Journal of the Earth and Space Physics, Vol. 41, No. 4, 2016, PP. 95-104

Reconnaissance exploration of potential geothermal sites in Kerman province, using Curie depth calculations

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(Received: 22 Feb 2014, Accepted: 17 Feb 2015)

Abstract

In this paper an indirect method is presented to detect potential geothermal sites in Kerman province, southeast Iran. Geothermal heat flux is one of the main parameters to be investigated in geothermal exploration programs. However, few direct heat flux measurements are available for Iran. Given the proved relation between Curie depths and heat flux, magnetic data can be used to calculate the Curie depths in the areas where few or no direct heat flow measurements are available. The method presented here uses an iterative forward modeling approach to calculate the Curie depth in Kerman Province. It has used the satellite magnetic crustal field model of MF5 obtained from CHAMP mission. The equivalent source magnetic dipole method was used to estimate the magnetic crustal thickness from the observed induced field. The obtained Curie map reveals an area with very low Curie depth in the southeast Kerman. The area may be considered as a potential geothermal site. Geological evidence confirmed our findings for the probability of a geothermal site in the area.

Keywords: Curie depth, Geothermal exploration, Iran, Kerman, Satellite magnetic field model.

1. Introduction

Although there are many potential geothermal reservoir sites in Iran, reconnaissance measurements have scarcely been carried out so far. Geothermal heat flux is one of the main parameters to be investigated in geothermal exploration. As shown in Figure 1, few direct heat flux measurements are available for Iran. Heat flux data acquisition is difficult and so costly, therefore, indirect reconnaissance studies of geothermal potential sites in various parts of Iran are recommended.

Many geological features of the Earth's lithosphere can create variations in the Earth's magnetic field that can be detected by satellite images. The resulting magnetic anomaly maps can provide new insights into tectonic features and broad structures of the lithosphere (Langel and Hinze, 1998). Recent considerable increase in satellite missions dedicated to measurement of the earth's magnetic field, new visions are opened for geothermal field studies. The CHAMP (Challenging Minisatellite Payload) magnetic field mission provided highly reliable measurements from which the global lithospheric magnetic field can be determined with unprecedented resolution and accuracy (Maus et al., 2007; Hemant, et al., 2005).

The crustal field model of MF5 has been used in this study to estimate the Curie temperature depths of Kerman region in Iran. The magnetic field models of MF series focus on the lithospheric field. The initial model of MF1 was only determined from scalar data, acquired during the first year of the CHAMP mission (Maus et al., 2002). MF2 and MF3 models were derived using CHAMP vector data. Improvements in the processing methodology were used in the 4th generation of lithospheric field models, MF4 (Maus et al., 2006). However, while downward movement of the MF4 at high latitudes, small-scale noise becomes visible. MF4x has overcome this problem (Lesur and Maus, 2006). MF5 model was derived with the aim to produce a model free of noise everywhere up to degree 100, even at high

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latitudes. In order to use the data obtained from lower flight altitudes, only the latest three years of CHAMP scalar and vector measurements were used. Compared with earlier models of the MF series, MF5 model shows more details (Maus et al., 2007).

Given the proved relation between Curie depths and heat flux changes (Maule, et al., 2009; Sarkar and Saha, 2006; Dolmaz et al., 2005; Salk et al., 2005), magnetic data can be used to calculate the Curie depths in the areas where few or no direct heat flow measurements are available. Rocks below their Curie temperature may sustain induced or remanent magnetization, but above their Curie temperature they become practically non-magnetic. Therefore, it is possible to calculate Curie depth from magnetic data. In the regions of high heat flow, the limiting depth of magnetic sources is controlled by the Curie point isotherm; a thermal boundary below which the magnetic body is continued, but is no longer magnetic (Wasilewski et al., 1979; Mayhew et al., 1985; Wasilewski and Mayhew, 1992; Rajaram et al., 2009). Curie point depths provide valuable information on the geothermal gradient and the regional geotemperature distributions (e.g., Shuey et al., 1977; Blakely, 1988; Espinosa-Cardeña and Campos-Enriquez, 2008). A region with significant geothermal field close to the surface of the earth is characterized by high temperature gradient and heat flow. It is, therefore, expected that regardless of the composition of the rocks, the region is associated with a conspicuously shallow Curie point isotherm related to the adjoining regions isotherm (Bhattacharyya and Leu, 1977). The results of aeromagnetic and satellite studies presented by numerous authors have also shown that the obtained Curie depths from magnetic measurements is correlated well with heat flux so that high heat flux is found in the areas of shallow Curie depths and vice versa (e.g. Mayhew, 1982; Mayhew, 1985; Okubo et al., 1985; Salk et al., 2005; Maule et al., 2005). In other words, minerals of equivalent Curie temperatures are magnetically stable at shallow depths in high heat flow regions, and to greater depths in low heat flow areas (Haggerty, 1978). The calculated Curie map of the area provides a valuable insight to delineate geothermal potential fields.

2. The study area

Interest in geothermal energy investigation was originated in Iran when James R McNit, a United Nations geothermal expert visited the country in December 1974. He reported very promising future on the geothermal energy development in Iran (Yousefi et al., 2006).

Kerman Province with an area of 180,726 km^2 is the second largest province out of the 31 provinces of Iran. The province is located in the southeast part of Iran with its administrative center in the city of Kerman (Fig. 2).

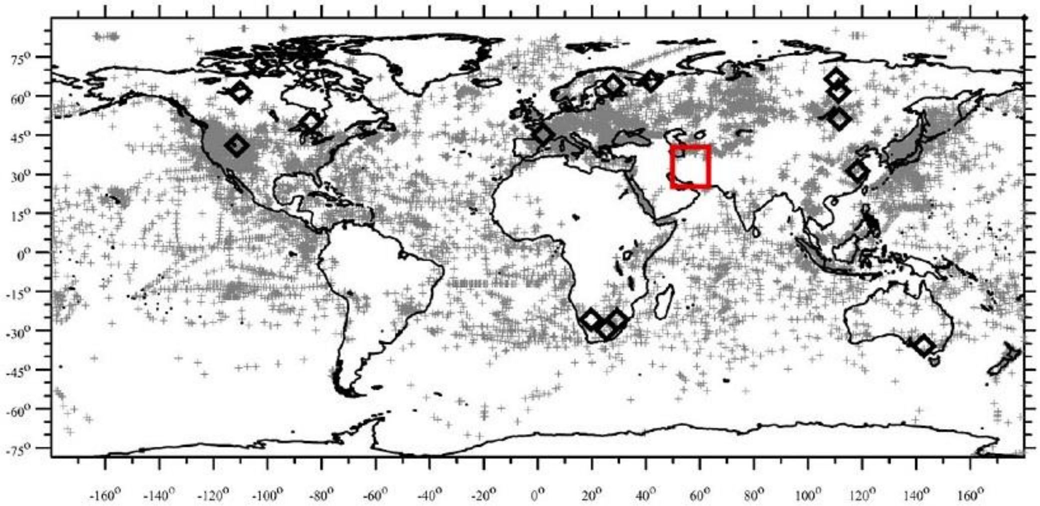

Fig. 1. Global heat flow data coverage (updated after Pollak et al., 1993). Crosses show the sites of borehole heat flow measurements (Artemieva, 2006). The solid red box on the figure shows where Iran is located. A close-up of Iran can be seen in Figure 2.

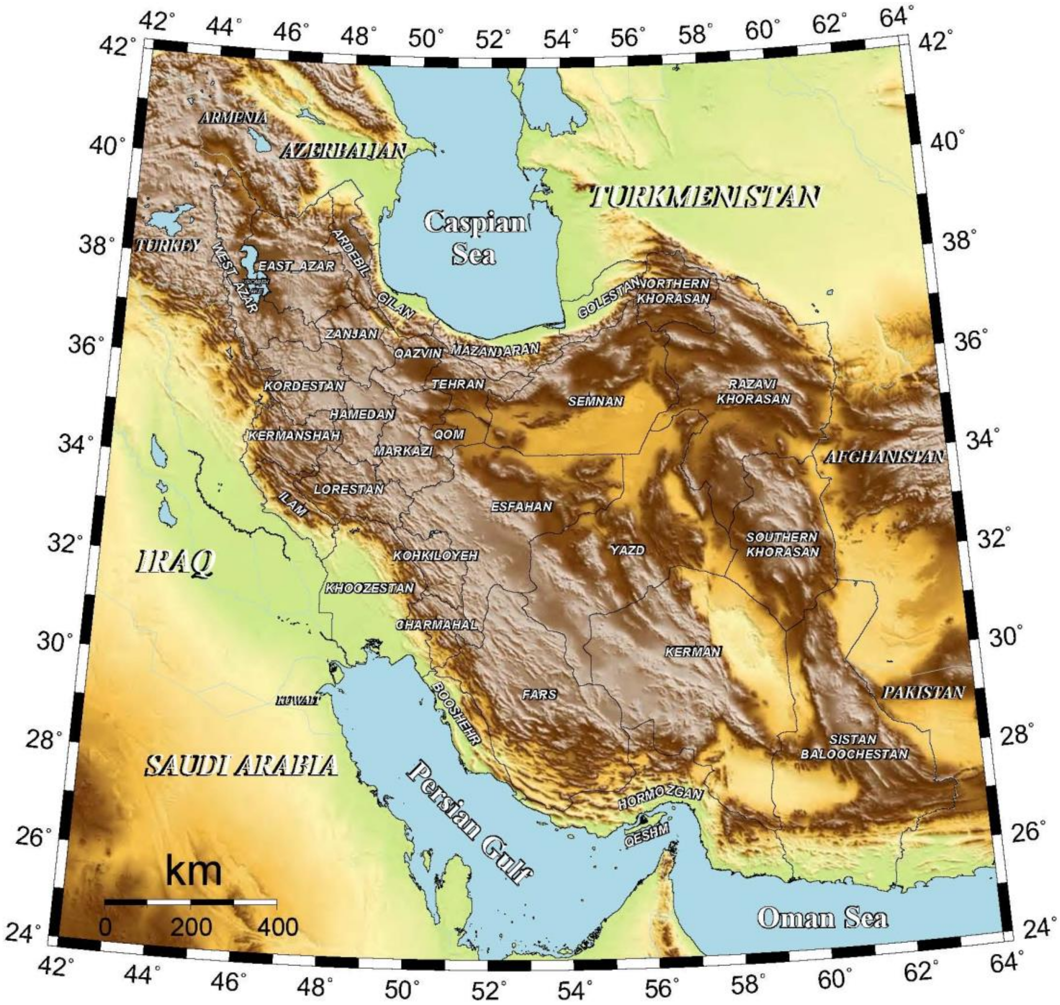

Fig. 2. Location map of Kerman Province in Iran.

Kerman Province is one of the richest provinces of Iran from the natural resources point of view. The altitudes and the heights of the province are continued from the central mountain ranges of Iran. They extend from the volcanic folds beginning in Azarbaijan, and by branching out in the central plateau of Iran, terminating in Baluchestan. These mountain ranges have brought about vast plains in the province of Kerman. The Bashagard and Kuh-e Banan Mountains are the highest in this region. They include peaks such as Toghrol, Aljerd, Palvar, Sirach, Abareq and Tahrood. Other ranges that stretch out from Yazd to Kerman and Challeh-ye-Jazmoorian include peaks including Medvar, Shahr-e-Babak, Kuh-e Panj, Chehel Tan, Lalezar, Hezarbahr, Aseman and others. In the central parts, Mount Hezar is the highest peak, 4465 meters above sea level.

Most of the province is largely covered by sandy desert. The climate in the province varies in different regions. The north, northwest, and central areas experience a dry and moderate climate, whereas in the south and southeast, the weather is warm and relatively humid.

3. Methodology

We started with the MF5 magnetic field model (Maus et al., 2007), using spherical harmonics of 16–100 degrees to represent the crustal field (Fig. 3a). The high resolution MF series derived from CHAMP data are being extensively used to interpret the magnetic anomalies in terms of geology and tectonics and composition of the Earth’s crust. The fifth generation in the series, MF5, is used in this research. This shows an unprecedented accuracy in the magnetic anomalies even in the downward continued map and has led to its increased use in interpretation of the crustal structures of wavelength ~200 km (Maus et al., 2007).

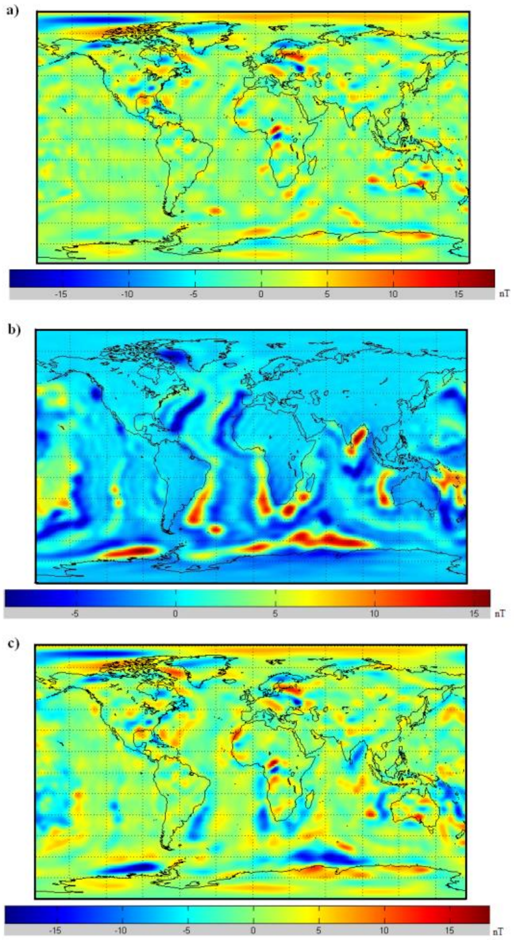

Fig. 3. (a) The radial component of the observed magnetic field based on MF5 model, (b) The radial component of the remanent magnetic field of the oceanic crust as given by the model of Dyment and Arkani-Hamed (1998a) and Purucker and Dyment (2000), (c) The radial component of the observed induced crustal field. All the models are calculated at 400 km altitude for spherical harmonic degrees 16–100.

Magnetization measurements and petrologic studies of rock samples brought to the surface from the mantle by structural and igneous processes indicate that ferromagnetic minerals, as the sources of most magnetic anomalies, generally are not present in the mantle (Wasilewski et al., 1979; Wasilewski and Mayhew, 1992), at least in continental regions. It is no problem for our case that mantle rocks are non-magnetic as the Curie isotherm lies shallower than the crust-mantle boundary in widespread continental regions. In particular, we are looking at geothermal sites where the Curie isotherm is shallower than average. Therefore, we would expect that the thickness of the magnetic crust we found in the region is most likely to be developed by the depth of the Curie isotherm and not by the crust-mantle interface.

The crustal field observed by satellites and described by field models is caused by remanent as well as induced magnetization of the crustal rocks. The induced magnetization is of interest here, as it depends on the thickness of the magnetic crust as well as on the susceptibility of the crustal rocks and the strength of the ambient field. To determine the magnetic crustal thickness, the induced part of the crustal field must be isolated. We do this by subtracting a model for the remanent crustal field from the observed crustal field (Maule et al., 2005).

For the remanent magnetization of the oceanic crust, we use the model by Dyment and Arkani-Hamed (1998a) and Purucker and Dyment (2000), where the remanent magnetization of the oceanic lithosphere is determined by ocean floor ages, plate motion, and polar wandering studies. The radial component of the remanent field from this model at 400 km altitude is shown in Figure 3b. Then, the remanent field is subtracted from the observed crustal field and therefore, the observed induced crustal field is obtained (Fig. 3c).

Finally, the equivalent source magnetic dipole method was used to estimate the magnetic crustal thickness from the observed induced field. In this method, a large and finite number of dipoles to represent the crustal magnetization is assumed to be distributed in the study area. Then, the magnetic moments of the dipoles should be determined so that the magnetic field at the desired altitude, which is calculated by summing the contribution of each dipole, approaches the observed field (Dyment and Arkani-Hamed, 1998b; Langel and Hinze, 1998). The study altitude is considered 400 km in our study. The following equation was used to calculate the magnetic crustal thickness (Maule et al., 2009).

$$m_j(r_j) = \frac{\kappa_j}{\mu_0} B(r_j) w_j h_j \qquad (1)$$

where $\mu_0=4\pi\times 10^{-7}$ Vs/Am is the vacuum permeability, m_j is the dipole moment of the j'th dipole located at r_j, $B(r_j)$ is the inducing field, κ_j is the magnetic susceptibility, h_j is the thickness and w_j is the surface area of the j'th crustal block.

It is noteworthy that J dipoles are scattered across the surface of the earth and the magnetic fields are observed at N locations. Each dipole has a magnetic moment of $\overline{m}_j$ located at $\overline{r}_j = (r_j, \theta_j, \phi_j)$. The purpose is to find its contribution to the magnetic field at the observation point $\overline{r}_i = (r_i, \theta_i, \phi_i)$.

If $\overline{d}$ is the vector of the magnitudes of the dipole moments and $\overline{b}$ is the vector of the values of A_r, the radial component of the magnetic field, at location 1, 2... N, let's define:

$$G_{ij} = -F^{ij}{}_{11} \sin I_j - F^{ij}{}_{12} \cos I_j \cos D_j + F^{ij}{}_{13} \cos I_j \sin D_j \quad (2)$$

where I_j and D_j are, respectively, proper projections of the inclination and declination of the main field at the dipole locations, and F^{ij} is a 3×3 matrix related to the magnetic field at $\overline{r}_i$ to the dipole at $\overline{r}_j$ with dipole moment $\overline{m}_j$. Then:

$$b_i = \sum_j G_{ij} m_j \quad (3)$$

The matrix form of Equation (3) is:

$$\overline{b} = G\overline{d} \quad (4)$$

Equations (1) and (4) describe how the magnetic field from the crustal dipoles can be calculated if the magnetic crustal thickness is known. The aim of our calculations, i.e., the magnitude of the dipole moments of the crustal dipoles from the observed field, is the inverse problem. In the general case, the number of observations and the number of dipoles are not necessarily the same, and the inverse of G cannot be found directly.

The surface area given by the chosen dipole distribution and the inducing field are both known. The strengths of the dipole moment are determined by the observed induced field, while their directions are given by that of the inducing field. There are two unknowns; the susceptibility of the crustal rocks and the thickness of the magnetic crust. In order to solve the problem for the thickness of the magnetic crust, we make the assumption that the susceptibility is constant for the continental crust and the oceanic crust with values of $\kappa=0.035$ SI and $\kappa=0.040$ SI, respectively (Schlinger, 1985; Purucker et al., 2002).

As described in the above paragraphs, an iterative forward modeling procedure is used to solve the problem for the dipole moments from the observations. To start the iterative procedure, an initial model for the magnetic crustal thickness is needed. Therefore, the induced field of the 3SMAC model (Nataf and Ricard, 1996), as the initial model of the crustal thickness, is first calculated. The observed induced field is then compared to the calculated field. If the difference between the two fields exceeds the uncertainty of the observations, the crustal thickness model needs to be improved. The induced field of the improved crustal thickness model is then calculated. Again, the observed induced field is compared to the calculated field until the induced field of the crustal thickness model approaches the observed induced field sufficiently. This is accepted as the final crustal thickness model for the study area.

4. Results and Discussions

We have determined the magnetic crustal thickness using 3SMAC (Nataf and Ricard, 1996) as the initial model for the crystalline crustal thickness. The result for the magnetic crustal thickness in the study area is shown in Figure 4. The calculations were done for an area covering a wide portion of the eastern Iran, within the latitude 28-36 N and the longitude 56-64 E. The main purpose is to detect the geothermal potentials in Kerman province.

As can be seen in Figure 4a, the obtained Curie map reveals an area with very low Curie depth in the southeast Kerman Province. The area may be considered as a potential geothermal site.

As mentioned before, there are not adequate heat flow data available for Iran (Fig. 1) to compare the agreement between the Curie depth map and the heat flow map. Therefore, we used the geological data as the geothermal evidence for our study.

The presence of volcanic rocks increases the probability of geothermal resources in a given area. Such rocks occur throughout Iran in an area about 145,973 km^2 (nearly 9% of Iran) (Yousefi et al., 2009). Figure 5 illustrates the geological map of Iran. It is seen that volcanic rocks are considerably present within the potential area detected on the Curie map.

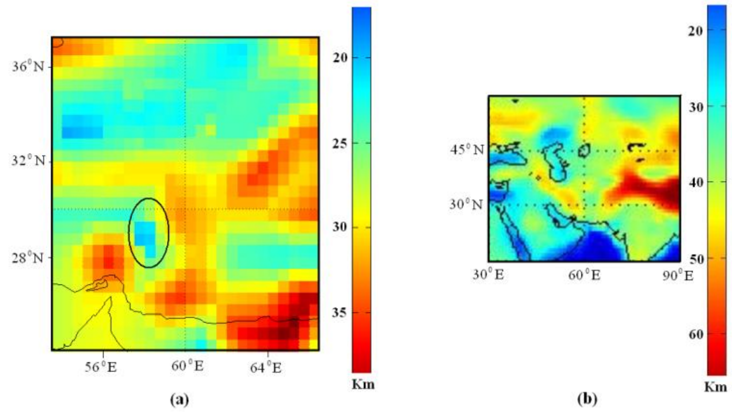

Fig. 4. (a) The final map of the magnetic crustal thickness (Curie depth) for the study area, (b) The initial magnetic crustal thickness of Iran based on the 3SMAC model.

Fractures and faults play an important role in geothermal fields since they control most of subsurface fluid flow. Hanano (2000) and many other researchers have pointed out that faults influence the character of natural convection in geothermal systems. A study was undertaken by Noorollahi et al. (2007) to investigate the relationship between faults and the location of geothermal wells in Japan at a scale of 1:250,000. Their results show that 95% of the wells are located within 6000m distance of the major faults. This is a greater distance than that was expected.

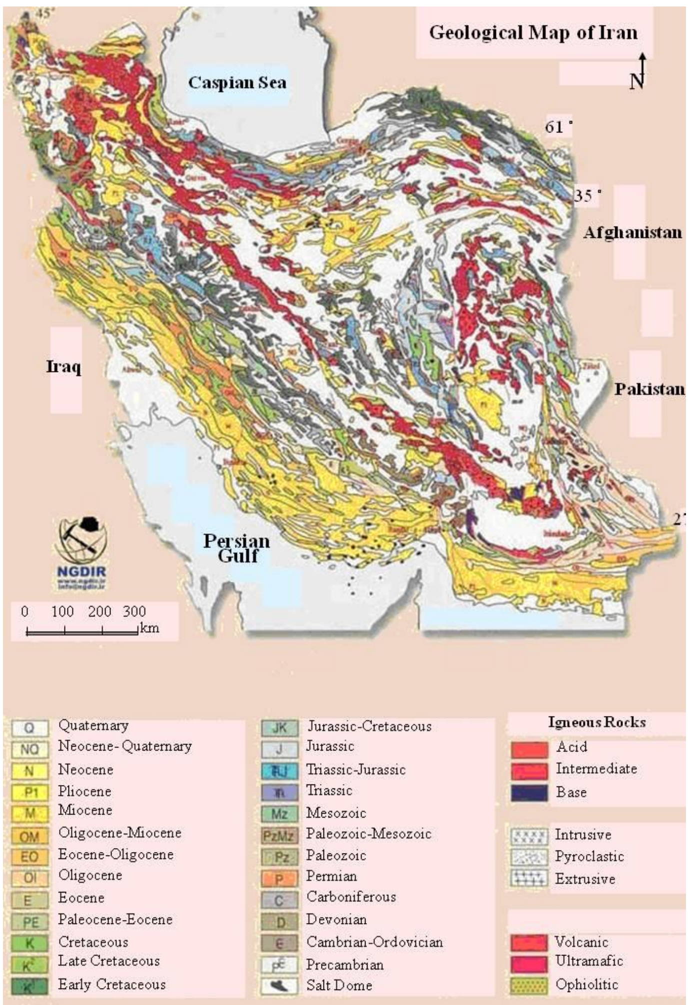

Fig. 5. The geological map of Iran (NGDIR).

Geomorphological observations reveal a major oblique fold-and-thrust belt in the province. Late Quaternary strike-slip and thrust faulting is widespread within the region (Walker, 2006). Major faulting in eastern Iran is shown in Figure 6.

The Nayband-Gowk fault system on the west side of the Dasht-e-Lut and particularly the Gowk section is of interest to our study. The Gowk fault is arranged in the Jebal Barez Mountains (Fig. 7). The Gowk fault strikes and forms a more complex system of fractures and scarps in a narrow linear valley with major mountain slopes on either side.

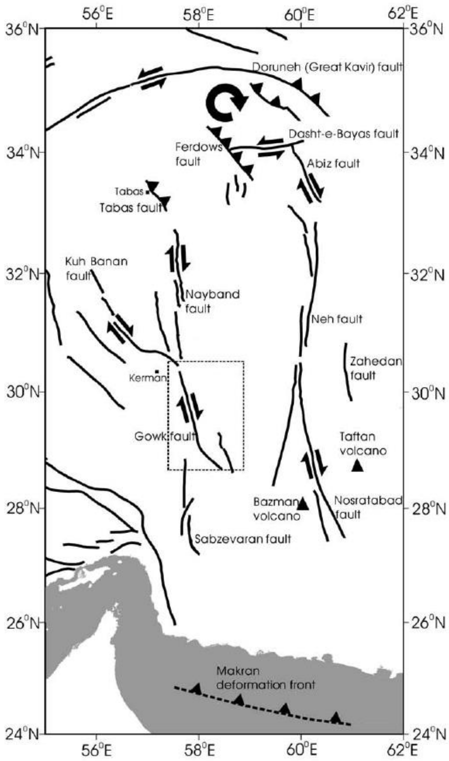

Fig. 6. Major faulting in eastern Iran (Walker and Jackson, 2002).

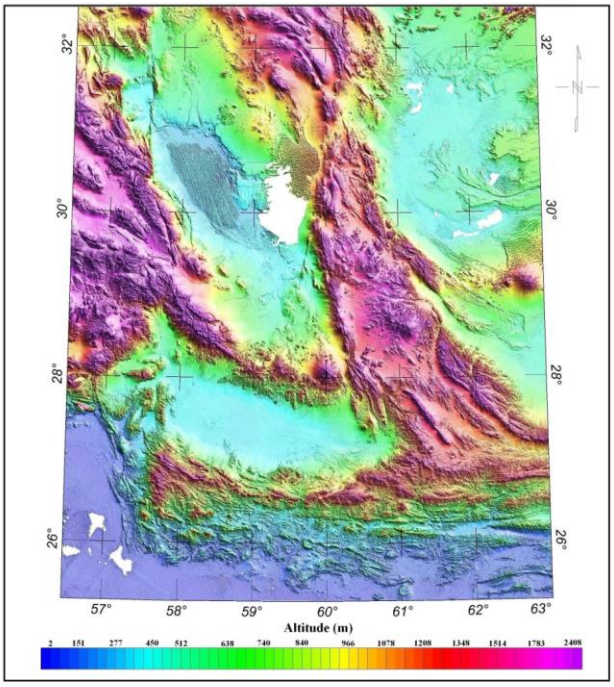

Fig. 7. The topographic map of the area located within 26-32ºN and 57-63ºE.

5. Conclusions

A comprehensive investigation is required for any geothermal field exploration. This may include geological, geophysical and geochemical studies. However, the potential application of satellite magnetic field models discussed in this paper can be widely used as a preliminary reconnaissance tool in the early stages of the geothermal site selection projects.

In this research, the radial component of the field from the MF5 model evaluated at 400 km altitude was used for spherical harmonics of 16-100 degrees. The radial component of the remanent magnetic field of the oceanic crust, as given by the model of Dyment and Arkani-Hamed (1998a) and Purucker and Dyment (2000), was then removed. Finally, an iterative forward modeling procedure was used to solve the problem for the dipole moments from the observations. The study area covers a wide portion of the eastern Iran. The calculated curie depth map shows a promising geothermal site in Kerman Province. Due to the insufficient heat flow data available for Iran, geological data were considered to compensate for the missing geothermal evidence for this study.

It should be noted that one of the potential sources of error in such satellite magnetic studies is the model for remanent magnetization. The remanent field model by Dyment and Arkani-Hamed does not account for remanent magnetism in the continental crust, although this does occur and can result in significant magnetic anomalies. Detailed maps of remanent magnetization neither exist for Iran nor for most continental areas. However, unrealistic (either too high or negative) magnetic crustal thickness values were not obtained in this study.

Another source of error that may influence the results is the susceptibility model. In this study, a constant magnetic susceptibility was assumed in the entire area. Global maps of the magnetic susceptibility of the crustal rocks are not available. Therefore, if the susceptibility of the rocks is underestimated, the magnetic crustal thickness may be overestimated.

Generally, the crustal field is weaker over the oceans than over the continents and the oceanic crust is in general thinner than the continental crust. The susceptibility values of oceanic rocks and continental rocks are overlapped to a large extent. However, there is a tendency for the mafic, oceanic rocks to have a slightly higher susceptibility than the felsic, continental rocks. Therefore, it seems reasonable to assume that the crustal thickness variations are dominated on the susceptibility variations.

Acknowledgements

We would like to thank Professor Tiku Ravat, Professor Micael E. Purucker and Professor Ricard Nataf for their advice provided in the early stages of this research.

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