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Three dimensional conductivity model of the Tendaho High Enthalpy Geothermal Field, NE Ethiopia

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ABSTRACT

Tendaho is one of the high enthalpy geothermal fields at advanced stage of exploration which is located in the Afar Depression in north eastern Ethiopia. Six deep and shallow geothermal wells were drilled in the field between 1993 and 1998. Here we present the first 3D conductivity model of the Tendaho high enthalpy geothermal field obtained from 3D inversion of magnetotelluric (MT) data. MT data from 116 sites at 24 selected periods in the period range from 0.003 s to 1000 s were used for the 3D inversion. The 3D conductivity model reveals three main resistivity structures to a depth of 20 km. The surface conductive structure (≤10 Ωm and >1 km thick) is interpreted as sediments, geothermal fluids or hydrothermally altered clay cap. The underlying high resistivity structure in the Afar Stratiod basalts is associated with the deep geothermal reservoir. At a depth >5 km, a high conductivity is observed across the whole of the Tendaho geothermal field. This structure is inferred to be the partial melt (heat source) of the geothermal system. The most striking feature in the 3D model is a fracture zone (upflow zone) in the Afar Stratoid basalts at the Dubti area, which acts as a pathway for geothermal fluids. Targeting the inferred fracture zone by directional drilling will likely increase the permeability and temperature of the deep reservoir in the basalts. Hence, the inferred presence of a fracture zone and shallow magma reservoir suggest that there is a huge potential (with temperature exceeding 270 °C at 2 km depth) at Tendaho for conventional hydrothermal geothermal energy development.

1. Introduction

The Afar Depression is an area of active extensional tectonics and volcanism where the Main Ethiopian Rift (MER), the Red Sea rift and the Gulf of Aden meet in north eastern Ethiopia (McKenzle and Morgan, 1969; Abbate et al., 1995). Tendaho is a high enthalpy geothermal field in the Afar Depression. The Tendaho geothermal field consists of three geothermal localities: Dubti, Ayerobera and Allalobeda (Aquater, 1996a). Geothermal exploration in the Afar depression and the MER was started in the 1970s (UNDP, 1973).

Several integrated geo-scientific studies have been conducted in the Tendaho geothermal field to investigate the geothermal potential of the area (UNDP, 1973; Aquater, 1979, 1980, 1996a,b). The methods used include surface geological mapping, geochemical and geophysical investigation, hydrogeological exploration and drilling temperature gradient wells (Aquater, 1996; Battistelli et al., 2002). Exploratory drilling of six shallow (500 m) and deep wells (2100 m) confirmed the existence of a geothermal resource with bottom-hole temperature in excess of 270 °C at depth of about 2 km (Aquater, 1996a; Battistelli et al., 2002). However, the geoelectric sounding technique used lacked depth of penetration beyond 1 km for delineating the deep geothermal reservoir in the Afar Stratoid basalts (Aquater, 1980).

Magnetotellurics (MT) is a method which can reliably probe to the depths needed to target geothermal reservoirs at about 2–3 km depth (Heise et al., 2007; Spichak and Manzella, 2009; Chave and Jones, 2012; Peacock et al., 2013; Muñoz, 2014). Geothermal systems are ideal targets for electromagnetic geophysical methods as geothermal fluids, partial melts and clay alteration minerals create higher conductivity that contrasts with the low conductivity of the host rock (Spichak and Manzella, 2009; Bertrand et al., 2012; Chave and Jones, 2012; Muñoz, 2014). Recent advances in 3D MT modelling and inversion codes (Mackie et al., 1994; Farquharson et al., 2002; Siripunvaraporn et al., 2005; Egbert and Kelbert, 2012) and the availability of high performance parallel computing make it possible to undertake 3D inversions of MT data. Here we present 3D inversion results from 116 MT sites along seven profiles acquired at the Tendaho high enthalpy geothermal field (Fig. 1).

2. Materials and methods

2.1. Geologic and tectonic setting

Tendaho graben is a NW–SE trending structural trough situated in the southern portion of the Erta–Manda Hararo rift system in the Afar

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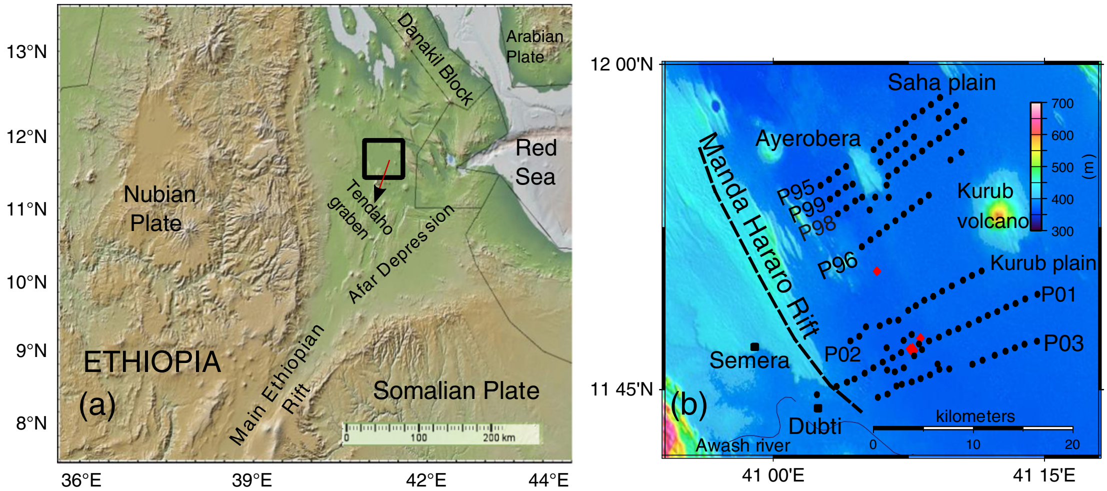

Fig. 1. Digital elevation map of Ethiopia and magnetotelluric (MT) sites of the survey area. (a) Afar Depression and the Main Ethiopian Rift. (Image from http://www.geomapapp.org). The black square survey area is expanded in Fig. 1b. (b) Seven MT profiles crossing the Tendaho geothermal field located within the Tendaho graben; red diamonds indicate geothermal wells.

depression (UNDP, 1973; Abbate et al., 1995; Aquater, 1996a, Fig. 1). It is 50 km wide and more than 100 km long from NW–SE (UNDP, 1973; Abbate et al., 1995). The margins of the Tendaho graben are comprised of the Afar Stratoid Series basalts and the rift centre is filled with lacustrine and alluvial deposits and post stratoid basalt flows (UNDP, 1973; Abbate et al., 1995; Aquater, 1996a; Fig. 2(a)). In the Tendaho region, NW and NNE trending normal faults predominate (Abbate et al., 1995; Aquater, 1996a; Fig. 2(a)); however, strike–slip faults are also observed in the area (Abbate et al., 1995; Aquater, 1996a).

The NNE trending faults most likely have played only a minor role in the evolution of the Tendaho graben, as the dominant structural elements are NW trending (UNDP, 1973). However, the intersection of these two fault trends appears to coincide with the locations of current hydrothermal activity (UNDP, 1973). Evidence for active NW striking faults includes aligned steaming grounds, fumaroles and hydrothermal deposits in the sediments within the Dubti area (Aquater, 1996a; Fig. 2(b)).

Six wells were drilled in the Tendaho geothermal field from 1993 to 1998 (Aquater, 1996a; Battistelli et al., 2002). Wells TD1, TD2 and TD3 are deep wells with depths of 1550 m, 1881 m and 1989 m, respectively (Fig. 2(a)). Wells TD4, TD5, and TD6 are shallow wells with depths of 466 m, 516 m and 505 m, respectively (Fig. 2(a). Wells TD2, TD4, TD5 and TD6 are productive. The recorded bottomhole temperature in the shallow and deep wells is in the range of 235–270 °C (Aquater, 1996b; Amdeberhan, 1998; Battistelli et al., 2002). A production test and feasibility study conducted on the shallow productive wells indicated electric power potential of about 5 MW_e and the potential of the deep reservoir in the basalts is estimated about 20–30 MW_e (Battistelli et al., 2002; Teklemariam and Beyene, 2005). According to the stratigraphy under the Tendaho graben floor revealed by geophysics and drilling, there are two major rock units (Aquater, 1996a). These are an upper unit of a thick sedimentary sequence consisting of fine to medium-grained sandstone, siltstone and clay, intercalated by basaltic lava sheets (>1 km thick); and a lower unit of basaltic lava flows of the Afar Stratoid Series.

The detailed surface geology of the Tendaho high temperature geothermal field and its surrounding was mapped at a scale of 1:50,000 with the following units identified by Megersa and Getaneh (2006): (i) a rift margin complex which consists of stratified rift margin basalts; and (ii) a rift axis complex comprised of volcanic and sedimentary sequences Fig. 2(b)).

The rift axis volcanic complex includes the Ayrobera–Semera water-laid pyroclastic and sedimentary sequence, Semera basalt, Kurub basalt, Gebelaytu rhyolitic rocks, Geblaytu scoria and Geblaytu–Asboda fresh

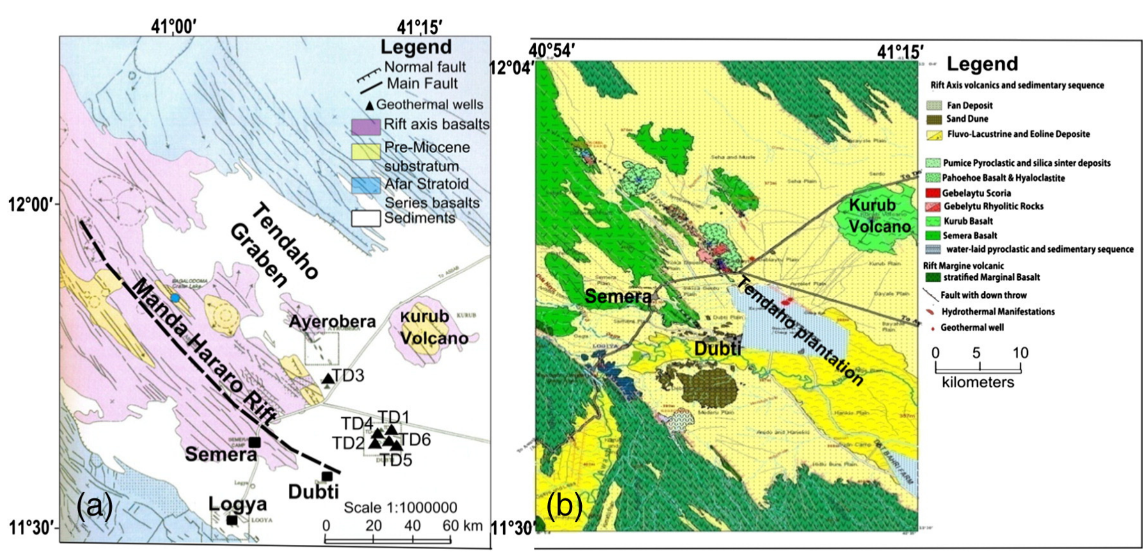

Fig. 2. Tectonic and geologic setting of Tendaho geothermal area. (a) Structural map of Tendaho (Abbate et al., 1995; Aquater, 1996a). (b) Local geology of NW Tendaho (Megersa and Getaneh, 2006).