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Two-Dimensional Magnetotelluric Modeling of the Sabalan Geothermal Field, North-West Iran

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Abstract

During 2007, a magnetotelluric (MT) survey in the frequency range of 0.002-320 Hz was carried out on southwestern of Sabalan geothermal region (Moeil valley, Ardabil); the aim of which was modeling of the shallow and deep electrical resistivity structures related to the local geothermal reservoirs and heat system recharge at depth. Twenty eight soundings were conducted in the study area, and the collected MT data were found to be two-dimensional (2D), based on dimensionality (skew parameter) analysis. The NNW-SSE (30°W) direction was identified as the dominant electrical strike in the area. Data along a profile crossing the hot springs with seven MT stations, have been implemented for modeling and inversion. Dimensionality analysis shows that a 2D interpretation of the data is justified, although the presumed geoelectric strike direction is not consistent over the whole profile and frequencies. MT data were analyzed and modeled using MT2DInvMatlab inversion source codes and the finite elements (FEM) method for forward modeling. Inversion parameters as an input file and appropriate mesh blocks design are prepared before start of the modeling and inversion. MT2DInvMatlab software includes a topography file into a forward model for terrain effects compensation in the inversion process. After setting up the model parameter, 2D inversion of the Sabalan magnetotelluric data was performed. Smoothness–constrained least square methods with a spatially regularization parameter estimation and the ACB (Active Constraint Balancing) algorithm were employed in MT2DInvMatlab to stabilize the model. Both apparent resistivity and phase data were used to have models with minimum misfit for TM, TE and joint TE+TM mode data. The TM mode apparent resistivity and phase are better fitted than the TE mode, as a consequence of the inductive nature of the 2D TE response in a 3-D geothermal field structures. However, the apparent resistivity and phase data are also well fitted in the joint inversion of TM and TE mode data. Although the TM mode data is often used for 2-D modeling of MT data in geothermal field studies, we have shown the other two dimensional electrical resistivity models, using apparent resistivity and phase data of TM, TE and joint TE+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 (Cap-rock) underlain by an anomalous conductive layer and other geological structures such as fluid-filled faults (about 500-1000 m below the ground surface). A very low resistivity (3-5 ohm-m) feature was found at the depths below 2000 m, bounded by two more resistive (100-500 ohm-m) features that can be interpreted as the main reservoir of the geothermal system in the area. 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. The deeper electrical structure was found to be more resistive (100 ohm-m) due to the presence of metamorphic rock formations. According to this results, heat source of the geothermal structure and heat transition zone from deep sources to shallow reservoir, is predicted at 2~7Km at depth.

Keywords: Magnetotellurics, Geothermal, Reservoir, MT2DInvMatlab, Sabalan.

1. 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 substantially different from and is generally lower than areas with colder subsurface temperature (Oskooi et al., 2005).

The investigation depth of the Direct Current (DC) Geoelectric and Time Domain ElectroMagnetic (TEM) methods is inadequate in areas where the geothermal circulation and related alteration takes place at depths of more than 1.5 km, and the Magnetotelluric (MT) method appears to be the most suitable survey method.

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MT studies have been conducted over crystalline rocks from shallow to deep crustal scale (Unsworth et al., 2005) for several purposes such as the imaging of fault and shear zones (Bedrosian et al., 2004), geothermal systems (Manzella, 2004; Heise et al., 2008) and mineralizations (Heinson et al., 2006). In 1998, a dense grid measurement of 212 MT stations in the frequency range of 1-8192 Hz was carried out on the Sabalan area that highlighted its resistivity structure and the relations between conductive anomalies and the geothermal reservoir condition (Talebi et al., 2005; Hafizi et al., 2002; Bromley et al., 2000; Fanaee Kheirabad et al., 2010).
The most productive areas of Sabalan geothermal field were explored in November 2007, to investigate any consistency between the resistivity models of the area and the conceptual resistivity model presented for high temperature geothermal fields.
Figure 1 shows a conceptual model and the main elements of high-temperature type of geothermal systems (Berktold, 1983).
The conceptual system is fed by fluid circulation through fractures and faults and heated by the molten magmatic chamber of a volcanic system. Resistivity in geothermal areas is related to the contain clays and the presence of hydrothermal alteration products. Clay minerals in natural environments are found from surface to metamorphic and hydrothermal conditions. The electrical resistivity can be reduced considerably when the clay minerals are distributed broadly (Spichak and Manzella, 2009).
The distribution of alteration minerals depends on the permeability of the area. When permeability is created by fractures and faults, such as in the Amiata area in Italy, then alteration minerals are localized and the change in electrical resistivity in the most parts is linked to the presence of hydrothermal fluids and partial melts (Volpi et al., 2003).
High-temperature geothermal systems, usually occur where magma intrudes into high crustal levels (<10 km), and hydrothermal convection can take place above the intrusive body (Ander et al., 1984; Mogi and Nakama, 1993).

2. Geological settings and prior electrical resistivity surveys in Sabalan area

Tectonic studies indicate that the Iranian Plateau is transected by closely spaced active and recent faulting, dominated by reverse faults (Berberian, 1981). Structurally, Sabalan area is located in a very complex and compressional tectonic zone, on the NE moving South Caspian sub-plate, near the junction of the Eurasian, Iranian, and Arabian plates. The systematic evaluation on geothermal resources of Iran was carried out in the 1970's. The previous studies resulted in an introduction to four major prospecting areas including Damavand, Sabalan, Khoy-Maku and Sahand geothermal fields. After the preliminary introduction of Sabalan geothermal field in the 1980's, complementary surveys in Sabalan were carried out (ENEL, 1983). Further exploration began in 1995 based on evidences that the region offered strong potential for power generation development. Detailed geological, geochemical and resistivity surveys using MT, TEM and DC Schlumberger methods have been carried out by Kingston Morrison Ltd (KML, 1998). In January 1998, 212 magnetotelluric (MT) stations using coincident TEM measurements, plus a DC resistivity survey were acquired over the flank of the Sabalan geothermal system. The primary objective of this survey was to delineate any resistivity anomalies that maybe associated with high temperature geothermal resources. During recent years, Mount Sabalan has been the subject of detailed volcanological, petrological and geophysical investigations. The geological setting in the Sabalan area is discussed in detail, and the broader geological and geophysical settings of the area are described by Bogie et al. (2000). The Sabalan geothermal field is a water-dominated system, with temperature reaching 270 °C at depth, which is exploited for the production of electric power (Talebi et al., 2005). The distribution of geothermal systems and their associated resistivity structures have already been studied by Yousefi et al. (2009).

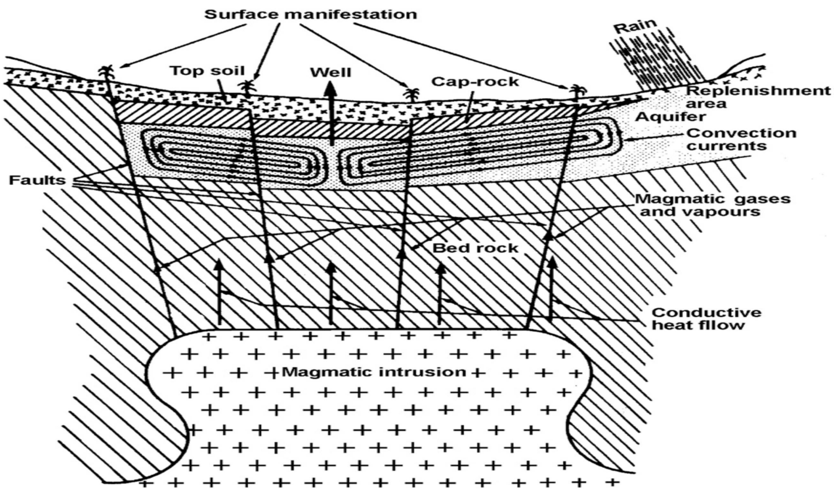
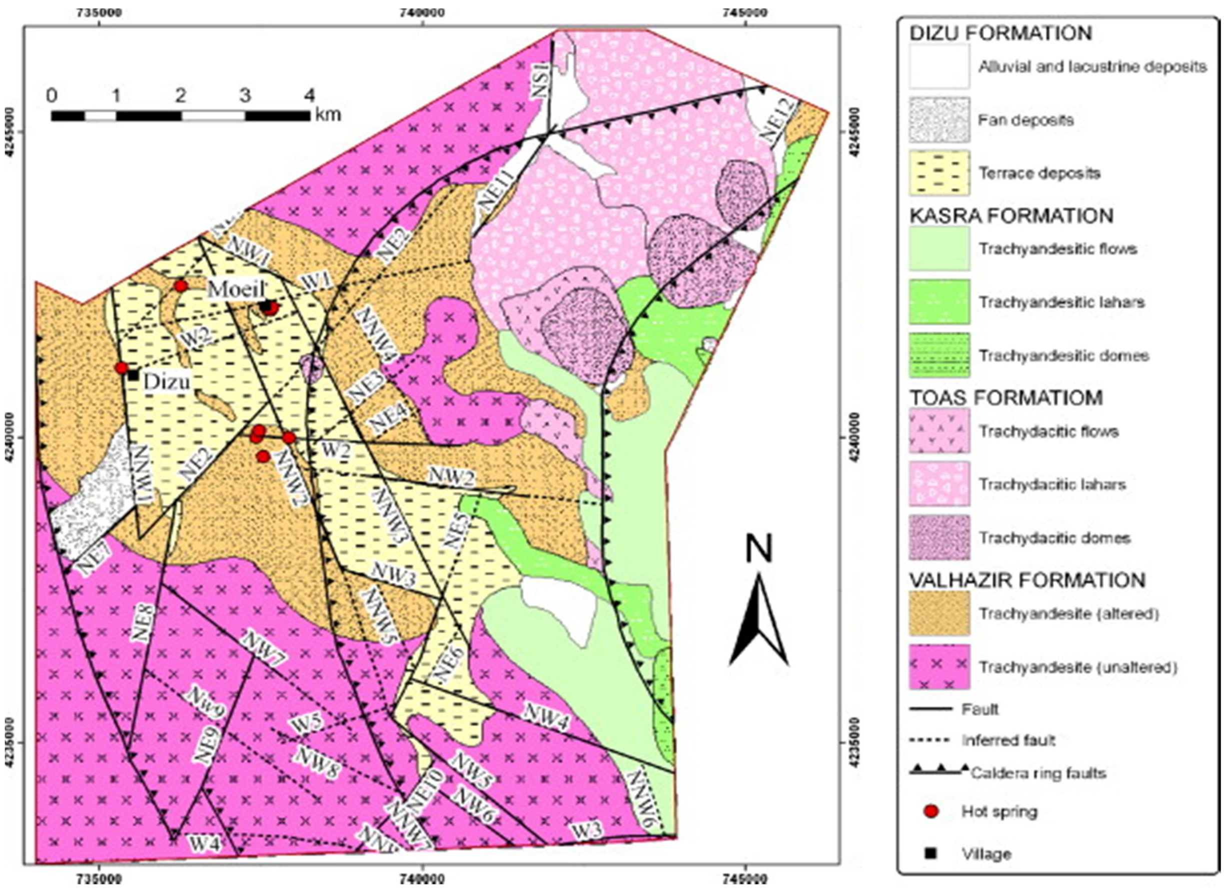
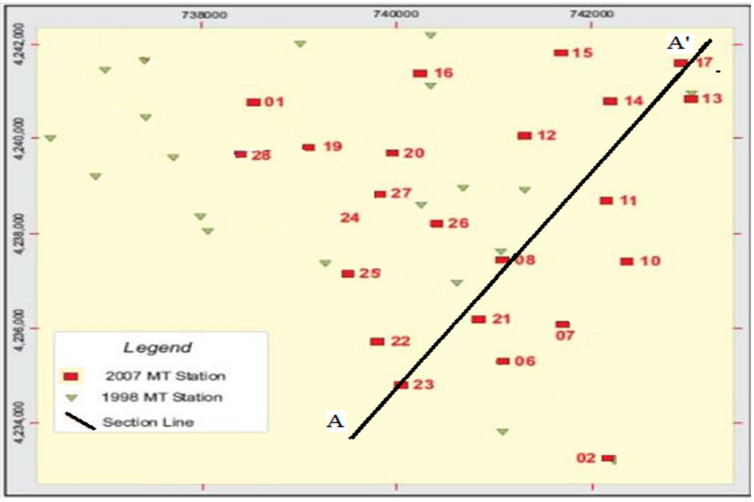


Figure 1. Conceptual resistivity model of a hyper-thermal field (after Berktold, 1983).

The Sabalan MT survey discussed in this paper was carried out in November 2007. MT field components in the 0.002–320 Hz frequency range, were collected at 28 sites. The selected profile (A-A') with seven MT stations at an average distance of 1.4 km in the region, crosses over the hydrothermally altered zones, which is perpendicular to the main geological structures shown in Figure 2. The MT sites were projected to a line for 2D modeling. The study area (Moeil valley) has some topographic relief, but all the MT sites were positioned at almost the same altitude, at an adequate distance in order to reduce topographic distortions.



(a)



(b)

Figure 2. Geological map (KML, 1998) of the Mt. Sabalan area (a) and the MT sites distribution (red square) in the area (b). The selected profile in the study area is shown as Line A-A'.

Bogie et al. (2005) provided a 2D resistivity section across the northern part of the geothermal reservoir in the area, which clearly evidenced the characteristics of a high-temperature geothermal system. Their 2D models gives a clear picture of the resistivity changes both laterally and with depth, and their relation to alteration clay minerals in the upper crust.

Magnetotellurics has been widely used in the study of volcanoes and geothermal systems considering electrical resistivity changes is expected in these structures due to hydrothermal fluids circulation (Heise et al., 2008; Muller and Haak, 2004).

3. Basic Concepts

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:

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

where, indices x and y denote magnetic North and East, and μ_0 is the magnetic permeability of vacuum. Z is usually displayed as apparent resistivity (ρ_a) and phase ($\emptyset$), which depend on the angular frequency (ω):

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

$$\emptyset(\omega) = arctan \frac{Im(Z(\omega))}{Real(Z(\omega))} \quad (3)$$

The high conductivity of the shallow subsurface prevents using direct current (DC) resistivity methods since the penetration depth is limited to the top of the first conductive unit. The MT method for mapping near surface low-resistivity zones caused by conductive fluids circulation in geothermal areas has proved very useful (Wannamaker et al., 2002).

4. Data processing

MT data at all sites is rotated to give the best estimation of the two dimensional MT transfer functions over the frequency range, using a standard robust processing algorithm in Winglink software (Geosystem, 2003). The available Sabalan MT data set has a good quality and do not require a special processing. The data along selected profile were of very good quality and noise level is not high for two selected sites, S14 and S17 shown in Figure 3. Data curves reveal that the quality is fairly consistent and high in observed apparent resistivity and phase data plotted for TE and TM mode as an example data.

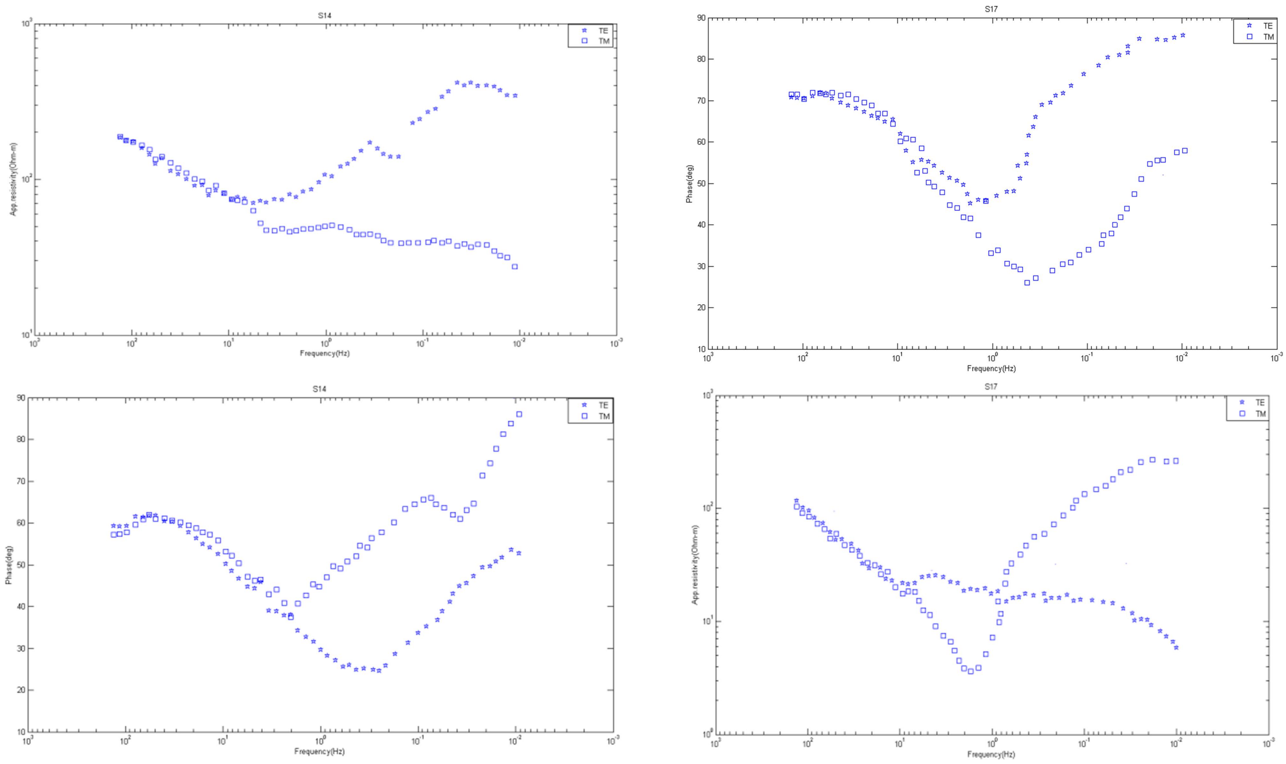


Figure 3. Example of data: Site 14, on the left and the Site 17, on the right TE and TM mode data curves.

The static shift problem arises from local resistivity perturbations that mainly affect the electric fields, causing a frequency independent shift of the apparent resistivity curves, while phase data, on the other hand, are not affected (Bertrand, 2010). The static shift of MT data is usually corrected by an independent geophysical method close to the MT site in order to determine apparent resistivity at high frequencies. Such a procedure was followed by other researchers (Brasse et al., 2002; Patro et al., 2005) as well.

In order to analyze the dimensionality of the data various skew parameters were estimated. Swift’s skew, defined as the ratio of the on and off diagonal impedance elements that approaches zero when the medium is 1D or 2D (Swift, 1967).

Skew values below 0.2 normally indicate that the study area could be approximated by a 2D structure, geoelectrically. MT sounding curves show a 2D effect with a clear separation between the curve where the electric field parallel to the strike (TE mode), and the curve is related to current circulation normal to the strike (TM mode).

Dimensionality analysis of the impedance tensor was performed to check the reliability of the 2D modeling along the profile. Early models (Swift, 1967; Zhang et al., 1987; Bahr, 1988) estimate the geoelectric strike from a minimization criterion through the rotation of the observed impedance tensor. Groom and Bailey (1989) proposed a tensor decomposition model that uses an inversion scheme to remove the non-inductive responses from the impedance tensor. The algorithm was extended by McNeice and Jones (2001) to statistically fit an entire data set simultaneously, based on factoring the distortion tensor into determinable (twist and shear) and non-determinable (anisotropy and site gain) components. Tensor decomposition is commonly used for distortion removal and to determine the geoelectric strike for assumed two-dimensional MT data. The singular value decomposition of the impedances is applied to obtain the maximum and minimum impedance amplitude and phase. Prior to the 2D modeling of MT data, the characteristics of the geoelectric strike direction of the subsurface structures, as defined by MT data, are derived. The results show small swift’s skew values (<0.2), which indicate that the underlying resistivity structure is 1D or 2D. Figure 4 shows the skew values of the impedance strike for all sites and frequencies.

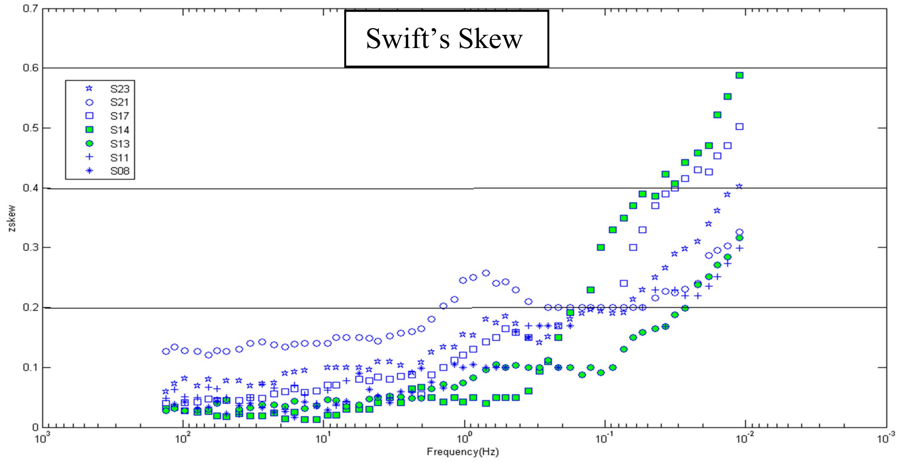


Figure 4. Variation of dimensionality Swift's skew values for all sites along the profile.

The data at some sites and frequencies show high skew values that are originated from either galvanic distortion or 3D subsurface structures. In cases where MT data display an overall 2D characteristics despite some 3D affects, results obtained using 2-D inversion algorithms can be valid (Ledo, 2005).

5. Resistivity Structure and Interpretation

To obtain the subsurface electrical resistivity structure, 2D inversion code MT2DinvMatlab (Lee et al., 2009) was used for seven MT sites along the profile. It is an open source MATLAB based software package for two dimensional (2D) inversion of magnetotelluric (MT) data that prepares a smooth model with the minimum number of prior information required to fit the observed data. Forward modeling in MT2DInvMatlab uses the finite elements (FEM) method in order to calculate 2D MT responses of the models. Regularization parameter estimation algorithm by Yi et al. (2003) for smoothness constrained least squares inversion with ACB (Active Constraint Balancing) algorithm has been implemented to obtain an optimal smoothness constraint. Also, topography or site elevation into a forward model by deforming rectangular elements to quadrilateral elements is available in MT2DinvMatlab package.

Apparent resistivity and the phase data were included for 2D modeling, but the topography (elevation) of the sites is ignored and excluded from inversion process. The MT transfer functions along the strike (TE-mode) and orthogonal (TM-mode) directions were inverted simultaneously to derive the 2D subsurface resistivity distribution. Static shifts were not corrected at this stage of the work, as we were missing other 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. Therefore, based on the similarity among the MT curves of adjacent sites, modeling and inversion were performed on the TE, TM and joint TM+TE mode data. The normalized root mean square (R.M.S) or data misfit error achieved after 10 iterations was around 0.7 for all data sets. The apparent resistivity and phase data and model responses from the inversion results of all data sets are shown separately. Resistivity model from the TM mode data inversion is shown in Figure 5.

Since TM mode typically suffers less by 3D distortion than TE mode (Wannamaker et al., 1984), some inversions consider only the TM mode data.

The inversion of TE mode data are shown separately in Figure 6. The results show a fairly good agreement between the observed data (Field Data) and model responses (Theoretical Data) along the profile. The resistivity and thickness of the obtained models depend on the mode used for the inversion. The resulting model for joint TE and TM mode data, as well as the inversion of TE and TM mode data are shown in Figure 7.

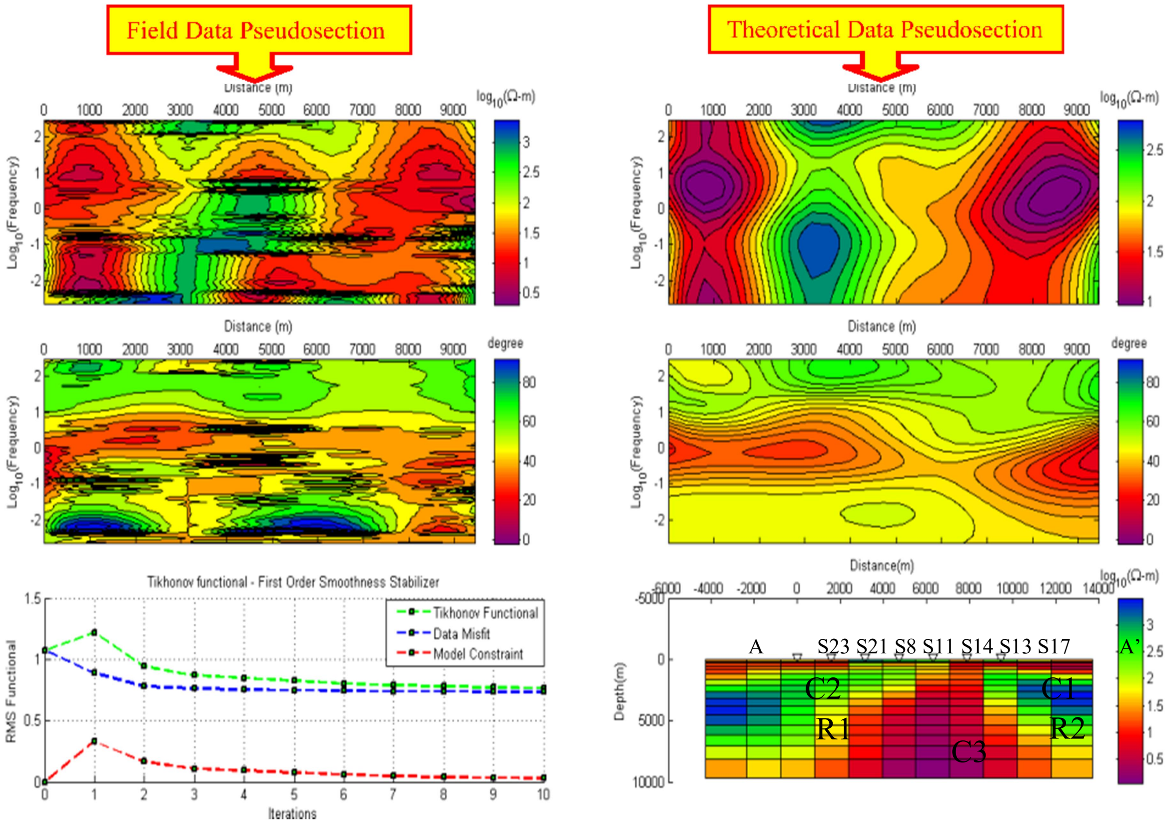


Figure 5. The electrical resistivity model resulting from the inversion of TM mode data.

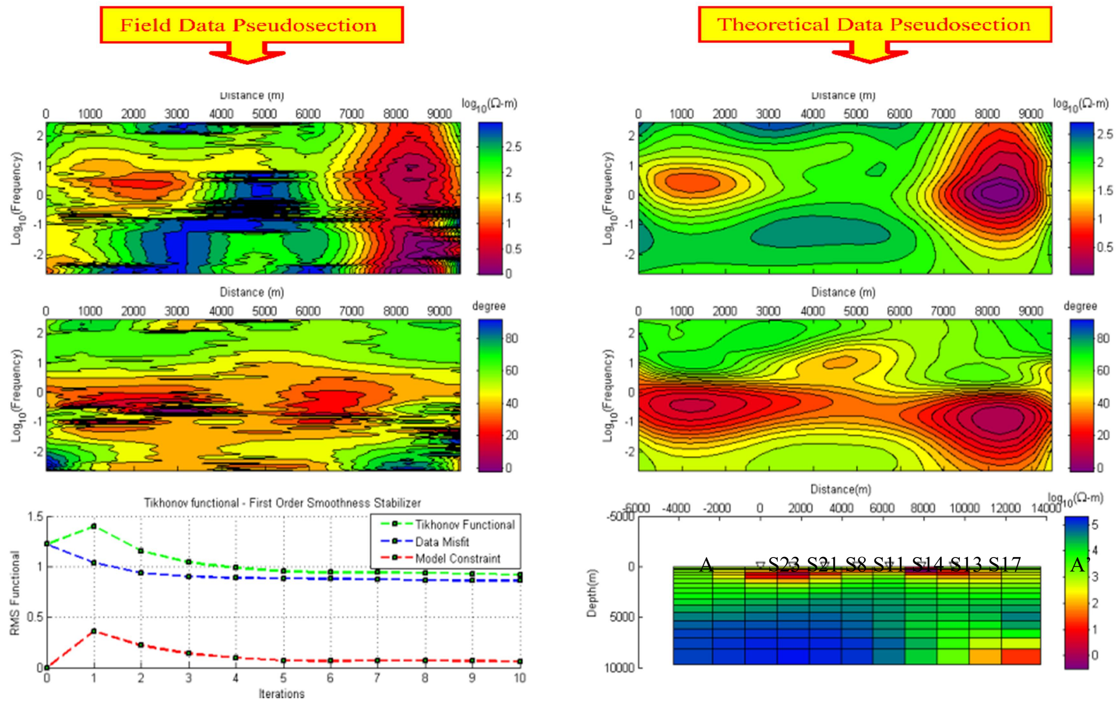


Figure 6. The electrical resistivity model resulting from the inversion of TE mode data.

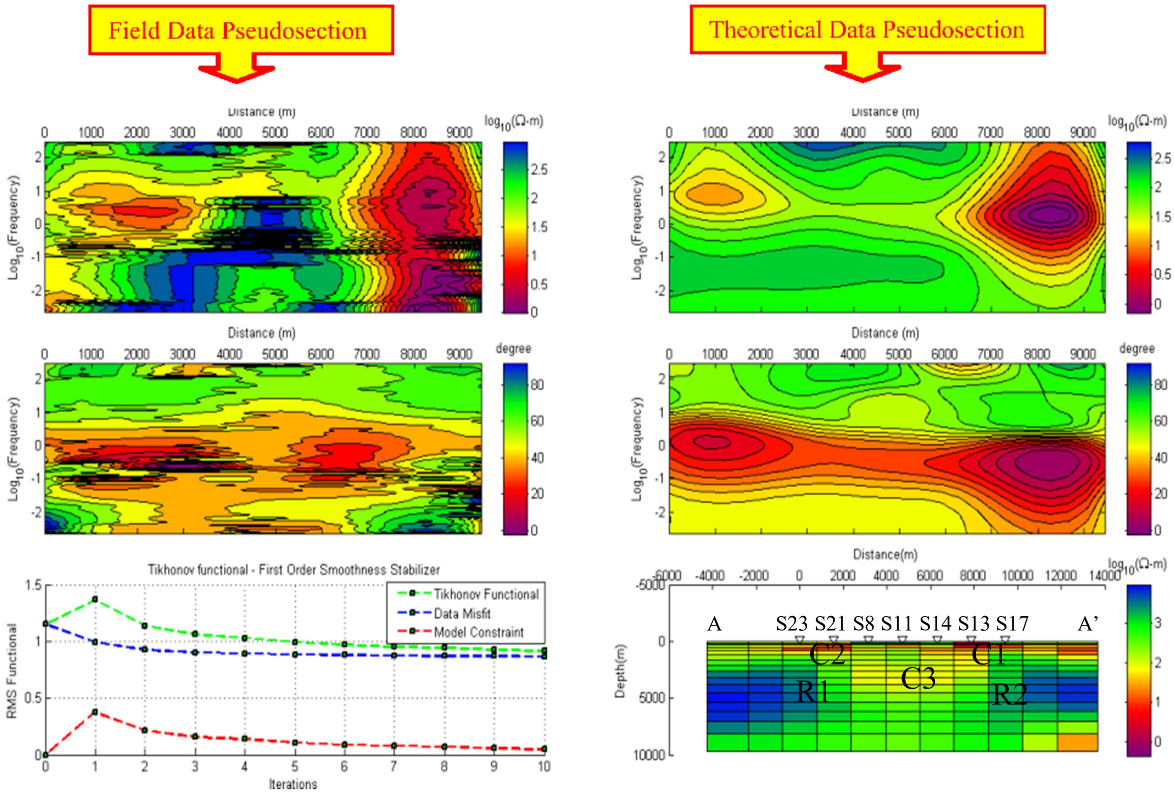


Figure 7. The electrical resistivity model resulting from the joint inversion of TM and TE modes.

TM mode data in a 2D inversion is simply fitted by model responses even for 3D –like structures and is often utilized for 2D inversion in geothermal energy investigation (Uchida et al. 2002; Oskooi et al., 2015; Ghaedrahmati et al., 2013). Also, in the case study in Sabalan geothermal area, the TM mode data inversion provides the best model with minimum misfit from apparent resistivity and phase data. The prominent structures in the resistivity model of TM mode data in Figure 5 and its relevance to the geothermal field are discussed below.

A resistive layer (>400 ohm-m) is recognized at the top of the model as the first layer at the earth surface in Figure 5. Between the 300 m and 1300 m depths (second layer), there are three separate conductive features (C1, C2, C3) between two resistive intrusive bodies (R1, R2). Conductive bodies show variable thicknesses along the 2D section, ranging from a few hundred meters above C1 and C2 to about 1300 m at C3. Below these conductors, there is an increase in resistivity with depth along the whole profile, except under sites 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 is characterized by a high resistivity (~1000 ohm-m) basement at depth, whereas in the middle of the profile the conductive feature C3 (<10 ohm-m) is followed by resistive layers (30–1000 ohm-m), which in turn is overlying a very conductive structure C3 (<5 ohm-m). This conductive structure is clearly constrained to the central part of the profile. The uppermost 0.5–4 km of the obtained 2D resistivity structures is fairly like the previous results from 1998 data modeling (Talebi, 2006; Fanaee Kheirabad and Oskooi, 2011; Oskooi et al., 2016).

6. Discussion and conclusions

The magnetotelluric method, with its ability to map deep conductive features can present a valuable role in the reconnaissance of deep geothermal systems in many geothermal areas of the world.

MT survey was carried out in the Sabalan area, deploying seven broadband MT sites along a nearly 10 km profile. In this paper, electrical resistivity models were interpreted in order to assess and recognize the location and depth of the three main parts of the Sabalan geothermal system, introduced in general conceptual geothermal models.

Analysis of different skew parameters indicates that the impedances are well described in terms of a 1D or 2D model. Some deviations from 2D behavior were noted for the data of some frequencies and sites where misfits were relatively high. 2D inversion yielded conductivity models with stable features, identifying the geothermal reservoir and related geological units.
2D inversion of the data is performed by using the MT2DinvMatlab code for TM, TE and joint TE and TM mode data. The resistive layer at the surface can clearly be interpreted as the geothermal system cap rock. There are remarkable signatures in obtained models that show the subsurface conductivity variations at depths.
The results of this study indicate that three conductive zones are present beneath the surface and suggest that a deep hydrothermal fluid circulation exists in this area. Estimated depth range of the reservoir is from 500 to 1000 m that is the center of flow of the fluids in the fractures of the rocks, which is saturated with penetrating hot water. The geothermal reservoir is connected at depth to a deeper conductor, representing the heat source of the system. The main result of the paper is that the electrical resistivity models in Sabalan area is perfectly comparable to the structures found in literature as conceptual resistivity model of a high temperature geothermal system, and MT survey provided very encouraging information about the resistivity structure of Sabalan geothermal field.

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