Two-dimensional electrical resistivity model of Sabalan geothermal field using Magnetotelluric data

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SUMMARY

The Sabalan Magnetotelluric (MT) survey discussed in this paper was carried out in November 2007. MT field components in the frequency band 0.002 – 320 Hz were collected at 28 sites at an average distance of 1.4 kilometer. The selected profile with seven MT stations in the region crosses over the hydrothermally altered zones and perpendicular to the main geological structures. The subsurface resistivity structure was modeled to assess the size of the geothermal resources and to prepare conceptual model for the hydrology of the geothermal fluid reservoirs. The MT sites were projected to a line for two dimensional (2-D) modeling. Electrical resistivity and impedance phase models were computed for TM and joint TE and TM mode data. These models resolved a good correlation between the features of the geothermal field and resistivity distribution at depth. The resulting models reveal the presence of a resistive cover layer underlain by an anomalous conductive layer at about 500 -1000 m below the ground surface. A very low resistivity (3 - 5 ohm-m) feature at the depths below 2000 m, bounded by two more resistive (100 - 500 ohm-m) features that interpreted as the main heat source of the geothermal system. At shallow depths, the resistivity model obtained from the MT data is consistent with the general conceptual resistivity model proposed for high-temperature geothermal systems at literatures.

Keywords: Geothermal exploration, Magnetotelluric, 2-D inversion, Electrical resistivity, Sabalan.

INTRODUCTION

Geothermal resources are ideal targets for electromagnetic (EM) methods since they produce strong variations in underground electrical resistivity. In thermal areas, the electrical resistivity is generally lower than in areas with colder subsurface temperature (Oskooi et al., 2005). Magnetotelluric (MT) studies have been conducted over geothermal systems (Spichak et al., 2009; Heise et al., 2008).
In 1998 a dense grid of 212 MT stations carried out on the Sabalan area that highlighted its resestivity structure and the relations between conductive anomalies and the geothermal reservoir condition (Talebi et al., 2005; Fanaee et al., 2010).
The most productive areas of Sabalan geothermal field were explored in November 2007. The primary objective of this survey was to delineate any resistivity anomalies that may be associated with high temperature geothermal resources. During recent years Mount Sabalan is considered as the subject of detailed volcanological, petrological and geophysical investigations (Oskooi et al., 2016; Fanaee et al., 2021; Oskooi et al., 2015; Ghaedrahmati et al., 2013).
Figure 1 show the geological setting in Sabalan area and the broader geological and geophysical settings of the area are described by Bromley et al. (2000).

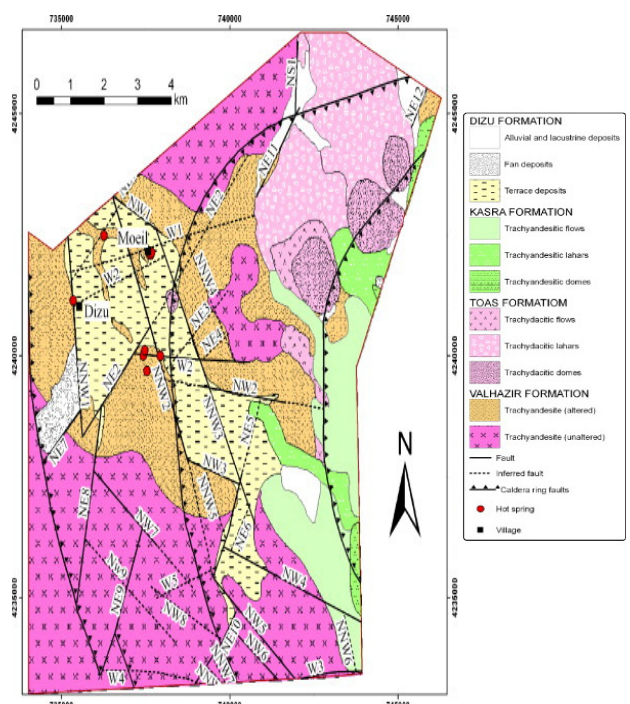

Figure 1. Simplified geological map of the study area (Emami, 1994).

METHODS

The basic principles of the MT method were introduced by Tikhonov (1950) and Cagniard (1953). The impedance tensor (Z) is defined as the relation in frequency domain between the components of the magnetic field B and those of the electric field E measured at the surface of the earth:

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \frac{1}{\mu_0} \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} B_x \\ B_y \end{pmatrix} \qquad (1)$$

indices x and y denoting magnetic North and East, μ_0 being the magnetic permeability of vacuum.

Z is usually displayed as apparent resistivity and phase which depend on the angular frequency:

$$\rho_a(\omega) = \frac{1}{\omega\mu_0} |Z(\omega)|^2 \qquad (2)$$

$$\phi(\omega) = \arctan \frac{\mathrm{Im}(Z(\omega))}{\mathrm{Re}(Z(\omega))} \qquad (3)$$

Simultaneously the variation of the vertical component (z-direction) of the magnetic field is also measured. Various skew parameters were estimated in order to analyze the dimensionality of the data. Swift's skew defined as the ratio of the on- and off diagonal impedance elements, approaches zero when the medium is 1-D or 2-D (Swift, 1967). Skew values below 0.2 in majority indicate that the study area could be approximated to a 2-D structure geoelectrically. MT sounding curves show a 2-D effect with a clear separation between the curve with the electric field parallel to the strike (TE mode) and the curve related to current circulation normal to the strike (TM mode). Skew values of the impedance strike shown in Figure 2 for the data from almost all sites and frequencies.

In cases where MT data display overall 2-D characteristics despite some 3-D effects, results obtained using 2-D inversion algorithms can be valid (Ledo, 2005).

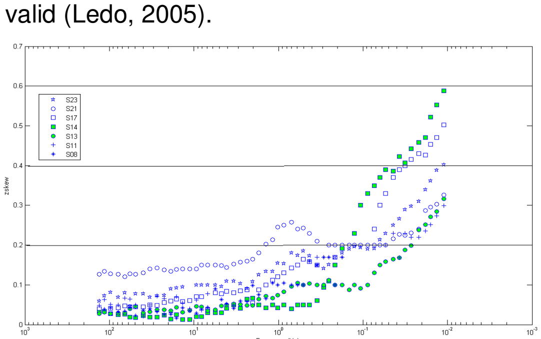

Figure 2. Variation of Swift's skew values (dimensionality factor) for all sites along the profile.

To obtain the subsurface structure along the profile, 2-D inversion code of REBOCC by Siripunvaraporn and Egbert (2000) was used. The code seeks a smooth model with the minimum amount of features required by the data. The data points were carefully selected between frequency ranges 0.002–320 Hz. The inversion started from a homogeneous half space with resistivity of 100 ohm-m.

In the inversion, apparent resistivity and phase data of both TE and TM modes were used. Reasonable RMS misfit was achieved usually after 10 iterations. The MT transfer functions along the strike (TE-mode) and orthogonal (TM-mode) directions were inverted simultaneously, to derive the 2-D subsurface resistivity distribution. Static shifts were not corrected at this stage of the work, as we were missing shallow subsurface information. However, apparent resistivity data on most sites show little difference between the two polarization curves at high frequencies and vary smoothly passing from one site to the next. Several inversions were performed of the TM and joint TM+TE modes. Since TM mode typically suffers less 3-D distortion than TE (Wannamaker et al., 1984), some inversions took into account only the TM mode data. The apparent resistivity was down-weighted during the inversion process to help to accommodate the possible static shift effects in the data. Error floor of 20% for the apparent resistivity and of 5% on the phase were assumed.

RESULTS

The inversion result of TM mode data is shown in Figure 3, respectively. By these levels of error on the data, the fit of the computed model response to the observed data was satisfactory (Figure 4). The resistivity and layer thickness of the obtained models depend on the mode used for the inversion. The normalized root mean square (rms) misfit was around 3 for obtained models.

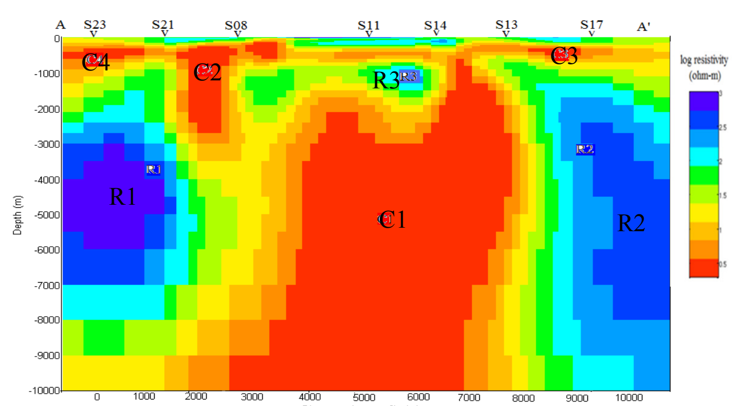

Figure 3. The resistivity model resulting from the inversion of TM mode data. C; conductive, R; resistive features.

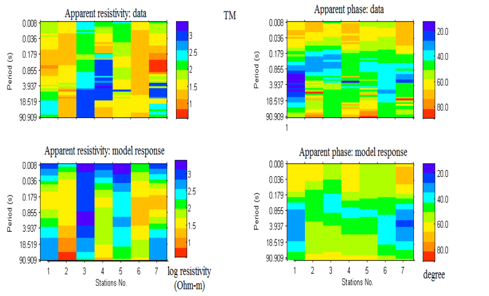

Figure 4. TM-mode data and model responses of the 2-D inversion.

The resulting model and data misfit for joint TE and TM-mode data is shown in Figure 5 and Figure 6.

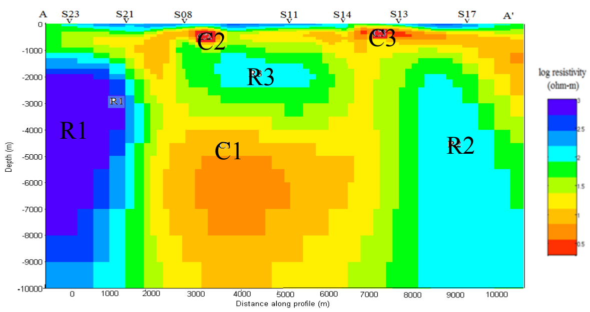

Figure 5. The resistivity model resulting from the joint inversion of TM and TE mode data.

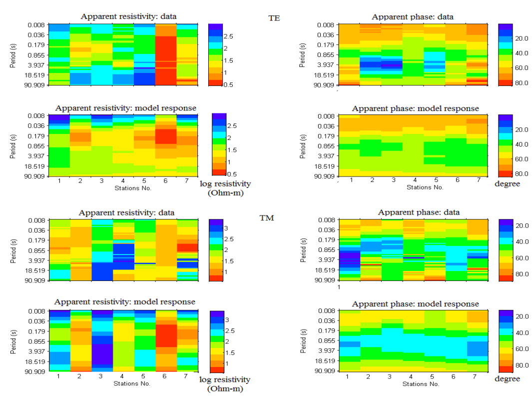

Figure 6. The TE and TM mode data and model responses from the joint inversion results.

DISCUSSION

In our case study, the inversion provides the valuable results. The prominent structures in the obtained resistivity models (Figure 3 and Figure 5) are discussed below:
A resistive layer (>400 ohm-m) is recognized at the top. At depth 300-1300 m there is a resistive feature (R3) among three separate conductive bodies (C1, C2, C3).

Conductive bodies show variable thicknesses along the 2D section, passing from a few hundred meters above R3 to about 3000m at C2. Below these conductors there is an increase of resistivity with depth along the whole profile, except under sites 8, 13 and 14, where the resistivity is always lower than a few tens of ohm-m in depth (<10 ohm-m). The opposite ends of the profile are characterized by a high resistivity (1000 ohm-m) structure, whereas in the middle of the profile the conductive feature, C4, (<10 ohm-m) is followed by a resistive layer R3 (>100 ohm-m), which in turn is overlying a very conductive structure C1 (<5 ohm-m).
The conductive structure is clearly constrained to the central part of the profile. The uppermost 0.5–4 km of the obtained 2-D resistivity structures is fairly like the previous results from 1998 MT data modeling (Fanaee et al., 2011). There is a highly conductive (<5 ohm-m) structure at depth of about 2.5 km in the middle of the profile. Most naturally magmatic intrusions acting as a heat source for the geothermal system, although there are no temperature data to confirm the presence of magma in Sabalan area. Another peculiar feature is the area beneath sites 8,21 and sites 13,14, where the 2-D model shows an abrupt transition to moderate resistivity values down to depths of 2-3 km where the deep conductive body begins. Most probably, an almost vertical fluidized or altered fault zone connecting the shallow and deep conductors together.

CONCLUSIONS

The magnetotelluric method and its ability to map deep conductive features, can make a valuable role in the reconnaissance of deep geothermal systems. A pilot MT survey was carried out in the Sabalan area, deploying seven broadband sites along a nearly 10 km profile. 2-D inversion results show conductivity models with stable features, identifying the main geological units. Analysis of the different skew parameters indicates that the impedances are well described in terms of 2-D models. Some deviations from 2-D behavior were noted for the data of some frequencies and sites where misfits were relatively large. The final 2-D model was stable and not depending on the a priori or starting models. Generally, the main result is that the two-dimensional electrical resistivity model is perfectly comparable to the structures found in literature as conceptual resistivity model of a high-temperature geothermal system (Berktold, 1983).

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