are more realistic and can be seen further away from the inferred fault. The conductive "up-doming" zone (C2) with resistivity ≤ 10 Ωm at a depth of 1–5 km is interpreted as a fault (fracture zone) filled with a geothermal fluid plume. Sensitivity tests using forward modeling and inversion indicate that C2 has connection to the surface conductor C1.

The drilling of shallow and deep geothermal wells confirmed two geothermal reservoirs at the Tendaho high-temperature geothermal field (Amdeberhan, 1998; Battistelli et al., 2002). These include a shallow reservoir in the sedimentary sequence (temperature 240–250 °C, depth 300 m–500 m) and a deep reservoir in the Afar Stratoid Series basalts (260–270 °C). The deep reservoir is characterized by low permeability (Amdeberhan, 1998; Battistelli et al., 2002). Hence, targeting a fracture zone/fault (C2) in the Afar Stratoid Series basalts by directional drilling will increase the permeability and productivity of the deep reservoir. The discontinuous alignment of the surface geothermal manifestations (fumaroles, boiling mud craters, steaming grounds, and hydrothermal deposits) in a NW-SE direction (N125 °E) shows that the Tendaho geothermal field is structurally controlled (Aquater, 1996; Battistelli et al., 2002).

The low-resistivity body (C3) at a depth of > 5 km, which has a horizontal width of 15 km, is interpreted as partial melt within the Afar Stratoid Series basalts. Within the Tendaho graben, the presence of a partial melt is a plausible explanation for the enhanced conductivity. The conductive body C3 can also be considered as the heat source of the Tendaho high-temperature geothermal system. A similar upper crustal magma reservoir is also observed at Krafla and Hengill high-temperature geothermal fields in Iceland (mid-oceanic ridge) (Árnason et al., 2010; Gasperikova et al., 2011). The structure (R2) at the bottom of the cross section has high resistivity compared to C3. However, only the TM mode of the MT measurements is sensitive to the increase in resistivity and long period MT measurement is needed to fully resolve the actual resistivity of R2.

3. CONCLUSION

The surface conductive structure in the model is associated with sediments, geothermal fluids, and smectite clay alteration (Aquater, 1996). The high background resistivity at a depth of about 2 km is interpreted as Afar Stratoid Series basalts or chlorite-epidote alteration mineralogy (Aquater, 1996). Targeting the inferred fracture zone (fault) in the Afar Statoid basalts by directional drilling will likely increase the permeability and temperature of the deep reservoir. The low-resistivity structure at a depth of >5 km is related to partial melt in the Afar Stratoid Series basalts. A melt fraction of about13% by volume is a minimum estimate for this structure as calculated by Didana et al., 2014. The inferred presence of a fault with hydrothermal fluid plumes and shallow magma reservoirs, which act as heat sources, makes the Tendaho graben a promising prospect for the development of conventional hydrothermal geothermal energy. Integrating long period MT data with seismic data will help to resolve the deep mantle source for the shallow magma reservoirs.

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