



Research Paper

Joint Inversion of Resistivity and Induced Polarization Data for Metal Deposit Exploration

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Electrical resistivity (RS) and induced polarization (IP) methods have an important role in exploration of disseminated metal and sulfide mineralization zones. In the exploration geophysics, in order to minimize the error in determining the dimensions and depth of anomalies, two integrated geophysical methods are common. This paper investigates the capability of the electrical resistivity and induced polarization methods in order to delineate the presence of minerals containing metal ore deposits. The presence of metal ore deposits in rocks generally lowers the resistivity. Ions in the vicinity of metallic grains in rocks increase the chargeability of the rock when measured using IP method. Since it is possible to define any arbitrary structure in forward modeling, it was used to generate data. Some noise was added to make the data look like real observed data. Also, a computer program was written in MATLAB for performing inversion modeling using finite element method. Finally, this program was applied to determine the limits of the existent anomalies based on the real data collected from Bardaskan region (Khorasan Razavi province in Iran) and to be sure, it was compared with the RES2D INV that the results were satisfactory.

Keywords: Electrical resistivity, Induced polarization, Metal ore deposits, Inversion modeling

Introduction

The idea of mineral exploration by the aid of electrical measurements was presented at about 1800 but the practical and promising application of the method was made possible about a century later (Mooney, 1980). The demand for mineral raw materials (metals, oil and coal) is

increasing exponentially with the current status of the international community and its future trend. Clearly, getting these diverse metal minerals is more difficult and more expensive every day. Visible mines at or near the surface of the earth have already been known and discovered. Current and future exploration should be done in

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areas where the minerals are worn and are deeper. This requires the use of geophysical methods such as electrical resistivity and induced polarization methods, which can provide geological subsurface information especially in mineral exploration (Telford *et al.*, 1990).

All geophysical techniques are based on the detection of contrasts in different physical properties of materials. Electrical methods depend on the contrasts in electrical Resistivity (Telford *et al.*, 1990).

Two techniques that were used in this study area were electrical resistivity (RS) and induced polarization (IP) method.

The electrical resistivity method due to its low equipment cost and ease of use is routinely used in mineral exploration. Electrical resistivity surveys are applied to get information on the depth of anomaly and resistivity of bedrock and overlying units. The presence of metal ore deposits in rocks generally lowers the resistivity. The IP method deals with chargeability indicates the strength of polarization effects to locate zones where metal deposit minerals are disseminated within their host rock. The presence of metallic ore deposits in rocks increases the chargeability of the rock (Wahyu Srigutomo *et al.*, 2016).

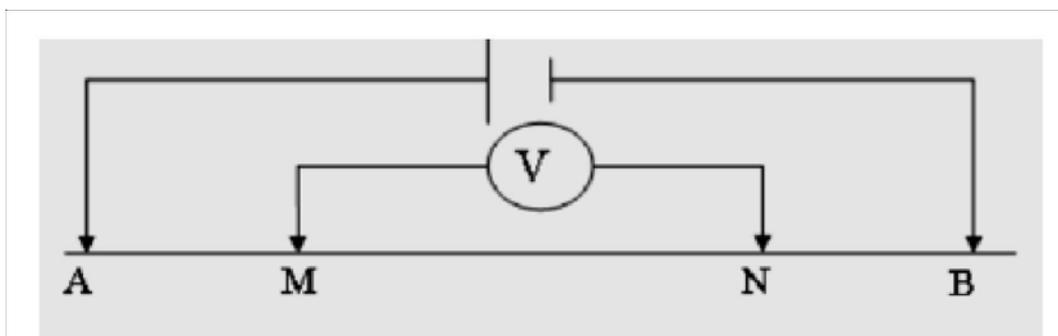
In this study we investigated the applicability of DC electrical resistivity and induced Polarization in written program for inversion modeling in MATLAB environment and then comparing the obtained result from real field data Bardeskan area with RES2DINV software.

Electrical Resistivity Method

The main purpose of electrical resistivity method is to measure the earth's resistivity. In these methods, in order to determine a subsurface property, its electrical resistivity must be significantly different from its surroundings. So, the use of electrical methods is limited to a state in which there is a resistance contrast (Mooney, 1980).

The specific resistivity is the general response related to the formation, porosity and permeability of the rocks, the amount of fluids in the cavities and pores and the extent of their salinity as well as the existence of mineralization in the ground's subsurface rocks. The specific resistivity of the subsurface structures can be estimated via injecting DC current (I) into the ground by two metal electrodes at the surface and measurement of the potential difference in the subsurface by two potential electrodes (ΔV) at the surface as shown in Figure 1 (Telford *et al.*, 1990).

Figure 1: Four Electrodes Array (A, B are DC Current Electrodes and M, N are Potential Electrodes)



The resistivity of the ground is the quantity value and denoted by ρ_a (apparent resistivity). The relationship between the actual resistivity and apparent resistivity is rather complex. To determine the actual resistivity of the subsurface structures based on the apparent resistivity values, inversion methods in computer software are utilized (Dahlin and Loke, 1998).

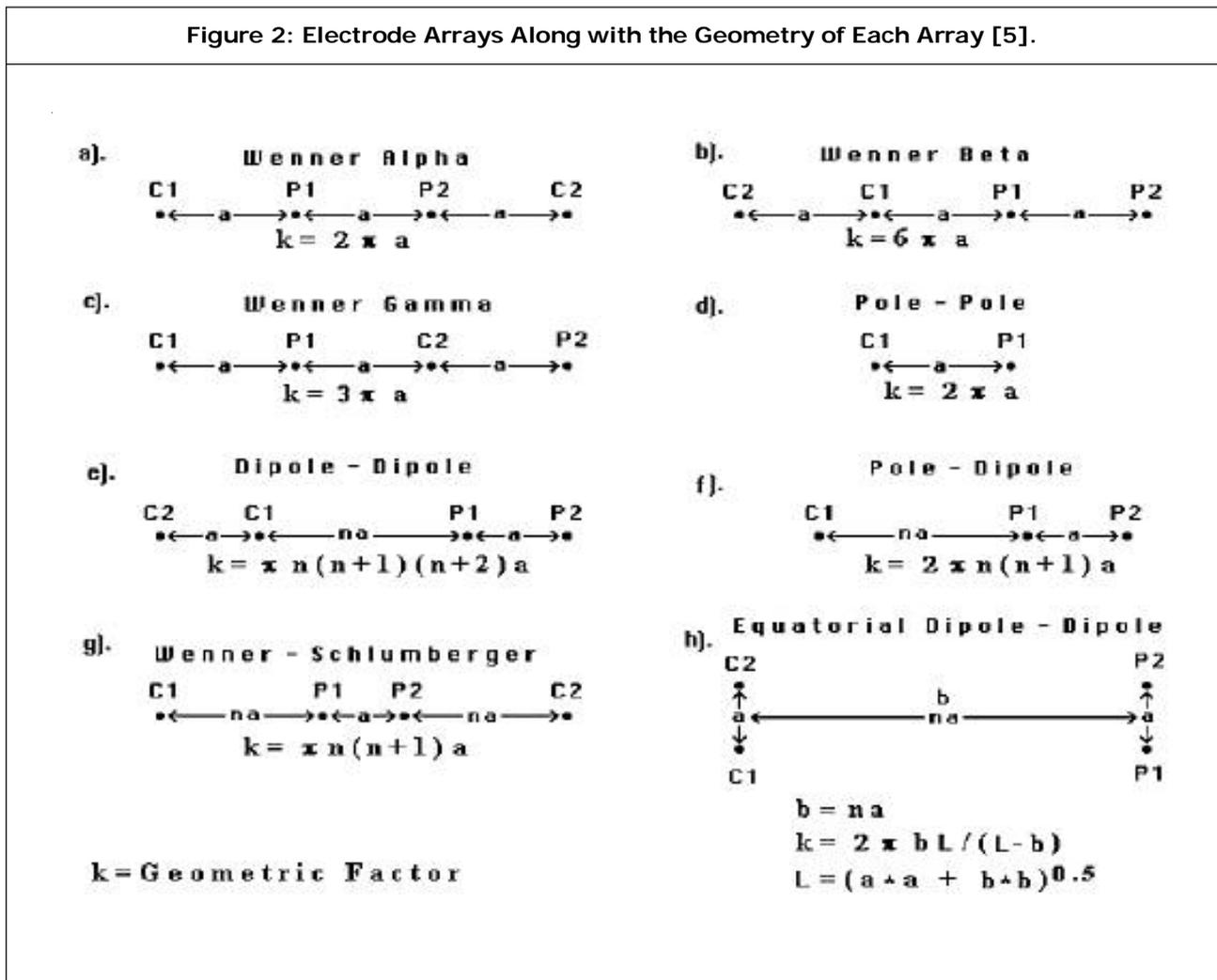
In the electrical resistivity method is convenient to express the measured data in terms of apparent resistivity (in ohm.m) as:

$$\rho_a = k \frac{\Delta V}{I} \quad \dots(1)$$

where K is geometric factor that depends on the arrangement of four electrodes. Imaging depth of resistivity method is dependent on the spacing between electrodes. By increasing the electrode spacing greater depth is achieved. The total length of electrode array also plays role in resulting greater imaging depth (Dahlin and Loke, 1998).

There are various electrode arrays (Figure 2). Each one has its own advantages and disadvantages. Choosing the appropriate array will depend on the space available to extend the array and array efficiency that will be used. The sensitivity of the arrangement to the lateral inhomogeneity and the sloping layer is also has great importance (Loke, 2004).

Figure 2: Electrode Arrays Along with the Geometry of Each Array [5].



The measured apparent resistivity distribution is presented in pseudosection as shown in Figure 3.

Induced Polarization Method

The induced polarization method is used extensively in the mining operation for exploring disseminated sulfide bodies and metallicore exploration. IP method is the value of capacitive action of the subsurface to locate zones where chargeable minerals are located within the host rock (Kearey *et al.*, 2002).

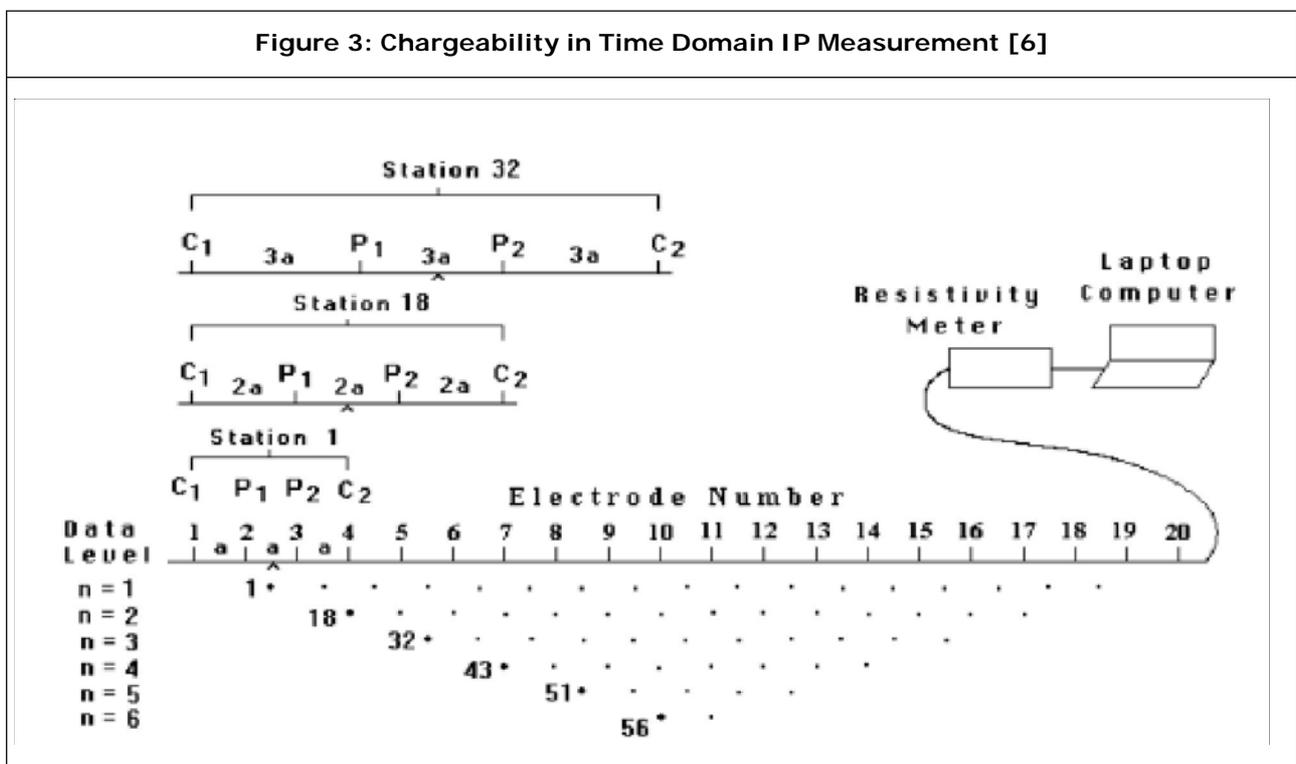
IP deals with chargeability to measures the voltage decay after the injected current is shut off as shown in Figure 4. Chargeability is defined as the area beneath the decay curve over a certain time interval normalized by the steady-state potential difference (Ward, 1990).

$$M = \frac{A}{\Delta V} = \frac{1}{\Delta V} \int_{t_1}^{t_2} v(t) dt \quad \dots(2)$$

The IP survey is very similar to electrical resistivity tomography. Resistivity and IP methods are often applied on the ground surface using multiple four-electrode sites. In an IP survey, in addition to resistivity measurement, polarization effects of the subsurface materials are determined as well [3].

In this study, the time domain IP for obtaining the pseudosection from synthetic and field data was used. It is also worth noting that a computer program was written in MATLAB to perform the calculation of the models based on the finite difference method, which helped simulate the model response proposed in the inversion stages. In order to data generation from any arbitrary structure a program was written for forward modeling. Also, Noise was added to the data to make them as similar as possible to actual observed data. A computer program was also written in MATLAB to perform the inversion. his

Figure 3: Chargeability in Time Domain IP Measurement [6]



program was also used to determine the limits of existing anomalies using actual data collected from Bardaskan, Razavi Khorasan Province, Iran, and the findings were compared with those obtained from RES2D for the sake of certainty.

Synthetic Data Modeling

Forward Modeling

In this study, a forward modeling program written in MATLAB environment was used to generate electrical resistivity and induced polarization data on different models. The first model is a structure that a conductive block buried in a resistive environment or a chargeable block enclosed in a non-chargeable environment. The model of this structure is shown in Figure 5. Some examples of electrical resistivity and induction polarization responses generated from various arrays are presented below.

Schlumberger Array

Figure 5 shows the pseudosection of the apparent resistivity obtained by the schlumberger array on

the structure of the conductive block with 10 Ohm buried inside a resistive 100 ohm medium.

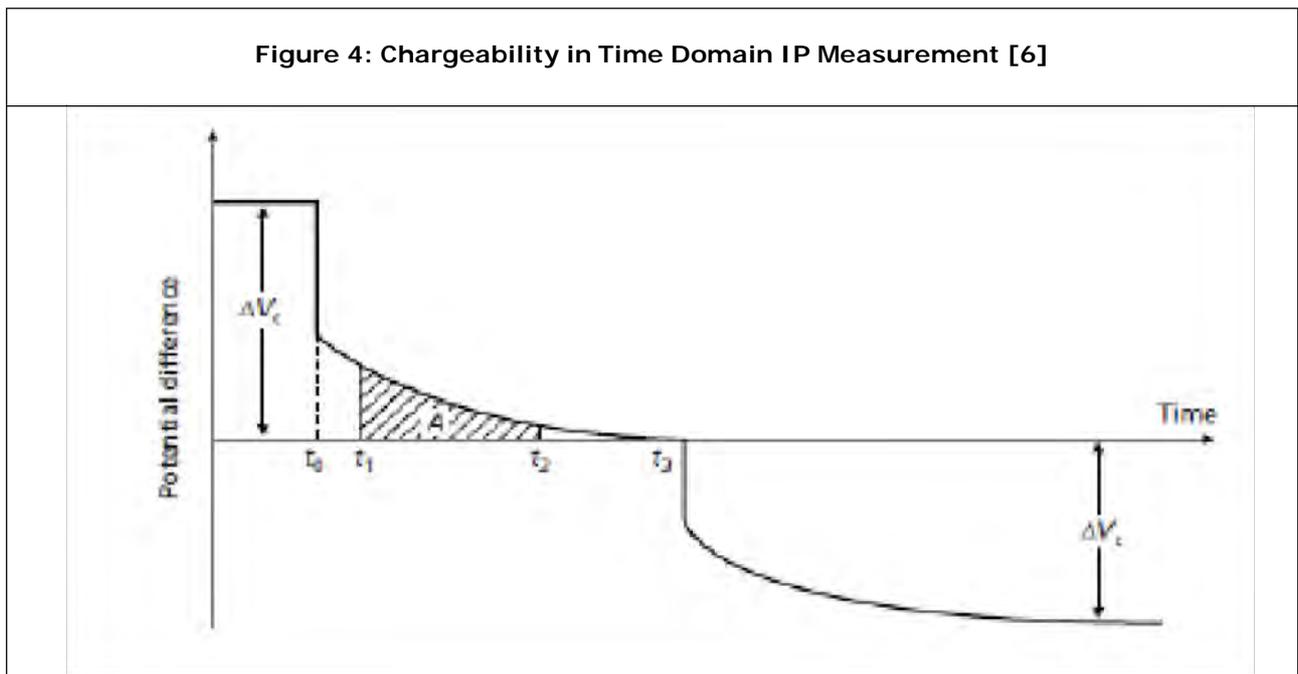
As it can be seen from b and c part of Figure 5, the data had a regular distribution, but are distorted when the noise is added.

Now, it is considered that the same previous structure as a high chargeability block in a lower chargeability medium (Figure 6a) for induced polarization. Figure 6a shows the apparent pseudosection on a structure in which a chargeable block of nearly $30 \frac{mV}{V}$ is located in a medium with chargeability near zero. The apparent chargeability pseudosection obtained from the schlumberger array on the above mentioned structure is shown in Figure 6b.

Inversion Modeling

The purpose of the inversion is to extract and estimate the parameter of the model obtained from the matching of the model's response and observed data. The answer of inversion is never

Figure 4: Chargeability in Time Domain IP Measurement [6]



unique, and all the answers are determined by a certain error (Roy, 2008). In the process of inversion, the least squares approximation method is used because of its high mathematical capability (Allaire, 2007).

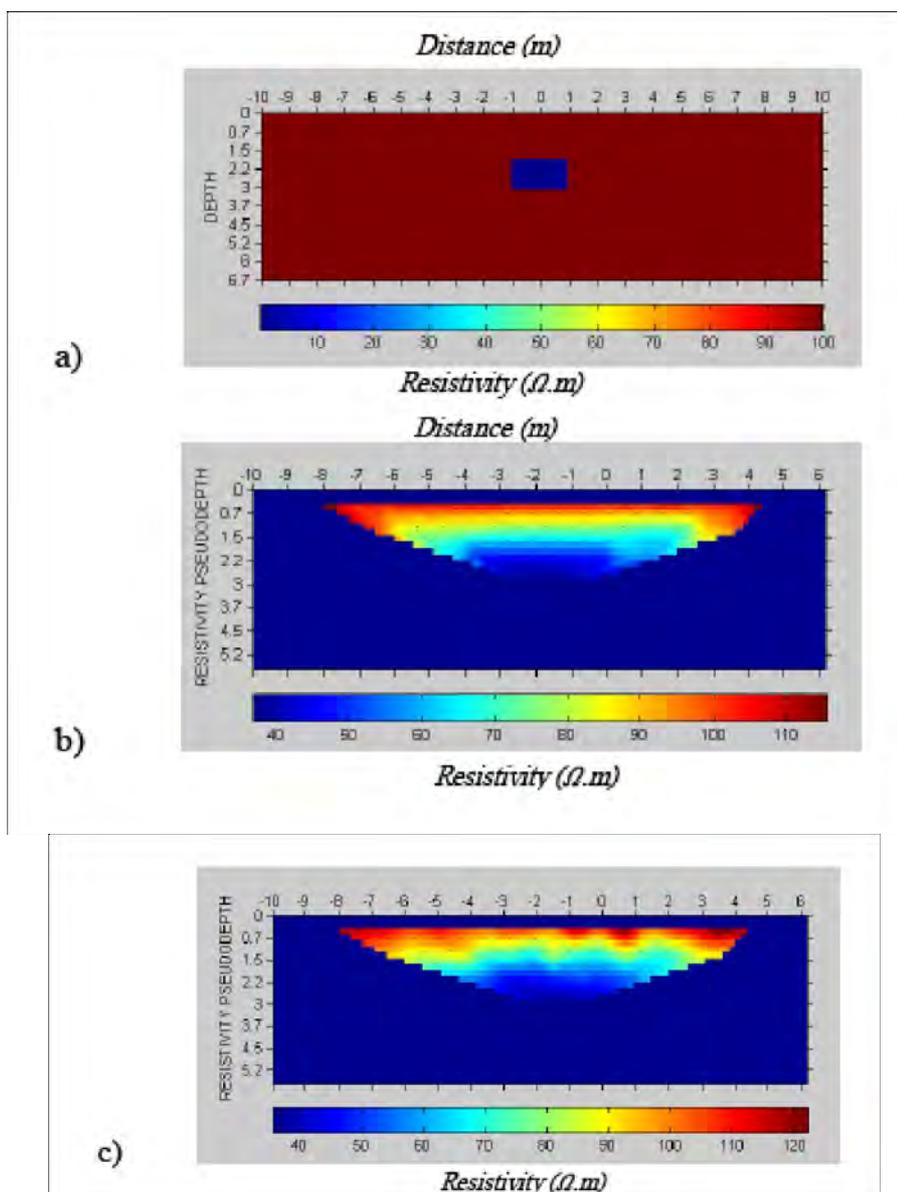
To get the inversion modeling from data, a computer program is written in the MATLAB

environment. Furthermore, the results of the inversion of the electrical resistivity (RS) and induced polarization (IP) data for the two buried conductive blocks are shown in Figure 7.

Two Separate Conductive Blocks

Figure 7 a shows two conductive blocks with different levels of conductivity and chargeability

Figure 5: A) Conductive Block Buried in a Resistive Medium; B) The Electrical Response of the Schlumberger Array on a Buried Conductive Block Using Direct Modeling; C) The Electrical Response of the Schlumberger Array for a Buried Conductive Block With a 5% Noise



relative to medium. These two blocks are more conductive than the medium with resistivity of 200-ohm, but they have not the same resistivity (one of them is 1 ohm and the other 40 ohm). Figure 7b and 7c represents the cross-section of the resistivity data inversion and cross-section of induced polarization method obtained from pole-

dipole array on the given structure in Figure 7a, respectively.

With a simple comparison, it can be seen that high chargeability is observed in areas with a low resistivity, although in the IP cross-section the location of blocks slightly displaced due to the noise effect.

Figure 6: a) A Chargeable Block is in an Unchangeable medium; b) The IP Response of the Schlumberger Array on a buried Chargeable Block; c) The IP Response of the Schlumberger's Array on a Buried Chargeable Block with a 5% Noise Pollution

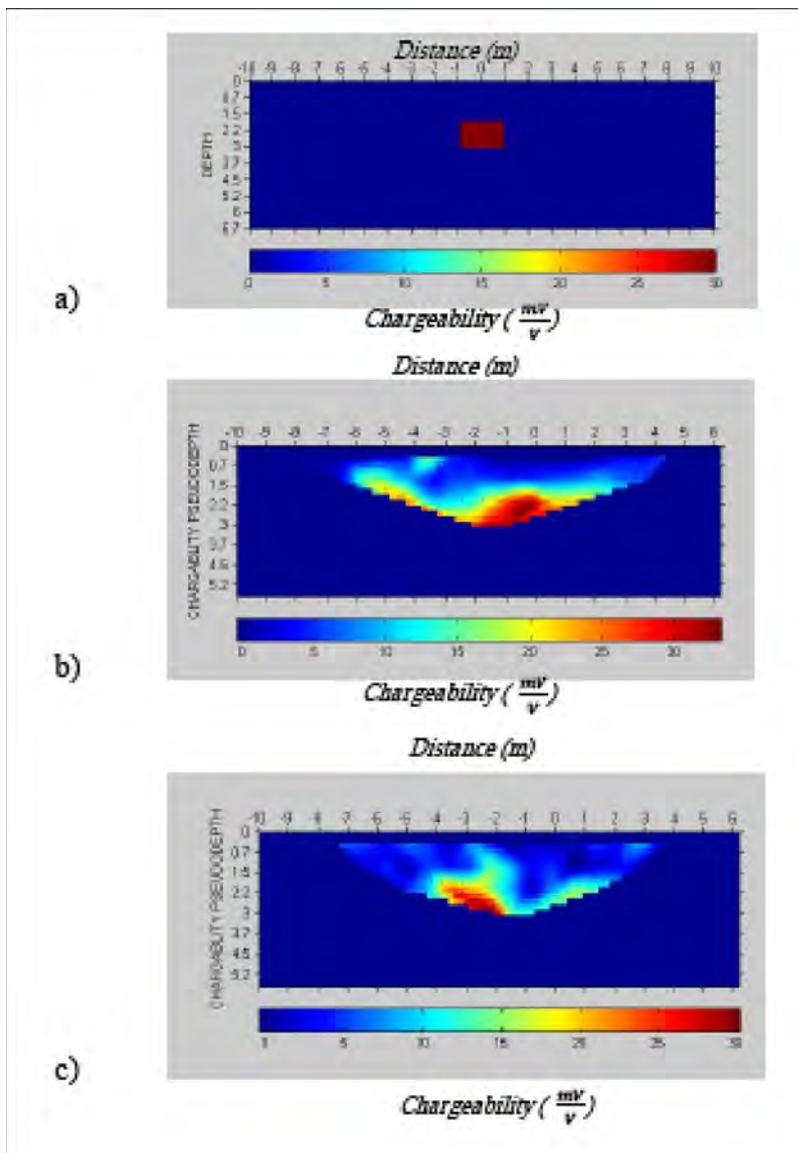


Figure 7b shows that pol-dipole arrays up to certain level detect these two blocks in terms of resistivity and separation but the contrast between the two blocks could not be well exposed to the background. The pseudosection of inversion of IP data has been able to better identify the more chargeable area (Figure 7c).

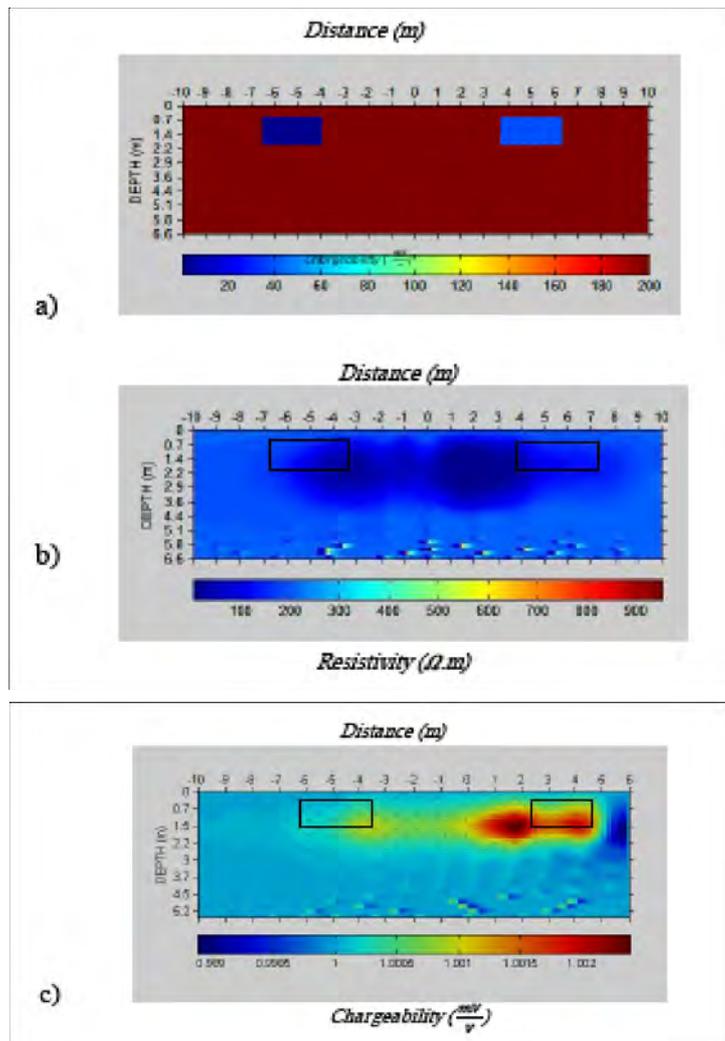
Figures 8a show the pseudosection of RS and IP method resulting from the inversion of data by

the wenner arrays on a structure mentioned in Figure 8a.

In Figure 8a, heterogeneous objects have an acceptable distinction to the environment, but the separation of two objects from each other does not appear in the image and instead of two bodies, only one object is drawn along the horizon in the image.

In the IP cross-section of Figure 8b, the chargeable area is better defined, obviously with

Figure 7: a) Shows Two Conductive Blocks in a Very Low Conductive Medium; b) The Obtained Inversion Pseudosection From the RS Data By Pole-dipole Array on Structure of Figure 7a; c) The Obtained Inversion Pseudosection From IP Data by Pole-dipole Array on A Structure of Figure 7a



precision in two cross-sections; it is possible to better determine the location of the anomaly.

With a general comparison for obtained cross-sections from the Wenner and pole-dipole arrays for RS and IP methods, it can be deduced that the polar-dipolar array in resistivity cross-section has been able to partially reveal two objects individually, however, the dimensions of the two bodies, as well as the depth of their burial, have not been properly shown. Also, on the result obtained from the Wenner array, due to the weakness in horizontal resolution, the anomaly is revealed in the form of a continuous object. However, it gives a better result on the depth of the burial, confirming the vertical separation power of the Wenner array.

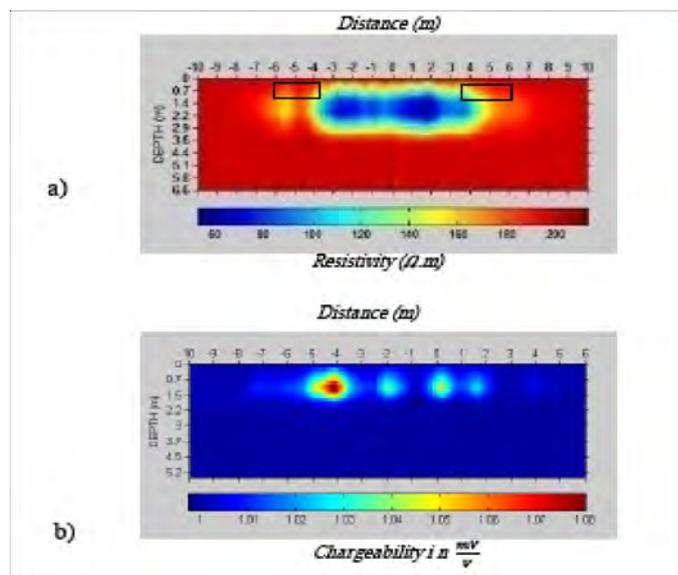
In general, the pseudosection of IP data inversion has been able to better determine the location of anomalies. However, in some cases, additional sections are created in the structure resulting from high noise levels.

Study of Geological Area and Materials

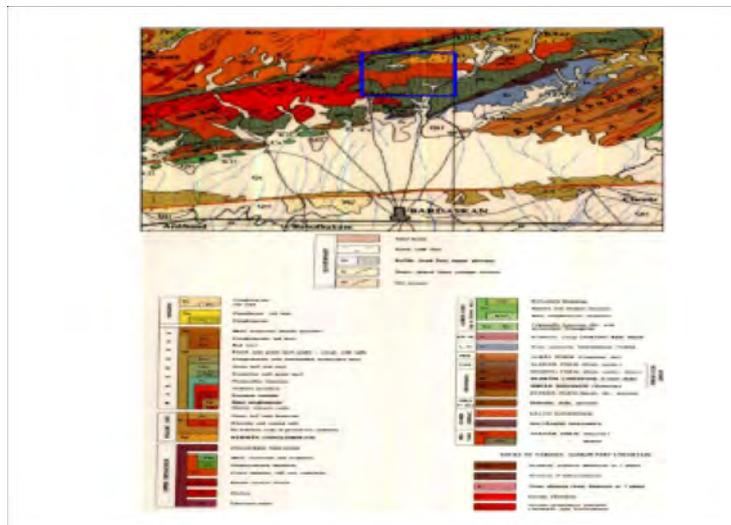
Field data collected from the region of Kaboodan-Bardaskan (Khorasan razavi province) in Iran by geological survey and mineral exploration of Iran (GSI) that they were used to investigate the proposed program. In the cited region, geophysical operations have been performed using RS and IP to discover copper. This area was surveyed using a Dipole-Dipole array and with the details of $AB=MN=20$ m. This device is adjusted in such a way that it injects current into current electrodes A and B and interrupts it every two seconds. The duration of current flow is also two seconds.

The study area is located in Kashmar 1:250000 and Bardaskan 1:100000 geological sheets. From geological viewpoints, the major portion of the study areas comprised the Tankar formation (dating back to the Precambrian era), including green schist along with metarhyolite layers with

Figure 8: a) The RS Cross-section Obtained From the Inverse of the Wenner Array Data; b) The IP Cross-section Obtained From the Inverse of the Wenner Array Data



**Figure 9: Geological Map of the Studied Area
(Taken from Geological Map of 1/250000 Kashmir)**



submarine acid tuffs origins. Malachite and sulfide evidence is also observed in chloritic sections. In some points, silicification and kaolinization as well as iron oxides formation can be observed.

stretch of N52°N24°E was considered in area. The location of these profiles was surveyed in this area with a station distance of 40 m and a jump of 20 m.

Field Data Modeling

To investigate the depth of the streak situated in this region, two dipole-dipole profiles with a

Study of Profile B5-DD1

The two dimensional pseudo cross-sections of the resistivity and IP derived from the inverse

Figure 10: Shows the Image of Generator, Transmitter and Receiver with Cables



Figure 11a: The Pseudo Cross-section of the RS of Profile B5-DD1

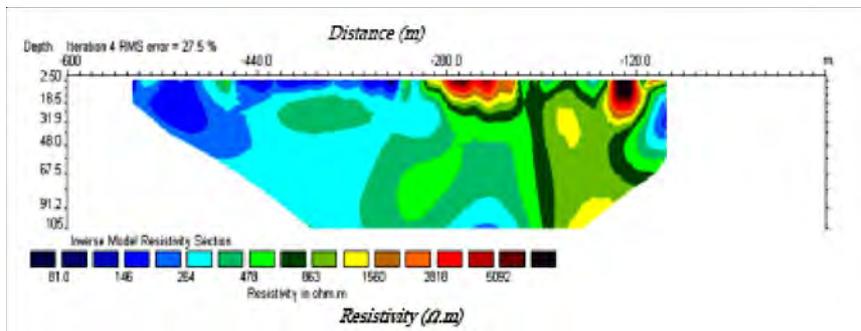
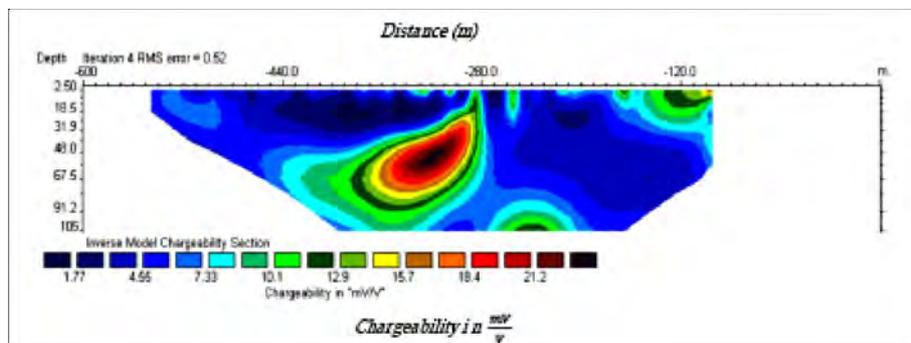


Figure 11b: The Pseudo Cross-section of the IP of Profile B5-DD1



modeling of this profile are presented with the RES2D commercial software. The minimum and maximum numerical values for load and resistivity are 2.6 to 13 mV, respectively, and 83 to 2420 ohm, respectively

In the IP map (Figure 11b), an anomaly range with a green to red color range is distinguished from other areas. A vein-shaped anomaly with a gradient of approximately 30 degrees relative to the horizontal (green to red) spectrum is located at a distance of 280 to 420 south. This anomaly correlates with areas with an average resistivity (300–700 ohm) in the RS map.

Hence, the observed anomalies on the map can be described as areas with high potential for mineralization. In Figure 11a, the resistivity values between the stations 120 and 280 are high. This area has been adapted to the metarhyolite and acid tuffs units which have a high resistivity.

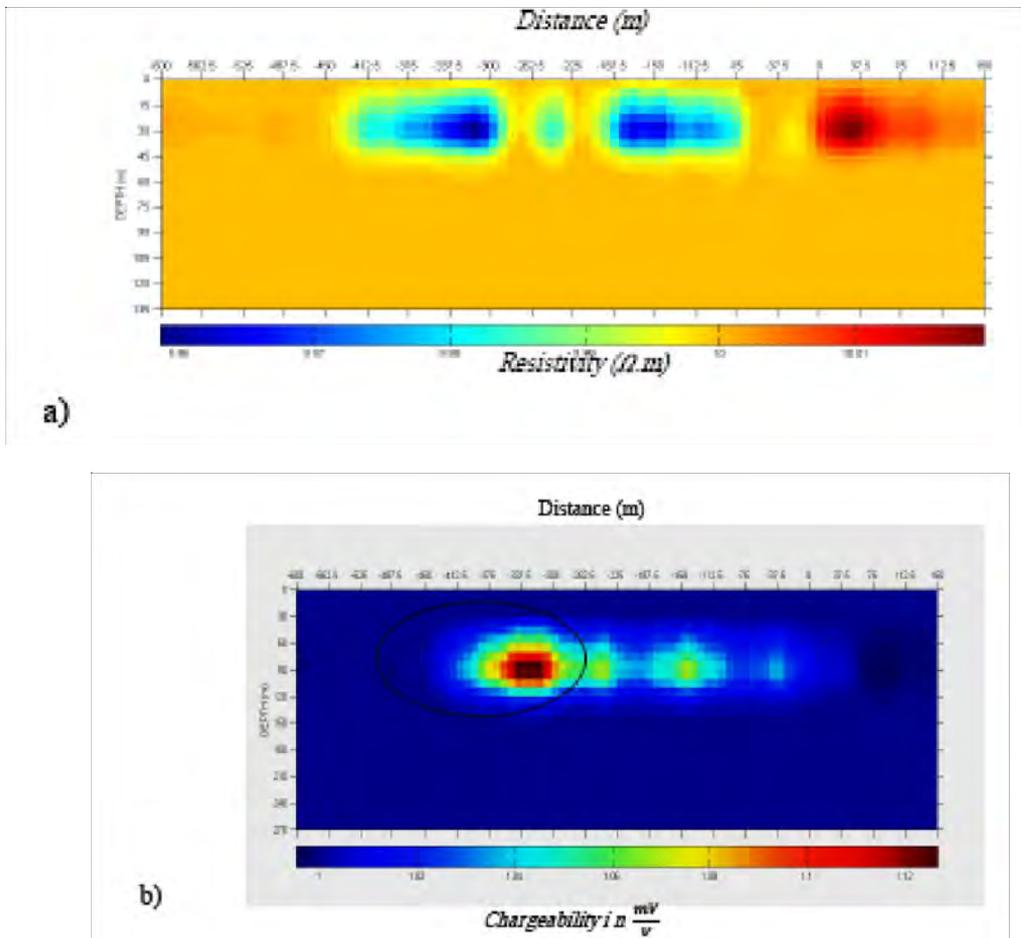
Given the discussed points, the exploratory bore was proposed based on the chargeability map to identify geological layers according to Table 1.

The result of a program designed in the MATLAB environment on real data can be seen

Table 1: The Proposed Location for the Exploratory Bore for Profile B5-DD1

Name	X (UMT)	Y (UMT)	Station	Drilling Depth	Azimuth (Degree)	Angle (Degree)
PBH5	585900	3919396	330 south	80 m	24	20

Figure 12: a) The Pseudo Cross-section of the IP Obtained From Actual Data; b) Figure 12a. The Pseudo Cross-section of the RS Obtained from Actual Data



in the Figure 12a and 12b. Figure 12a and 12b represent cross-section of the RS and IP on the actual data of the profile B5-DD1, respectively.

As shown in the cross-sections, the program perfectly shows high contrast values of RS and IP. The response obtained from MATLAB is about 18% different from that obtained from the RES2DINV, which is associated with determining anomalies and can be justified by arguing that no unique solutions are obtained from inversion.

Study of profile B5-DD2

Figure 13a and 13b shows 2D dimensional

pseudosection of RS and IP resulting from the inversion modeling of this profile. The minimum and maximum values for chargeability and resistivity are 1.7 to 17.6 mV, respectively, and 126 to 973 ohm, respectively.

In the IP map, the anomaly region is distinguished from other regions using green to red colors.

A streak-shaped anomaly with an approximate slope of 30 degrees compared to the horizon with a relatively high chargeability value (the color spectrum of green to red) is located between stations 330 to 480 north and

at an approximate depth of 20-80 m. This anomaly coincides with regions with a moderate resistivity in the RS map (200-700 ohm). This anomalies has a significant similarity to the anomalies observed in sections (12a, 12b) in terms of appearance, i.e. slope and extension, and values of chargeability and resistivity.

Given the discussed points, the exploratory borehole was proposed based on the chargeability map according to Table 2 (excavation angle is measured versus the perpendicular line), which confirmed the

results obtained from the cross-sections. The drilling location can be observed on the cross-sections.

The results of the program written in MATLAB on the actual data of the B5-DD2 profile are presented below.

As observed in the figures, the program was able to determine the anomaly region like the RES2D INV software; nevertheless, about 25% difference is observed between the results obtained from the two programs in determining the depth of anomaly.

Table 1: The Proposed Location for the Exploratory Bore for Profile B5-DD2

Name	X (UMT)	Y (UMT)	Station	Drilling Depth	Azimuth (Degree)	Angle (Degree)
PBH6	586099	3919340	420 north	70 m	52	30

**Figure 13a) Pseudosection of RS of the B5-DD2 Profile;
b) IP Pseudosection of the B5-DD2 Profile**

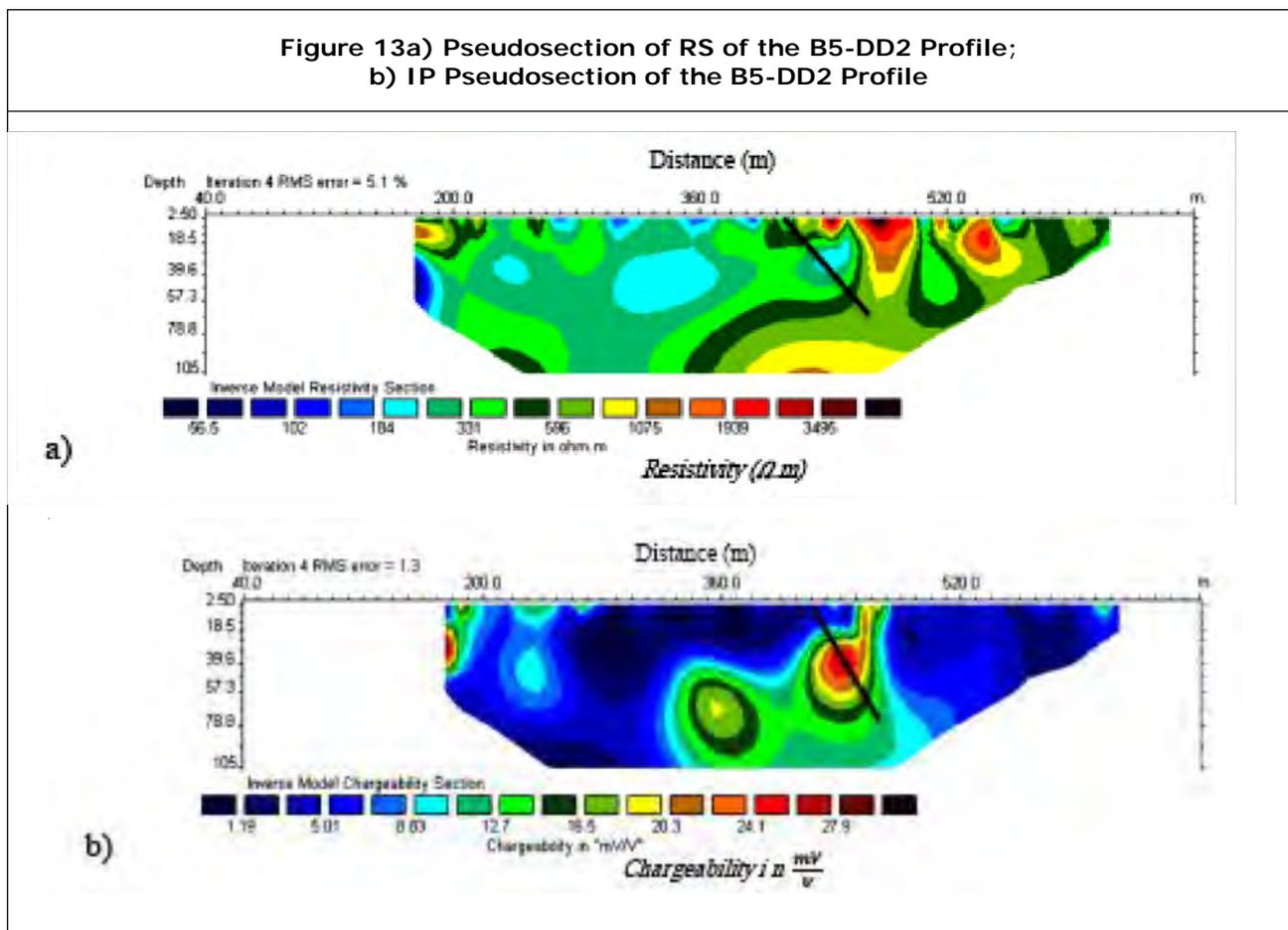
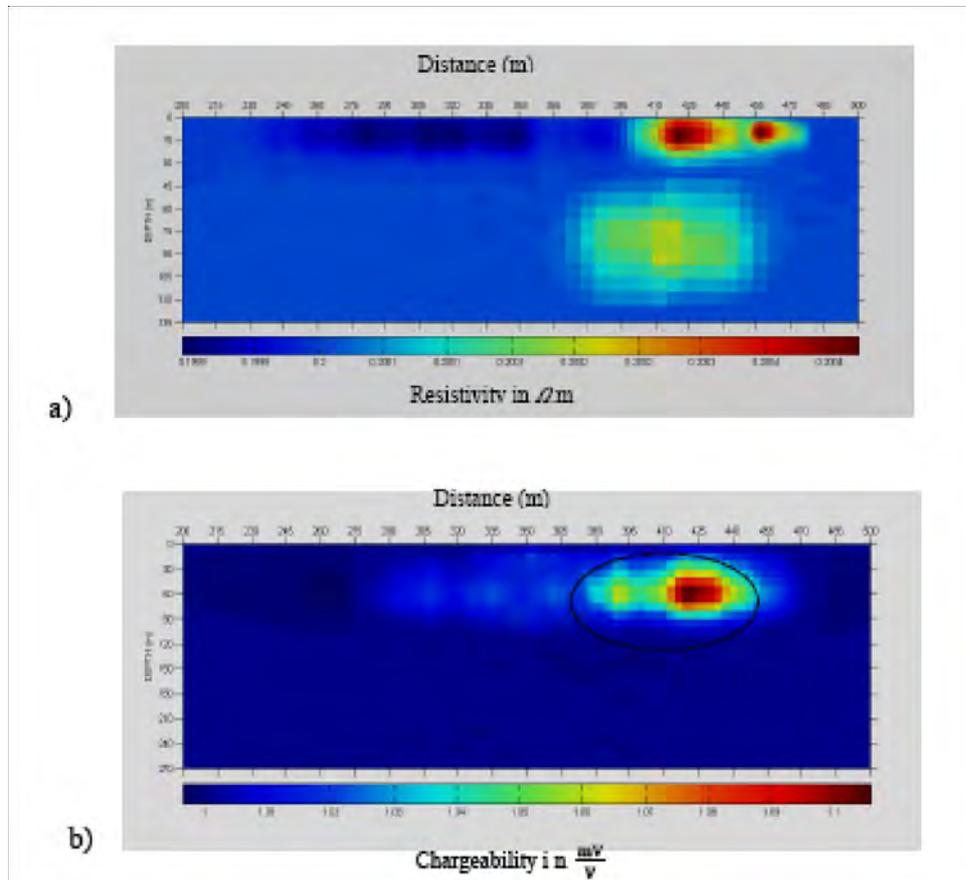


Figure 13a) Pseudosection of Resistivity Response Obtained from Real Data of Profile B5-DD2; b) Pseudosection of Induced Polarization Response Obtained from Real Data of Profile B5-DD2



Conclusion

Investigation of the inversion of the data associated with resistivity and induced polarizations have been performed and the results have been compared.

Due to high ability of lateral separation for the dipole-dipole array and the high ability of vertical separation for the Wenner's array, these arrays were selected. Inversion was then applied to the actual data collected from Bardaskan in Razavi Khorasan Province, Iran.

The results are as follows:

1. Both methods of specific resistivity and induced polarization were found to work best in the absence of noise for detecting the location of anomalies.
2. In the presence of noise, an error was observed in locating the anomalies. In induced polarization, this error was greater than that of the resistivity method, since its data had a lower range of variation and a higher sensitivity.
3. The results of the program written in MATLAB on the actual data of Bardaskan were compared with those obtained from RES2D.

The results of the mentioned comparison suggest a good consistency. About 15%-25% difference was observed in the results obtained from the two programs in determining the depth of anomalies.

4. Based on results obtained from MATLAB, in both RS and IP methods, anomalies with high contrasts were displayed better than those with low contrasts.

References

1. Mooney H M (1980), *Handbook of Engineering Geophysics*, Vol. 2, Electrical Resistivity, Bison Instruments, Inc.
2. Telford W M, Geldart L P and Sheriff R E (1990), *Applied Geophysics*, 2nd Edition, Cambridge University Press.
3. Wahyu Srigutomo *et al.* (2016) , "2D Resistivity and Induced Polarization Measurement for Manganese Ore Exploration", Conf. Ser. 739 012138.
4. Dahlin T and Loke M H (1998), "Resolution of 2D Wenner Resistivity Imaging as Assessed by Numerical Modeling", *Journal of Applied Geophysics*, Vol. 38, pp. 237-249.
5. Loke M H (2004), *Tutorial: 2-D and 3-D Electrical Imaging Surveys*, pp. 1-129.
6. Kearey P, Brooks M and Hill I (2002), *An Introduction to Geophysical Exploration*, Blackwell Science Ltd.
7. Ward S H (1990), "Resistivity and Induced Polarization Methods in Geotechnical and Environmental Geophysics", *Society of Exploration Geophysicists*, pp. 147-189, Tulsa.
8. Roy K K (2008), *Potential Theory in Applied Geophysics*, Springer, Berlin, New York.
9. Allaire G (2007), *Numerical Analysis and Optimization*, Alan Craig, Oxford Science Publications, New York.