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Magnetotelluric interpretation of the Sabalan geothermal field in the northwest of Iran

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Abstract

In this paper, fourteen MT stations along a profile perpendicular to the main geological structure were used in order to identify the geology of Sabalan geothermal field including the extension of the surface cap-rock and clay-cap layers. The MT data collected between 1-8192 Hz is of useful quality and provides good control on the surface layers in many areas. It means that reliable modeling should be possible to a depth of 1000 m depending on resistivity distribution. TE and TM-mode data and skew parameter show that the earth dimensionality differs from site to site, so we examined the 1D and 2D modeling along the profile. To have the best possible interpretation we used determinant data for 1D modeling and joint TE and TM-mode data in 2D modeling. The data was processed and modeled using an improved modeling method. One-dimensional modeling was performed using a forward operator based on reflection coefficient of the layers (Zhadanov and Keller 1998) and the two-dimensional inversion has been done by using a code from Siripunvaraporn and Egbert (2000).The resulting 1D and 2D models show a high–very low–low resistivity sequence with depth. The high resistive layer at the surface was assigned to basalt, andesitic and old trachyandesitic flows and other impermeable rocks that have thermal conduction and act as the cap-rock of the system. The role of the cap-rock is very important in sustainability of the system, because it prevents the reservoir from cooling by mixing with surface water. The second layer is a very conductive layer and is interpreted as the reservoir that has thermal convection and hot fluids contained in its fractures and pores. The resistive basement is a hot and solid magmatic intrusion and is interpreted as a heat source that produces a conductive heat flow towards the reservoir. As a result, the shallow resistivity model of the Sabalan area is in a good correlation with the geological features. It shows the common conceptual resistivity model which has been presented for the geothermal reservoirs.

Key words: Magnetotelluric, Geothermal, Reservoir, 1D and 2D modeling , Sabalan, Iran

تفسیر داده‌های مگنتوتلوریک میدان زمین‌گرمایی سبلان واقع در شمال غرب ایران

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چکیده

در این مقاله مدل‌سازی و تفسیر داده‌های مگنتوتلوریک ۱۹۹۸ منطقه زمین‌گرمایی سبلان با هدف بررسی و تعیین وضعیت مقاومت ویژه در لایه‌های فوقانی مخزن حرارتی به‌ویژه سنگ‌پوش مخزن صورت پذیرفته است. برای این منظور یک نیم‌رخ از داده‌ها به طول تقریبی ۱۳ کیلومتر عمود بر ساختارهای اصلی زمین‌شناسی در جنوب مشکین‌شهر (منطقه موئیل) انتخاب و مدل‌سازی روی داده‌های

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۱۴ سایت در امتداد آن صورت پذیرفته است. برای مدل‌سازی یک‌بُعدی ، برنامه‌ای به زبان مطلب و براساس رهیافت مبتنی بر محاسبه ضرایب بازتاب موج الکترومغناطیس از لایه‌ها (ژادانو و کلر، ۱۹۹۸) تنظیم شده است و برای مدل‌سازی دوبُعدی از برنامه REBOCC (سریپون وارایورن و ایگبرت، ۲۰۰۰) استفاده شده است.

تعیین وضعیت سنگ‌پوش مخزن در تحقیقات زمین‌گرمایی از اهمیت بسزایی برخوردار است، به‌طوری که بررسی آن می‌تواند در تعیین تجدید پذیری سامانه زمین‌گرمایی و پیشنهاد محل حفر چاه‌های اکتشافی، بسیار مفید واقع شود. به‌منظور توضیح ساز وکار مخازن زمین‌گرمایی تاکنون چند مدل فرضی جهانی عرضه شده است که هریک از این مدل‌ها برای تفسیر پدیده زمین‌گرمایی در منطقه خاصی معتبر است. نتایج به‌دست آمده از مدل‌سازی یک‌بُعدی و دوبُعدی داده‌ها در این تحقیق بیانگر وجود الگوی مقاومت ویژه زیاد- خیلی‌کم- زیاد در منطقه سبلان است که با مدل جهانی عرضه شده فعلی در توافق است.

واژه‌های کلیدی: مگنتوتلوریک، زمین‌گرمایی، مخزن، مدل‌سازی یک و دوبُعدی، سبلان، ایران

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 generally lower than in areas with colder subsurface temperature (Oskooi et al., 2005). Electromagnetic methods have been developed and employed to recognize the geothermal fields in many regions. Due to its lateral resolution and also greater depth penetration, the MT method is one of the effective electromagnetic techniques to electrically image the subsurface structures.

Magnetotelluric transfer functions are calculated from measurements of horizontal electric and magnetic fields at the surface of the earth and can image the subsurface electrical resistivity. MT data were collected and interpreted over the entire Sabalan volcano located in Ardebil Province in the northwest of Iran. The selected MT profile in the region crosses over the hydrothermally altered zones and different geological structures (Fig.1). Based on the results of the other geophysical research and reports (KML, 1998), we selected the MT profile in the Moil Valley region as our study area.

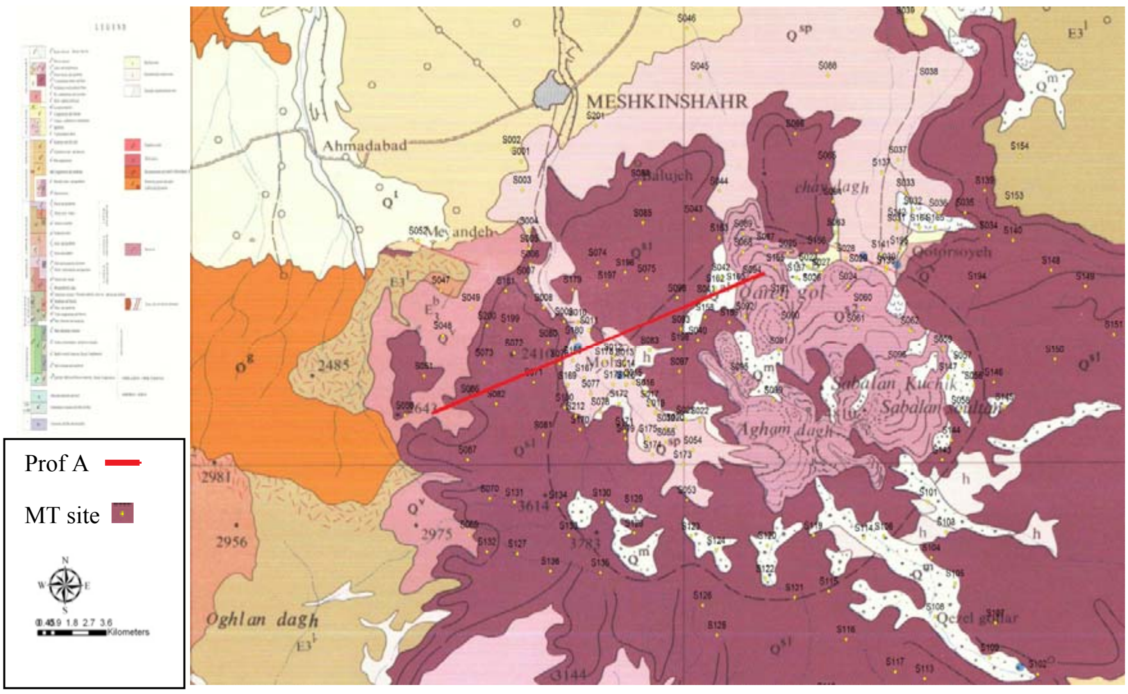

Figure 1. The geographic location of Sabalan in Ardebil province and the distribution of MT sites on the simplified geological map of Sabalan.

2 PREVIOUS WORKS

The systematic evaluation on geothermal resources of Iran was carried out in the 1970's which resulted in the introduction of four major prospects including Damavand, Sabalan, Khoy-Maku and Sahand geothermal fields. Gravimetric surveys in Sabalan were carried out by, the Ente Nazionale per l'Energia eLettrica Company (ENEL, 1983).

After the preliminary introduction of the Sabalan geothermal field in the 1980's, further exploration began in 1995 based on evidence that the region might offer 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 1998 the Renewable Energy Organization of Iran (SUNA) completed a resistivity survey consisting of D.C., TEM and MT measurements and finally three exploration wells were proposed the in Sabalan area. The magnetotelluric (MT) survey in Sabalan was conducted by New Zealand Institute of Geological and Nuclear Sciences (GNS) and two hundred and twelve MT stations were recorded in 1998.The broader geological and geophysical settings of the area were described by Bogie et al. (2000) and Bromley et al. (2000). The 2D inversion of Sabalan 1998 MT data using Occam's inversion codes show a geothermal model with a 100 ohm-m cap-rock overlaying a 5 ohm-m reservoir (Hafizi et al., 2002).

3 CONCEPTUAL MODELS OF GEOTHERMAL AREAS

Typically, when fluids are tapped at the surface either by natural manifestation or through drilling, hot water or steam is produced and its energy is converted into marketable products (electricity, process or space heat). A hydrothermal system is made up of three main elements: a heat source (very often represented by a magma chamber or intrusive bodies), a reservoir (i.e. a constituent host rock and the natural fluids contained in its fractures and pores), and a cap rock, i.e. a low permeability layer which restrains the main fluid flow at a depth where the temperature is high and is prevented from cooling by mixing with surface water (Spichack and Manzella, 2009).

In geothermal areas where the permeability is high and alteration is pervasive, the conceptual model of the reservoir shown in Fig. 2 is appropriate. Reservoirs of this type have been found, for example, in Iceland, New Zealand, El Salvador, Indonesia and Japan (Oskooi et al., 2005).

In this model, the lowest resistivity corresponds to a clay cap overlying the geothermal reservoir, while the resistivity of the reservoir itself may be much higher.

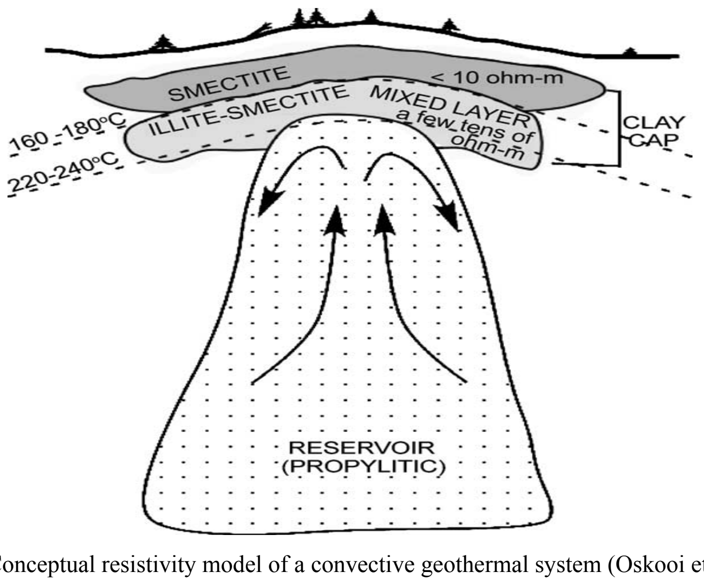

Figure 2. Conceptual resistivity model of a convective geothermal system (Oskooi et al., 2005).

When topography is steep and a significant hydrological gradient is present in the subsurface, the overall structure of the geothermal system is more complex (Fig. 3).

The conductive clay layer, e.g. smectite, may be quite deep over the system up flow and much closer to the surface in cooler out flow areas. In these cases, the resistivity anomaly at the surface is not centered over the geothermal reservoir (Spichak and Manzella, 2009).

High-temperature geothermal systems, which are required for electric power production, usually occur where magma intrudes into high crustal levels (b10 km) and hydrothermal convection can take place above the intrusive body (e.g., Ander et al., 1984; Mogi and Nakama, 1993; Bai et al., 2001; Veeraswamy and Harinarayana, 2006; Zlotnicki et al., 2006).

Fig. 4 shows a conceptual model showing the main elements of this type of geothermal system (Berktold, 1983).

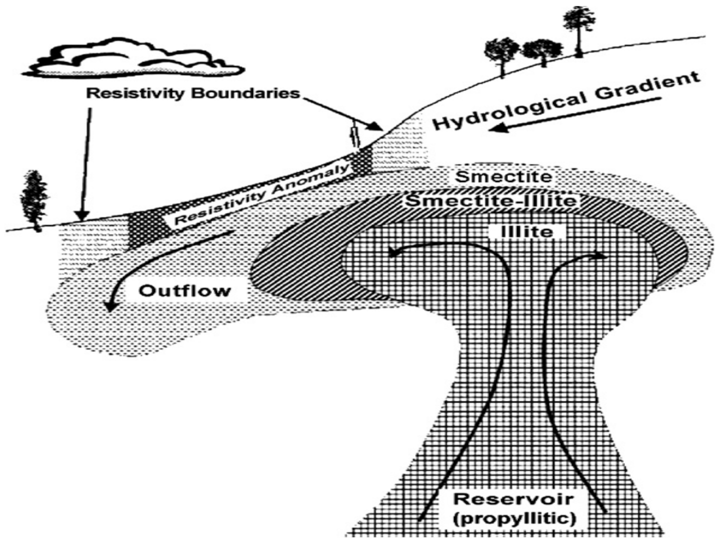

Figure 3. A generalized geothermal system in a steep terrain (Spichak and Manzella, 2009).

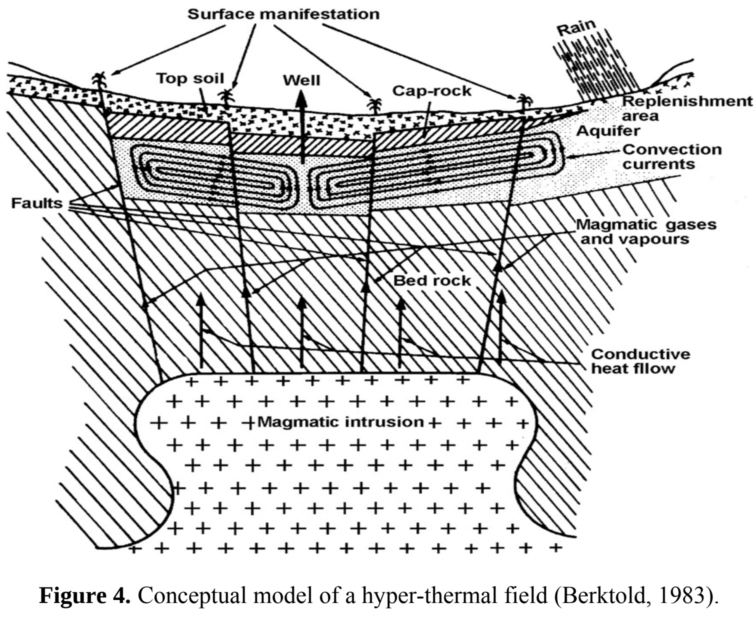

Figure 4. Conceptual model of a hyper-thermal field (Berktold, 1983).

4 GEOLOGICAL SETTING

The Mt. Sabalan region lies on the South Caspian Plate, which underthrusts the Eurasian Plate to the north. It is, in turn underthrust by the Iranian Plate, which produces compression in a northwestern direction (Noorollahi et al. 2007). Geological structures in this area are complicated further by a dextral rotational movement caused by the northward underthrusting of the nearby Arabian Plate beneath the Iranian Plate (McKenzie, 1972).

Due to this tectonic framework, the Cenozoic geologic history and the stratigraphy of the region are complex, with units of different structural characteristics (Emami, 1994). Manouchehri, 1989 Manouchehri, M., 1989. 1:250,000 Geological quadrangle map of Iran. Tabriz-Poldasht No. B1 & B2. Ministry of Mines and Metals, Geological Survey of Iran, Tehran. Igneous activity began in the Eocene with the accumulation of potassic alkalic volcanics over a sequence of Mesozoic and Paleozoic sediments. These rocks were thermally metamorphosed by an Early Miocene monzonitic batholith, which is elongated in a NW–SE direction and is exposed on the western ridge of Mt. Sabalan. Significant uplift and erosion of the batholith followed, and a sequence of Late Miocene sediments were deposited to the southwest and southeast of the batholith (KML, 1998) KML, 1998 KML, 1998. Sabalan geothermal project, Stage 1—Surface exploration, final exploration report. Kingston Morrison Limited Co., report 2505-RPT-GE-003 for the Renewable Energy Organization of Iran, Tehran, 83 pp.

A geologic study of the North Sabalan area confirmed that there were two major types of structural settings: a set of linear faults and several ring-faults. Interpretation of satellite imagery and aerial photographs indicated a WNW-trending major structural zone, running through the area. The faults strike predominantly towards the northwest and northeast (KML, 1998).

5 METHODOLOGY

The Magnetotelluric method was first introduced by Tikhonov (1950) and Cagniard (1953). It is a passive electromagnetic method utilizing the field induced by magnetospheric or ionospheric currents. Since the source is considered very far away, the field can be treated as a plane wave (Zhdanov and Keller, 1998).

The depth investigation of the MT method is much larger than that of other electromagnetic methods used for geothermal resource exploration. The measured electromagnetic field components at right angles at the surface of the earth make inferences about the earth's electrical structure which can be related to the geology tectonics and subsurface structures. Measurements of the horizontal components of the natural electromagnetic field are used to construct the full complex impedance tensor as a function of frequency. The second theorem of the Maxwell equation states that (Zhdanov and Keller, 1998),

$$\text{Curl } E = -\partial B/\partial t. \qquad (1)$$

Whereas E is the Electric field and B is the magnetic field.

Since a plane wave is utilized ($E_z = 0$) and the frequency of the signal is usually considered low, the equation can be expanded into

$$\begin{vmatrix} dx & dy & dz \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & E_y & 0 \end{vmatrix} = -i\omega\mu_0(H_x dx + H_y dy) \qquad (2)$$

where $B=\mu_0 H$. By expanding equation (2), we end up with two independent equations:

$$H_x = -\frac{1}{i\omega\mu_0}\frac{dE_y}{dz} \qquad H_y = -\frac{1}{i\omega\mu_0}\frac{dE_x}{dz} \qquad (3)$$

From this point one can apply a solution of the Helmholtz operator to the equations to yield a simple relationship between the electric field (E) and the magnetic field (H) to get the impedance tensor (Z)

$$Z_{xy} = \frac{E_x}{H_y} \qquad Z_{yx} = -\frac{E_y}{H_x} \tag{4}$$

Furthermore, one can derive the corresponding apparent resistivities as:

$$\rho_{xy} = \frac{1}{\omega\mu_0}\left|Z_{xy}\right|^2 \qquad \rho_{yx} = \frac{1}{\omega\mu_0}\left|Z_{yx}\right|^2 \tag{5}$$

For MT signals electric and magnetic fields are a function of conductivity (σ), dielectric permittivity (ε), and magnetic permeability(μ) of the material.This relationship can be formulated as(Zhdanov and Keller, 1998);

$$\{E, H\} = A(\sigma, \varepsilon, \mu) \tag{6}$$

Where A is a forward operator applied to $\sigma, \varepsilon,$ andμ. σ is simply $1/\rho$.
The corresponding inverse problem is

$$\{\ \sigma, \varepsilon, \mu\ \} = A^{-1}\{E, H\} \tag{7}$$

In most presentations, E and H are usually combined together as an apparent resistivity ρ_a, ρ_{xy} or ρ_{yx} .This is a nonlinear problem, therefore finding the forward operator A is sometimes rather complicated. One of the simplest one-dimensional forward operators is based on the reflectivity coefficient. The result is used to develop a forward model as follows.

For N layers, the reflectivity coefficient of the very bottom interface is
(Zhdanov & Keller, 1998)

$$R(1) = 1 \tag{8}$$

The reflectivity coefficients for the successive layers can be calculated as,

$$R(j) = \frac{1 - K(j)e^{-2ikud\,(N-j+1)}}{1 + K(j)e^{-2ikud\,(N-j+1)}} \tag{9}$$

$$K(j) = \frac{1 - \frac{ku}{kl}R(j-1)}{1 + \frac{ku}{kl}R(j-1)} \tag{10}$$

$$ku = \sqrt{i\omega\sigma\mu(N - j + 1)}$$
$$ku = \sqrt{i\omega\sigma\mu(N - j + 2)} \tag{11}$$

where d is the thickness of the layers. At the very bottom interface the K (1) is also equal to one. To obtain a series of $\rho_a$or model responses, the equations should be looped over the desired period. The depth of penetration for a signal in MT can be calculated using the following equation (Vozoff, 1991).

$$\delta = 503\sqrt{\rho \times T} \tag{12}$$

where δ is the skin depth in meters, T period and ρ apparent resistivity. For a 1*D* structure in which the resistivity of the earth varies only with depth, the diagonal elements of the tensor are equal to zero, whilst the off-diagonal components are equal in magnitude and have opposite signs. In a 2*D* case, wherein *X* or *Y* is aligned along the geoelectric strike, the diagonal element of the impedance tensor would be zero. The principal values of the tensor are two complex quantities which are expressed in terms of rotational invariants, and, hence are independent of the direction of the axes (Berdichevsky and Dimitriev, 2002).

We can define the geometric mean of these principal values as Determinant impedance which is a simple approximation of the Tikhonov-Cagniard impedance and it is unique and independent of the strike direction (Pedersen and Angels, 2005). Determinant apparent resistivities and phases are computed and used for the 1D modeling, which is the geometric mean of ρ_{xy} and ρ_{yx} (Raharjo et al., 2002).

$$\rho_{at} = \frac{1}{\mu_0\,\omega}\ \left|Z_t\right|^2$$
$$\rho_{inv} = (\rho_{xy} \times \rho_{yx})^{0.5}$$
$$\varphi_t = Phase(Z_t) \quad t = xx, xy, yx, inv\ or\ DET \tag{13}$$

In 2D earth, the MT tensor decouples into two independent modes, the transverse electric (TE) mode and the transverse magnetic (TM) mode. The TM mode accurately delineates boundaries and also provides accurate values of apparent resistivity. The TE mode provides poor boundary delineation and underestimates the resistivity of 3D bodies but the joint inversion of the two modes data provides improvement in the inversion. Also the earth dimensionality, strike, and detection of galvanic distortion propose the joint inversion of both data modes to increase the accuracy of the results (Volpi et al., 2003).

6 MODELING AND INVERSION

One-dimensional modeling of the determinant data was performed by using a forward operator and algorithm from Zhdanov and Keller (1998). The joint TE and TM-mode data were inverted for the 2D conductivity models by using a code from Siripunvaraporn and Egbert (2000).

The inversions were computed using many a priori models with a uniform earth resistivity. A noise floor of 2% for the apparent resistivity and 5% for the phase were used. The normalized root mean square (rms) misfit achieved was around 4 for joint TE and TM mode inversion. The data were calculated as apparent resistivities and phases. 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.

6.1 One-dimensional modeling

One-dimensional modeling of the data was carried out by minimizing the rms error and the residuals between observed and calculated resistivity and phase differences of data and model responses. Different starting models were taken to achieve a reasonable 1D result. The 1D resistivity models of the Determinant data for two example sites (86 and 158) along the profile together with the resistivity and phase data and model response are shown in Figures 5 and 6.

The final models show acceptable misfits (1 <rms <1.5) between the measured data and the model responses. The 1D model for all sites shows common features and is interpreted as a three layer earth in the area. The resistivity models show an electrical resistivity view of the subsurface material from the top to a depth of 1 km. The average thickness of the surface resistive layer in Figure 5 (site 86) is about 300 m and a transition from a high resistive formation (≅ 500 ohm-m) to a completely low resistive structure (about 10 ohm-m) at 1000 m depth is resolved.

Regardless of the true dimensionality, it is practicable to is this correct an overview of the subsurface resistivity with 1D modeling of the rotationally invariant data. Based on the results of the 1D modeling, a reasonable starting model and strategy can be constructed for the two-dimensional inversion.

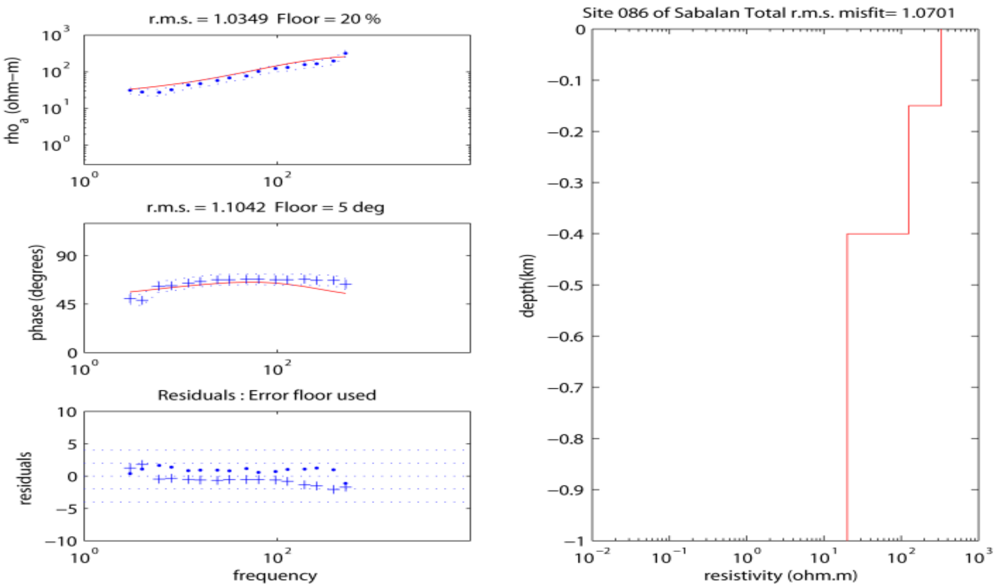

Figure 5. One dimensional modeling results of site 086.

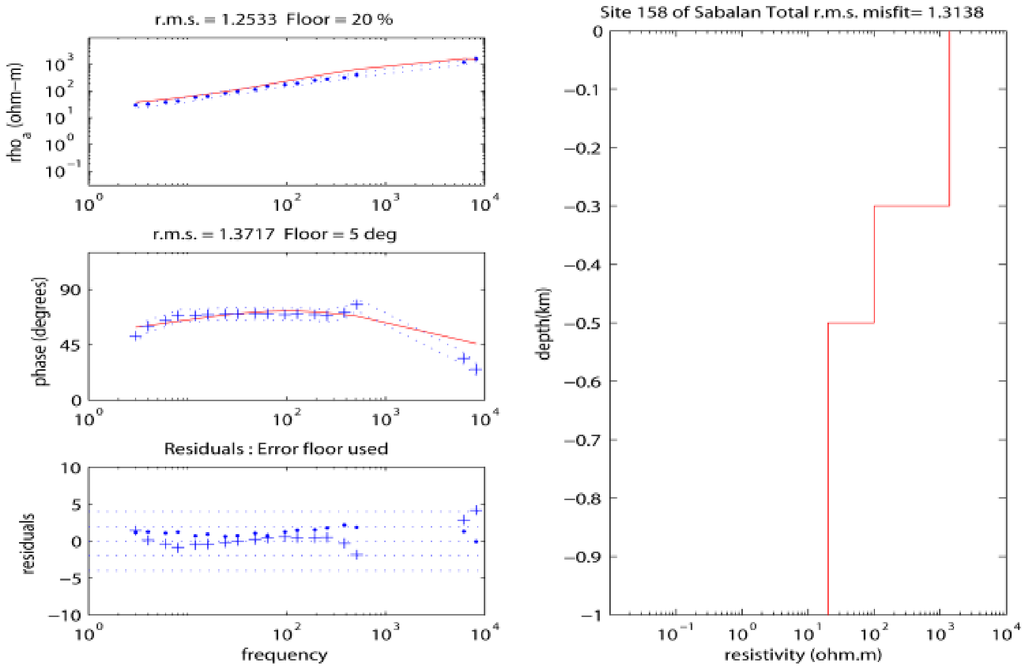

Figure 6. One dimensional modeling results of site 158.

6.2 Two-dimensional inversion and interpretation

We performed joint 2D inversions of both TE and TM-mode responses. Bimodal inversion reproduces a 2D structure with a greater reliability than a TM mode inversion. The resulting model for joint TE and TM-mode data is shown in Fig.7. To suppress the effects of the distortions on the TE-mode data, a relatively large error floor was considered for the apparent resistivity data of TE-mode while for its phase data and TM-mode data an error floor of 2% to 5% on the impedances was assumed. By these levels of errors on the data, the RMS misfit of the computed model response to the observed data was around 4 and is acceptable. In order to check the convergence of the inversion, we took several half space models with different **resistivities** as initial models. The resulting models showed the same resistivity structure. A resistive layer (>400 ohm-m) was recognized on top (Fig. 7). The second layer was very conductive (<50 ohm-m), and shows a variable thickness along the 2D section, ranging from a few hundred meters at Site 12 to about 2200 m at Site 71.

The conductive layer could be consistently resolved in both 1D and 2D models. Below this conductor there is an increase in resistivity with depth along the profile, except under sites 82, 71 and at the east side of the profile where resistivity is lower than a few tens of ohm-m. In the middle part of the profile the second conductive layer (<10 ohm-m) is followed by a high resistive basement (≅500 ohm-m) in depth.

The very resistive layer at the surface can be assigned to impermeable rocks such as alkali andesite, basalt and old Sabalan trachyandesitic flows which are interpreted as the cap-rock of the system. The second conductive layer shows variable thickness along the profile and can naturally be interpreted as the clay zone that acts as system reservoir. At greater depths there is a highly resistive (>400 ohm-m) structure that extends downwards to a depth of about 5 km in the middle of the profile. This resistive medium can be interpreted as magmatic intrusions acting as the heat source of the geothermal system.

Another peculiar feature of the section is the area beneath sites 82 and 71, where the 2D model shows an abrupt transition to moderate resistivity values down to depths of 5 km. Due to relief topography compared with the depth of investigation, a flat topography is assumed along the profile.

The collected data (observed apparent resistivity and phase data), model response (calculated data) and the residuals (data misfit) for each mode (TE and TM) are shown in Fig 8.

The residuals are simply the arithmetic difference between the observed and calculated data. In some cases there is some misfit which most probably is due to attempt to 2D model the 3D structures.

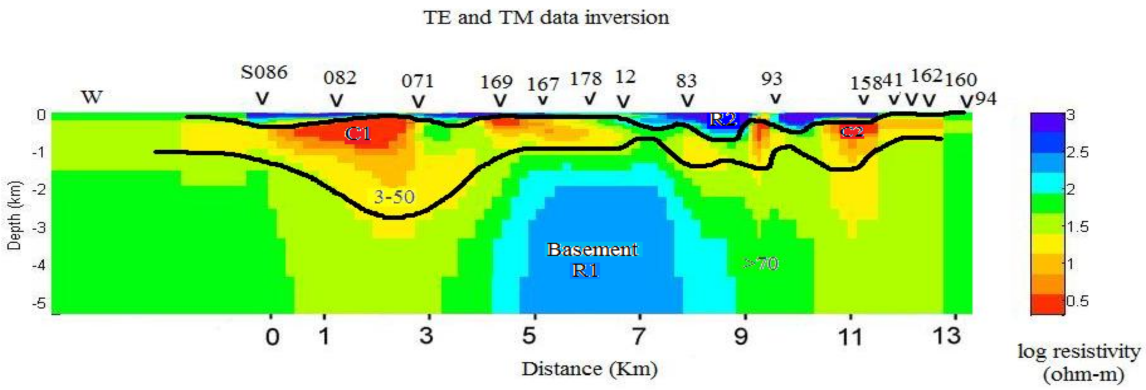

Figure7. 2D inversion model of joint TE and TM-mode data.

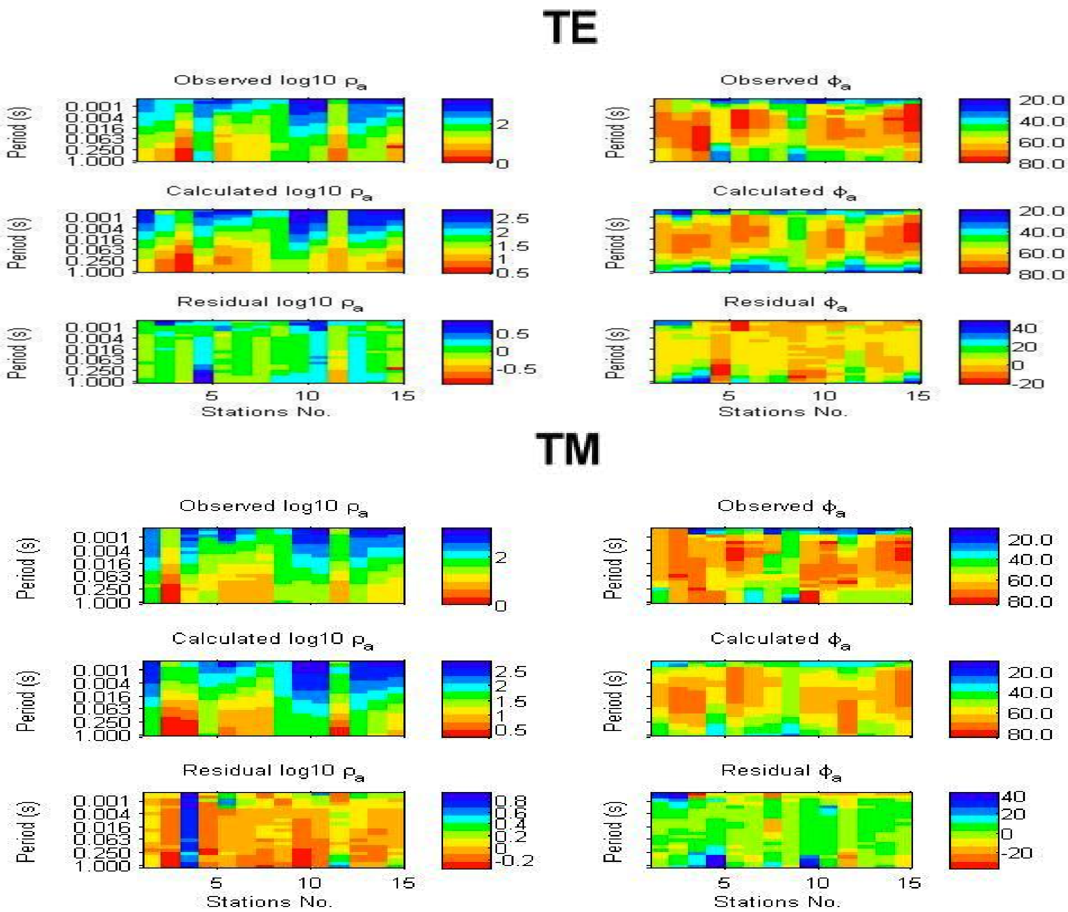

Figure 8. TE and TM-mode data, model responses and residual of the 2D inversion.

7 DISCUSSION AND CONCLUSIONS

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

The results of our study indicate that there is an agreement between the Sabalan resistivity model deduced from MT data and the global conceptual resistivity model reported for hyper-thermal fields. Resistivity models in Sabalan show three main elements of a hyper-thermal field as;

a resistive layer at the surface which plays the role of the cap-rock of the geothermal system, a highly conductive layer interpreted as the reservoir and a deep resistive intrusive structure in the central part of the profile forming the heat source of the geothermal reservoir.

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REFERENCES

Ander, M. A., Gross, R. and Strangway, D., 1984, A detailed magnetotelluric/ audiomagnetotellurics study of the Jemez Volcanic Zone, NewMexico, J. Geophys. Res. **89**(B5), 3335–3353.

Bai, D. H., Meju, M. A. and Liao, Z. J., 2001, Magnetotelluric images of deep crustal structure of the Rehai geothermal field near Tengchong, southern China, Geophys. J. Int. **147**, 677–687.

Berdichevsky, M. and Dmitriev, V., 2002, Magnetotelluric in the context of the theory of ill posed problems, Published by Society of Exploration Geophysicists.

Berktold, A., 1983, Electromagnetic studies in geothermal regions, Geophys. Surv. **6**, 173–200.

Bogie, I., Cartwright, A. J., Khosrawi, K., Talebi, B. and Sahabi, F., 2000, The Meshkin Shahr geothermal prospect, Iran. Proceedings, World Geothermal Congress 2000: 997-1002.

Bromley, C. J., Khosrawi, K. and Talebi, B., 2000, Geophysical exploration of the Sabalan geothermal prospects in Iran, Proceedings, World Geothermal Congress 2000: 1009-1014.

Cagniard, L., 1953, Basic theory of the magnetotelluric method in geophysical prospecting, Geophysics, 8, 605-635.

Emami, M. H., 1994, 1:100,000 Geological map of Iran Sheet 5566, Ministry of Mine and Metals, Geological Survey of Iran.

ENEL., 1983, Geothermal power development studies in Iran, General Report on Sabalan Zone, Ministry of Energy, Islamic Republic of Iran, 120 pp.

Hafizi, M. K., Aiobi, M. and Rahimi, A., 2002, The combination of 2-D and 1-D inversion for 2.5D interpretation of magnetotelluric geothermal sites, Expanded abstr. EAGE 64th Conference, Florence, Italy.

KML., 1998, Sabalan geothermal project, stage 1-surface exploration, final exploration report, report number, 2505-RPT-GE-003, Renewable Energy Organization of Iran and Kingston Morrison Limited Co. pp. 83

McKenzie, D. S., 1972, Active tectonics of the Mediterranean region, Geophys. J. R. astr.Soc. **30**, 109-185.

Mogi, T. and Nakama, S., 1993, Magnetotelluric interpretation of the geothermal system of the Kuju volcano, southwest Japan, J. Volcanol. Geotherm. Res. **56**, 297–308.

Noorollahi, Y., Itoi, R., Fujii, H. and Tanaka, T., 2007, Geothermal resources exploration and well site selection with environmental consideration using GIS in Sabalan Geothermal area, Iran, Proceedings, Thirty-Second Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 22-24.

Oskooi, B., Pedersen, L. B., Smirnov, M., Arnason, K., Eysteinsson, H., Manzella, A. and the DGP Working Group, 2005, The deep geothermal structure of the Mid-

Atlantic Ridge deduced from MT data in SW Iceland, Phys. Earth. Planet. Int., **150**, 183-195.

Pedersen, L. B., Engels, M., 2005, Routine 2D inversion of magnetotelluric data using the determinant of the impedance tensor, Geophysics, **70**, G33-G41.

Raharjo, I., Wannamaker, P., Allis, R. and Chapman, D., 2002, Magnetotelluric intrepretation of the Karaha geothermal field Indonesia, 27th Workshop on Geothermal Reservoir Engineering, Stanford University, in press.

Siripunvaraporn, W. and Egbert, G., 2000, An efficient data-subspace inversion method for 2D magnetotelluric data, Geophysics, **65**, 791-803.

Spichak, V., Manzella, A., 2009, Electromagnetic sounding of geothermal zones, Journal of Applied Geophysics, **68**, 459–478.

Tikhonov, A. N., 1950, On determining electrical characteristics of the deep layers of the Earth's crust, Doklady, **73**, 281-285.

Veeraswamy, K. and Harinarayana, T., 2006, Electrical signatures due to thermal anomalies along mobile belts reactivated by the trail and outburst of mantle plume: evidences from the Indian subcontinent, J. Appl. Geophys. **58**(4), 313–320.

Volpi, G., Manzella, A. and Fiordelisi, A., 2003, Investigation of geothermal structures by magnetotellurics (MT): an example from the Mt. Amiata area, Italy, Geothermics, **32**, 131–145.

Vozoff, K., 1991, The magnetotelluric method. in Nabighian, M. N. (Ed.), Electromagnetic Methods in Applied Geophysics, II. Society of Exploration Geophsyicists.

Zhdanov, M. S. and Keller, G. V., 1998, The geoelectrical methods in geophysical exploration, method In Geochemistry and Geophysics, **31**, 261-346.

Zlotnicki, J., Vargemezis, G., Mille, A., Bruere, F. and Hammouya, G., 2006, State of the hydrothermal activity of Soufriere of Guadeloupe volcano inferred by VLF surveys, J. Appl. Geophys. **58**(4), 265–279.