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Dimensionality analysis of subsurface structures in magnetotellurics using different methods (a case study: oil field in Southwest of Iran)

M. Filbandi Kashkouli[1], A. Kamkar Rouhani[1*], A. Moradzadeh[2] and H. Assi[3]

1. School of Mining, Petroleum & Geophysics Engineering, Shahrood University of Technology, Shahrood, Iran
2. School of Mining Engineering, College of Engineering, University of Tehran, Tehran, Iran
3. National Iranian Oil Company (NIOC), Tehran, Iran

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**Corresponding author: kamkarr@yahoo.com (A. Kamkar Rouhani).*

Abstract

Magnetotelluric (MT) method is an electromagnetic technique that uses the earth natural field to map the electrical resistivity changes in subsurface structures. Because of the high penetration depth of the electromagnetic fields in this method (tens of meters to tens of kilometers), the MT data is used to investigate the shallow to deep subsurface geoelectrical structures and their dimensions. In order to have a higher accuracy in modeling the MT data, dimensions of the subsurface structures should be determined. The objective of this research work is to determine the dimensions of subsurface structures in an oil field located in the southwest of Iran. Using parameters such as the normalized weighted index, ellipticity, and Wall's rotational invariant measure, this goal could be achieved. Using the ellipticity factor at the frequency range of 1-320 Hz, the earth can be represented as a 2D form. However, at lower frequencies, the earth should be represented as a 3D form. In most MT stations, the normalized weighted index has indicated that the earth is in a 2D form on the surface or shallow subsurface, although it is represented by a 3D shape at higher depths. In this regard, the Wall's rotational invariant measure shows more heterogeneity. This measure indicates that the earth is in the 2D and 3D forms on the surface or shallow subsurface, and is perfectly 3D at higher depths, although the earth dimensions cannot be determined in some certain frequency ranges. The earth in both the shallow and deep parts of the studied area has a high heterogeneity.

Keywords: *Magnetotellurics, Dimensional Analysis, Normalized Weighted Index, Ellipticity, Wall's Rotational Invariant Measure.*

1. Introduction

Magnetotelluric (MT) method is a passive electromagnetic technique, in which the time-variant and perpendicular components of the electric and magnetic fields are measured at the same time on the surface. The main source of the electromagnetic fields in the MT method can be divided into two categories: electromagnetic fields with frequencies less than 1 Hz, and those with frequencies more than 1 Hz. The first set of fields has a significant importance since they can be used in deep explorations. Because of the variable penetration depths of the electromagnetic waves (from shallow to deep) in this method, they can be used to determine the dimensions of the geoelectrical subsurface structures in such depths.

The first key parameter used in this work for determination of the dimension of subsurface structures was the skewness parameter. It was introduced by Swift in 1967 [1]. Then Ward et al. [2] employed the ellipticity parameter to determine the dimensionality of the geoelectrical subsurface structures. In 1988, Bahr introduced a skewness parameter sensitive to the phase. The parameter of polar plots of the impedance tensor was introduced in 1990 [3]. In accordance with the Wall's rotational invariant method, Marti et al. [4] presented a method that could identify the existence of surface heterogeneity. Hamzeloei [5] and Zeinalpour [6] have presented a dimensionality analysis of the MT data from different areas in the Sabalan region, located in the northwest of Iran. Hashemi [7] made a dimensionality analysis on the MT data acquired from the Kopeh Dagh area, northeast of Iran, as well as the MT data from the Oklahoma areas and Papua New Guinea. In this work, a dimensionality analysis of the geoelectrical subsurface structures in an Iranian oil field was made using different parameters.

2. Geology of studied area

The studied area is located in one of the southwest oil fields in Iran. The geological map of the area is presented in Figure 1. In this area, exposure of the Gachsaran formation at the ground surface and the highly tectonized zone have caused problems such as failure in the acquisition and interpretation of the seismic data. Almost all of the Iran oil formations in this region, due to the tectonics and uplift, can be seen at the ground surface, while the predominant formation is Gachsaran. Due to the failure in the acquisition and interpretation of seismic data, the MT surveys in this area were carried out by a Chinese company in 2011. The location of the MT survey lines in the studied area is shown in Figure 2.

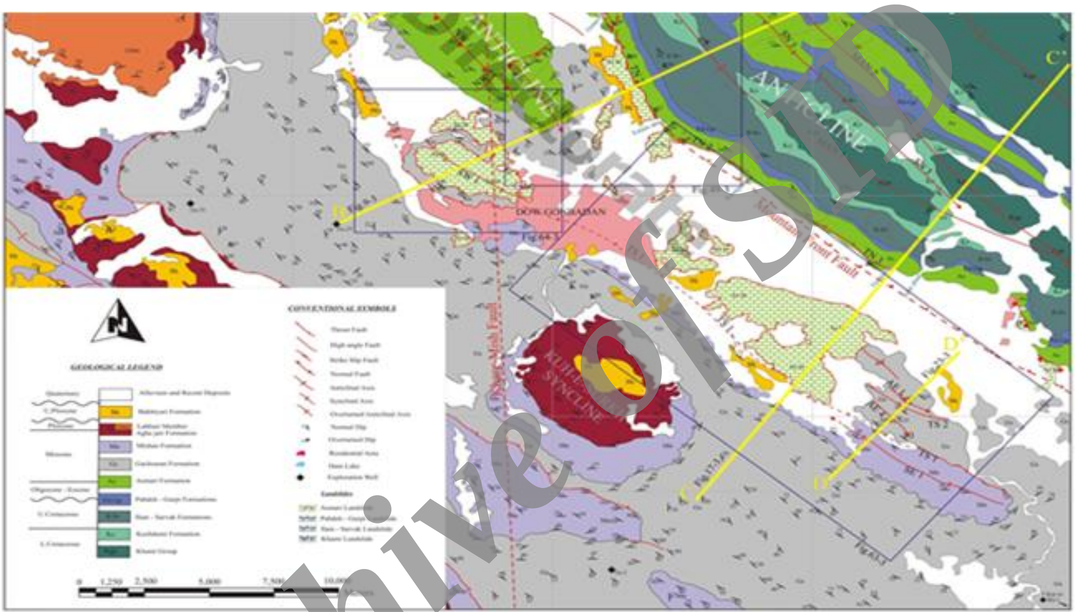

Figure 1. Geological map of studied area (1:50000, adopted from areport on geology of studied area, provided by Exploration Directorate of National Iranian oil Company [8].

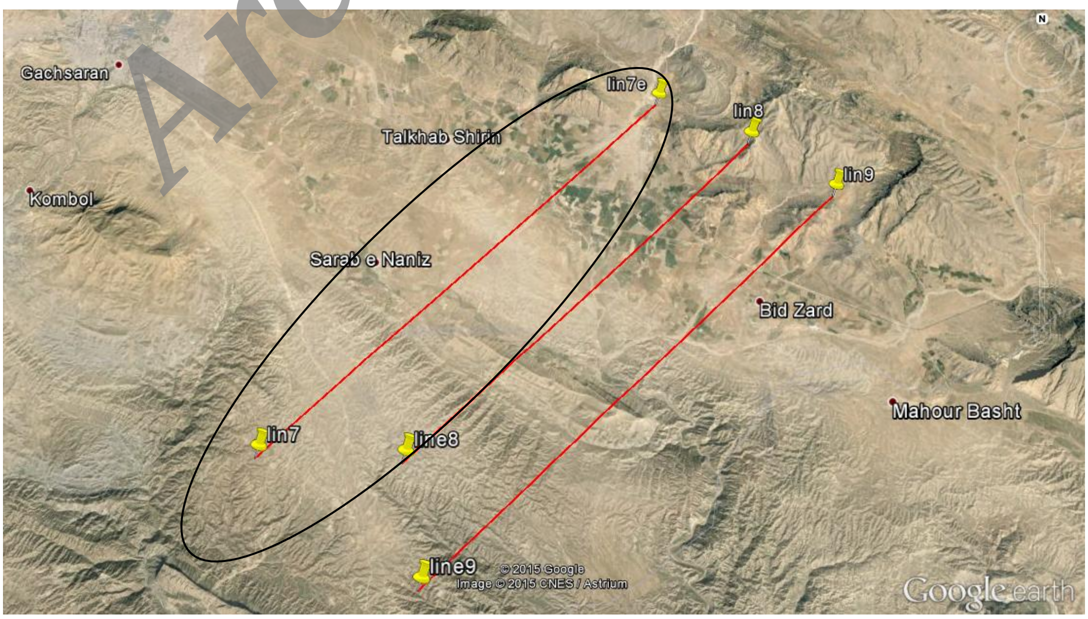

Figure 2. Locations of MT survey lines. MT survey line investigated in this study is surrounded by an ellipse.

3. Dimensionality analysis using different MT parameters

The MT method uses the earth natural electromagnetic field as a field source. In this method, the time changes of the horizontal components of the electric and magnetic fields are measured perpendicularly at the surface. Then the earth impedance is calculated at different frequencies after a series of complex mathematical operations is made. By means of amplitude changes and impedance phase calculated using these fields, the subsurface resistivity structure is interpreted [9].

$$\rho_{i,j} = 0.2T\left|Z_{ij}\right|^2 \quad (1)$$

$$\phi_{i,j} = \tan^{-1}\left|\frac{\operatorname{Im}\left|Z_{ij}\right|}{\operatorname{Re}\left|Z_{ij}\right|}\right| \quad (2)$$

In the above equations, ρ is the apparent resistivity, T is the measurement period, ϕ is the phase of measurement impedance, $\operatorname{Im}\left|Z_{ij}\right|$ is the imaginary part of the electrical impedance, and $\operatorname{Re}\left|Z_{ij}\right|$ is the real part of the electric impedance. i and j are the x and y directions.

The values obtained for the resistivity and impedance phases are used in the interpretation and modeling. Modeling of the MT data can be done as one, two or three dimensions. Thus for any electrical structure with regard to the electric and magnetic fields on an MT site, the impedance tensor is achieved:

$$\begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} & Z_{xz} \\ Z_{yx} & Z_{yy} & Z_{yz} \\ Z_{zx} & Z_{zy} & Z_{zz} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} \quad (3)$$

In the MT method, E_z is normally close to zero (except at very high frequencies) because the vertical component of the electric field is quickly damped. Therefore, in a 2D structure, Eq. (3) is modified as:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \quad (4)$$

in which, $Z(\omega) = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix}$, a complex matrix in the frequency domain, is called the impedance tensor, and is determined for each frequency [10]..

The compositions of the rotational invariants Z_1, Z_2 , Z_3, and Z_4 are expressed as [11]:

$$\begin{aligned} Z_1 &= \frac{(Z_{xy} - Z_{yx})}{2} \\ Z_2 &= \frac{(Z_{xx} + Z_{yy})}{2} \\ Z_3 &= \frac{(Z_{xy} + Z_{xy})}{2} \\ Z_4 &= \frac{(Z_{xx} - Z_{yy})}{2} \end{aligned} \quad (5)$$

Given the above relationships, the skewness parameter can be defined as:

$$S = \frac{|Z_2|}{|Z_1|} \quad (6)$$

In situations where S > 0, it is an indication of the 3D subsurface structures; and when S = 0, the electrical subsurface structures are 1D or 2D.

One of the main issues is the disagreement on the upper limit of the skewness for the 3D structures. Some researchers have defined the skewness upper range to be 0.12-2 for the 2D structures [11, 12], while others have changed the range to 0.001-0.72 because of the turbulence of the surface heterogeneity [13].

Another parameter, ellipticity, is defined as follows:

$$e = \frac{|Z_4|}{|Z_3|} \quad (7)$$

Similar to the quantity of skewness, the ellipticity quantity is zero or close to zero in the 1D or 2D structures, and the ellipticity values greater than zero indicate the 3D structures.

Definitely, using these parameters, the three-dimensionality of a subsurface structure cannot be determined. The experience from actual modeling shows that, in many cases, the skewness values is about 4.0 or more, while other evidences point to 1D or 2D structures [14]. For this reason, Kao and Orr [14] introduced the weighted indices, and Bahr [3] introduced the phase-sensitive skewness as a measure of the regional structure size:

$$\eta = \frac{C^{1/2}}{|Z_1|} \qquad C = \left[\mathrm{Im}\left(Z_3.Z_4^{*}\right)\right] - \left[\mathrm{Im}\left(Z_1.Z_2^{*}\right)\right] \tag{8}$$

The "*" sign in the above equation indicates the complex conjugate of the sentence.

Kao and Orr [14] designed the normalized weighted indices, which show proportions of each of the one, two or three-dimensional structures. Neither of these indices can show the absolute value of the earth dimension, although if they are interpreted globally, they may provide an estimate of different structure distributions.

The relationships associated with these indices are given below:

$$D_1 = \frac{|Z_1|}{\gamma} \qquad D_2 = \frac{|M_1|}{\gamma} \qquad D_3 = \frac{|Z_3|}{\gamma} \qquad D_3' = \frac{|M_2|}{\gamma} \tag{9}$$

$$\gamma = (|Z_1| + |M_1|) + (|Z_2| + |M_2|)/2 \qquad M_1 = \left(Z'_{xy}(\theta_0) + Z'_{yx}(\theta_0)\right)/2 \qquad M_2 = \left(Z'_{xx}(\theta_0) - Z'_{yy}(\theta_0)\right)/2 \tag{10}$$

θ_0 is an angle, in which $|M_1|$ has its maximum value. γ, M_1, and M_2 are the parameters related to the impedance values, which are defined by Eqs (10).

All of these indices vary between zero and one. For the 1D structures, the condition $D_1 > D_2 > D_3$ is expected, while D_1 and D_2 behave reversely. Great values for D_2 and D_3 (more than 2.0) state that there are 2D and 3D structures in the area. [15]

When the acquired data has a high quality (which means that the multiple coherence between the electric and magnetic field components is about 0.9 or more), values greater than 0.1 for D_2 and D_3 represent the 2D and 3D structures in that region. In the dead band frequency (in which the multiple coherence between the electric and magnetic field components is between 0.9 and 0.7), for the 2D and 3D structures, even the values 0.2 and 0.3 appear instead of 0.1 [14, 10]].

3.1. VALDIM dimensionality analysis

Marti et al. [4] have developed the VALDIM program as a complete one for the numerical analysis of the MT data based on the Weaver et al. [16] rotational invariants. Rotational invariants are parameters that are defined in a series of algebraic equations of the impedance tensor components. These parameters remain constant against the rotation of impedance tensor.

Weaver et al. [16] have defined eight rotational invariants, and presented a dimensionality analysis method for the MT data. One of the important issues in the use of the procedure introduced by Weaver et al. [16] is that it can be applied to real data. The real data are usually noisy. Because of the noise, it rarely happens that a zero value parameter is exactly zero. In other words, the rotational invariants in real data may never be precisely zero.

Therefore, it is essential that some appropriate thresholds are defined for some rotational invariants. This problem has been resolved in the VALDIM program. This program has also other considerations in comparison with the procedure introduced by Weaver et al. [16]. For example, the dimensionality analysis can be performed on the desired frequency range, and in the calculation of all parameters, the error is considered. The VALDIM program not only does a full dimensionality analysis of MT data but also includes all the criteria existing in the strike analysis [17] and phase tensor programs [18].

4. Dimensionality analysis of subsurface structures

For having an appropriate quantitative model of the MT data, the subsurface structures should be identified. The sounding information may include 1D, 2D or 3D structural components. In this study, the data from 5 stations of the survey line number 8807 in the studied area was selected and evaluated in several different ways.

4.1. Normalized weighted indices

As mentioned earlier, these parameters display the portion of 1D, 2D, and 3D structures. For the 1D structures, $D_1 \rangle D_2 \rangle D_3$ is expected, and for the 2D and 3D ones, the D2 and D3 values are expected to be greater than 0.2. Figure 3 shows the normalized indices for the MT stations 103, 110, 132, 148, and 169.

In most of the above MT sites, in the frequency range of 1-320 Hz, we can see that $D_1 \rangle D_2 \rangle D_3$. This indicates that the surface or shallow subsurface structures are 1D, and as the depth increases (i.e. frequency decreases), the earth would become more complex and the subsurface structures would be 2D or 3D. The chart for the MT stations 132 and 169, shown in Figure 3, indicates that the D_2 and D_3 values are greater than 0.2 and greater than D_1. This means that the earth is complex at the surface as well or it is 2D or 3D.

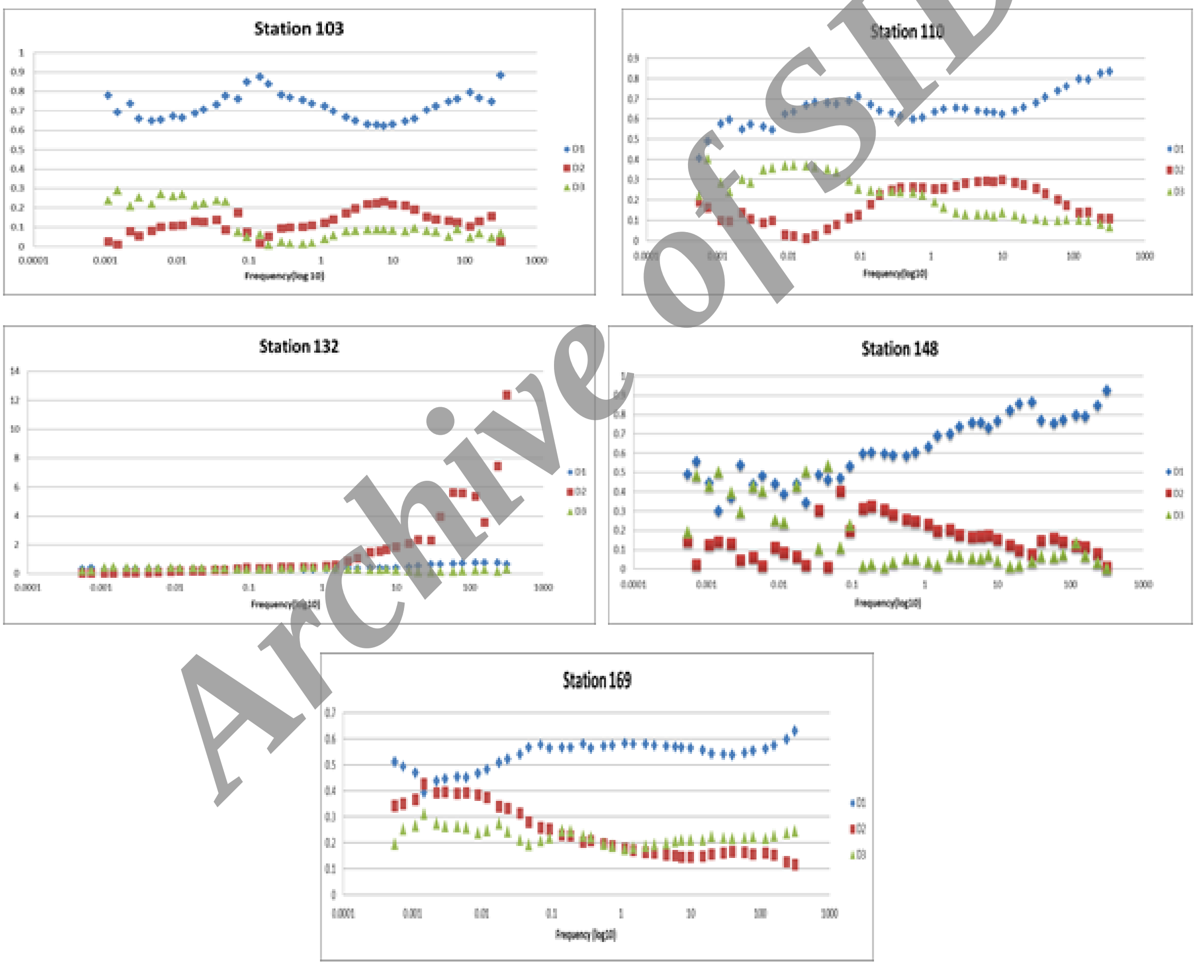

Figure 3. Values for normalized indices in different stations.

4.2. Ellipticity

The ellipticity values greater than 1 state the 3D structures, and less than that shows the 1D or 2D subsurface structures. The ellipticity values in the MT stations 103, 110, 132, 148, and 169 can be seen in Figure 4.

According to the chart in Figure 4, in the three MT sites 103, 110, and 148, in the frequency range of 1-320 Hz, the ellipticity values are about zero, which implies the display 1D or 2D subsurface structures. In the MT stations 132 and 169, in most frequencies, the ellipticity values are greater than 1, which show the three-dimensionality of the studied area.

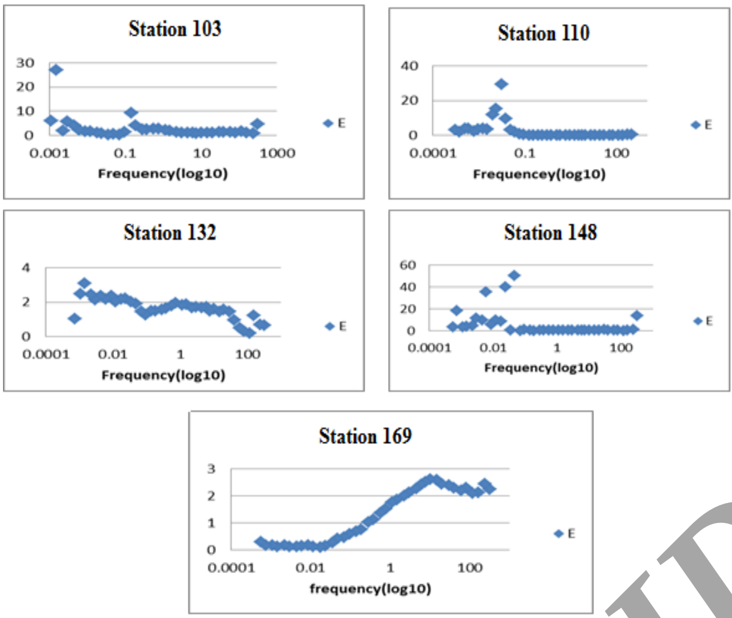

Figure 4. Ellipticity values in different stations.

4.3. Dimension indication using Wall's rotational invariant measure

The analysis of the Wall's rotational invariant measure is presented in Table 1. Each value shows the following characteristics:

Undetermined 1: 1D 2: 2D 3: 3D/2D only twist 4: 3D/2D general 5: 3D 6: 3D/2D with regional inclined tensor 7: 3D/2D or 3D/1D indistinguishable

Using the Table, one can see in the high frequencies that the earth surface is 3D/2D or 3D, and in the low frequencies, corresponding to the deeper parts, the earth in the depth is completely 3D or indistinguishable 3D/2D.

Table 1. Wall's rotational invariant measure analysis in various stations.

Site	Band	Min. Frequency	Max. frequency	Dimensionality
103	1	240	360	5
	2	30	160	3
	3	4.5	20	5
	4	2	3	7
	5	0.37	1.5	0
	6	0.00055	0.281	4
110	1	240	360	5
	2	30	160	3
	3	4.5	20	5
	4	2.25	3	7
	5	0.37	1.5	0
	6	0.00055	0.281	5
132	1	120	320	5
	2	40	80	3
	3	0.141	30	5
	4	0.047	0.094	3
	5	0.0088	0.035	0
	6	0.0014	0.0059	7
	7	0.00055	0.0011	0
148	1	40	320	5
	2	10	30	4
	3	4.5	7.5	5
	4	2.25	3	3
	5	0.141	1.5	5
	6	0.023	0.094	4
	7	0.0176	0.0293	7
	8	0.00055	0.0022	5
169	1	240	320	4
	2	20	160	3
	3	6	15	7
	4	0.0176	4.5	5
	5	0.0088	0.0117	4
	6	0.00055	0.0059	5

5. Discussion and conclusions

The normalized weighted indices in the high frequency range (which shows the earth surface) represent 1D earth. This is not evident in all stations because of the area heterogeneity. In low frequency ranges, the normalized weighted indices show 3D earth. In 3 out of 5 studied stations, the ellipticity values show shallow earth as a 1D or 2D structure, and in the other stations, it is greater than 1, showing 3D earth.

The wall's rotational invariant measure displays 3D earth in most of the stations and frequency ranges.

By comparing the results obtained from the dimensionality analysis obtained from the three methods discussed, we can see that for the MT stations 132 and 169, in most frequencies related to the shallow and deep subsurfaces, the earth structures are 2D and 3D. Moreover, for the MT stations 103, 110, and 148, the ellipticity parameter or method predicts the earth region in the 1-320 Hz frequency range as 1D and 2D, while the other two dimensionality analysis parameters or methods predict the earth as 2D and 3D.

Figure 5 displays the results obtained for the 2D inverse modeling of the MT data along the survey line 8807 in the studied area. This 2D model has been produced using the WinGLink software by the non-linear conjugate gradient inverse modeling method. The modeling results clearly show that in certain stations, the earth has a great heterogeneity. This heterogeneity is quite obvious in the distance ranges of 4-10 and 13-15 Km (where a higher resistivity is observed in the surface than in the depth). In a deeper part, the normal attitude of increasing resistivity with depth is clear, which generally confirms the results obtained from the dimensionality analysis. The 2D modeling of the MT data, shown in Figure 5, can be an approximate and acceptable subsurface model from the area as most of the subsurface structures are 1D or 2D, according to the dimensionality analysis carried out in this research work. However, the 3D subsurface structures that exist in some parts cause the accuracy of the model shown in Figure 5 to be reduced. Furthermore, this model is generally in good agreement with the geological information from the area.

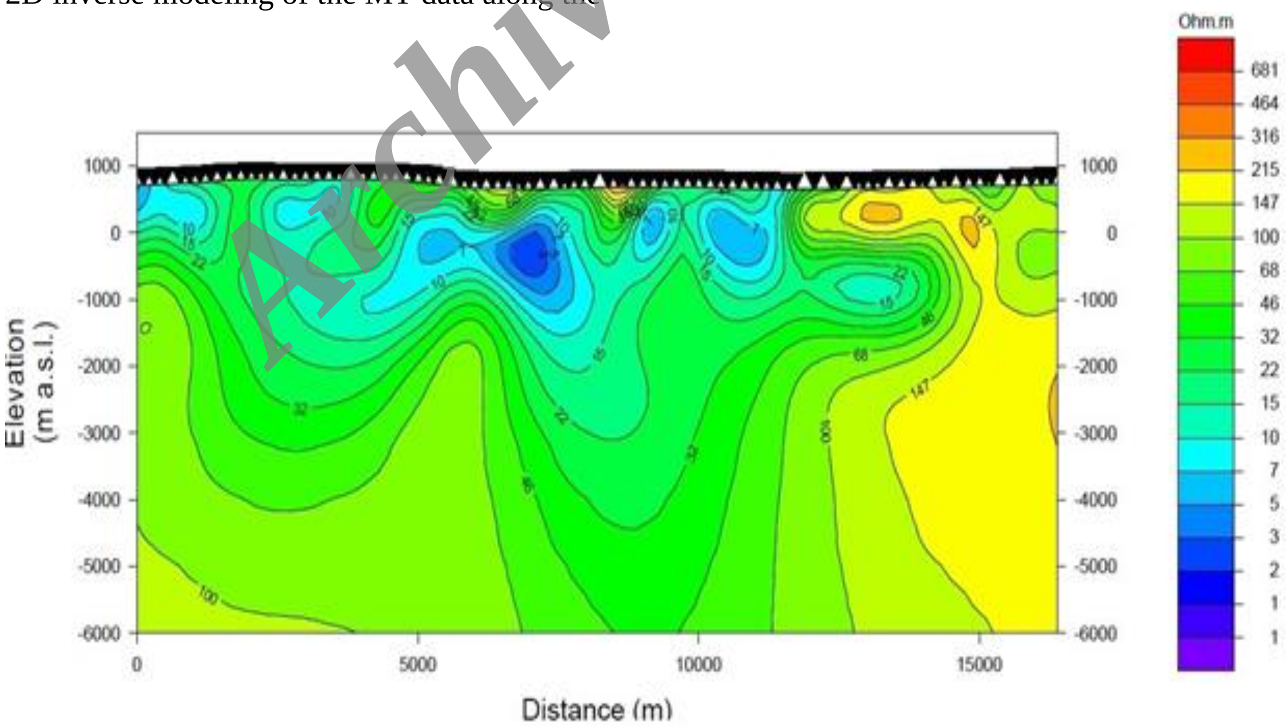

Figure 5. 2D-modeling along survey line 8807.

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تحلیل ابعادی ساختارهای زیرسطحی با استفاده از پارامترهای مختلف مگنتوتلوریک دریکی از مناطق نفتی جنوب غرب ایران

محمد فیلبندی کشکولی[۱]، ابوالقاسم کامکار روحانی[۱*]، علی مراد زاده[۲] و حسین عاصی[۳]

۱- دانشکده مهندسی معدن، نفت و ژئوفیزیک، دانشگاه صنعتی شاهرود، ایران

۲- دانشکده فنی و مهندسی، دانشکده معدن، دانشگاه تهران، ایران

۳- مدیریت اکتشاف و تولید شرکت ملی نفت ایران، ایران

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* نویسنده مسئول مکاتبات: kamkarr@yahoo.com

چکیده:

روش مگنتوتلوریک یکی از روش‌های الکترومغناطیسی است که از میدان‌های طبیعی زمین برای به نقشه درآوردن تغییرات مقاومت ویژه الکتریکی زیر سطح زمین استفاده می‌کند. عمق نفوذ بالای میدان‌های الکترومغناطیس درروش مگنتوتلوریک (از ده‌ها متر تا ده‌ها کیلومتر) باعث شده است که از داده‌های مگنتوتلوریک برای بررسی ساختارهای ژئوالکتریک زیرسطحی و ابعاد آن‌ها از اعماق کم تا اعماق زیاد استفاده شود. برای اینکه مدل‌سازی کمّی از دقت بالاتری برخوردار باشد لازم است تا ابعاد ساختارهای زیرسطحی مشخص شوند. هدف از انجام این مطالعه تعیین بعد ساختارهای زیرسطحی دریکی از مناطق نفتی جنوب غرب ایران است که این مهم با پارامترهایی همچون شاخص‌های وزنی نرمال‌شده، بیضی‌وارگی و معیار نامتغیر چرخشی وال به دست می‌آید. با استفاده از پارامتر بیضی‌وارگی در فرکانس ۱-۳۲۰ هرتز زمین مورد بررسی به‌صورت دوبعدی و در فرکانس‌های پایین‌تر، زمین مورد نظر سه‌بعدی به دست آمد. در بیشتر ایستگاه‌ها اندیس‌های نرمال‌شده در سطح، زمین را دوبعدی و سه‌بعدی نشان دادند ولی در عمق، زمین را سه‌بعدی نشان دادند. معیار نامتغیر چرخشی وال ناهمگونی‌های بیشتری را نشان داد و در سطح سه‌بعدی و دوبعدی بودن را برای زمین مشخص کرد و در اعماق بیشتر زمین سه‌بعدی کامل نشان داده و در برخی بازه‌های فرکانسی نیز موفق به تعیین بعد نشد. نتیجه‌گیری کلی این بود که زمین در سطح و عمق دارای ناهمگونی‌های بسیاری است.

کلمات کلیدی: مگنتوتلوریک، تعیین ابعاد، اندیس‌های وزن‌دار نرمال شده، بیضی‌وارگی، معیار نامتغیر چرخشی وال.