Detection of subsurface salinity and conductive structures in Inche-boroon, Golestan, Iran, using magnetotelluric method

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1. Introduction

Magnetotelluric (MT) method is an important passive surface geophysical method which uses the Earth's natural EM fields to investigate the electrical resistivity of the subsurface. The depth of investigation of MT is much higher than other electromagnetic (EM) methods. The electrical conductivity of upper few kilometers of the Earth's upper crust is controlled by many parameters among them salinity of the subsurface structures. Very conductive Iodine structures are one of the subsurface salinity structures which can be formed at upper few hundred meters of the crust. Thus to study those kind of structures, magnetotelluric (MT) is the most effective method.
Gorgan plain is located in the northern Iran. In Feb-March 2006, an MT survey was conducted in the area. Data were collected along four east-west profiles (37 sites in total). Sites distances are 1 km and profiles distances are 1.5 km (Fig. 1 & 2).

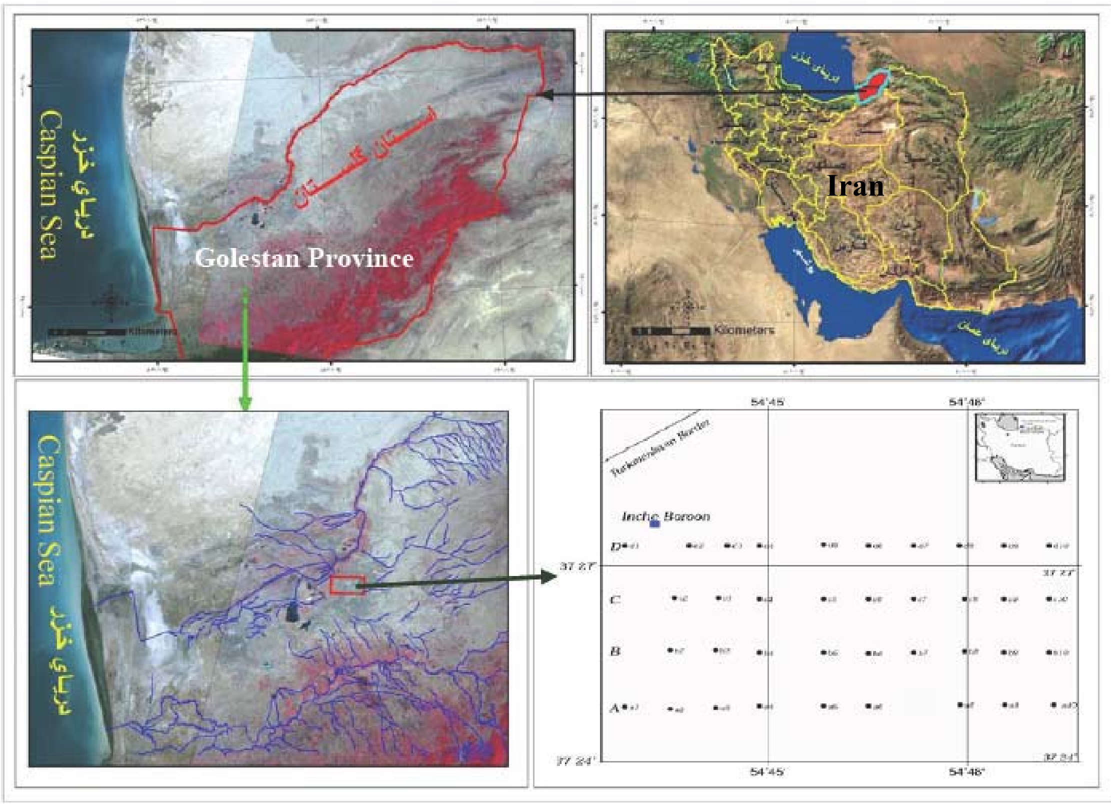


Figure 1. Geographic location of study area.

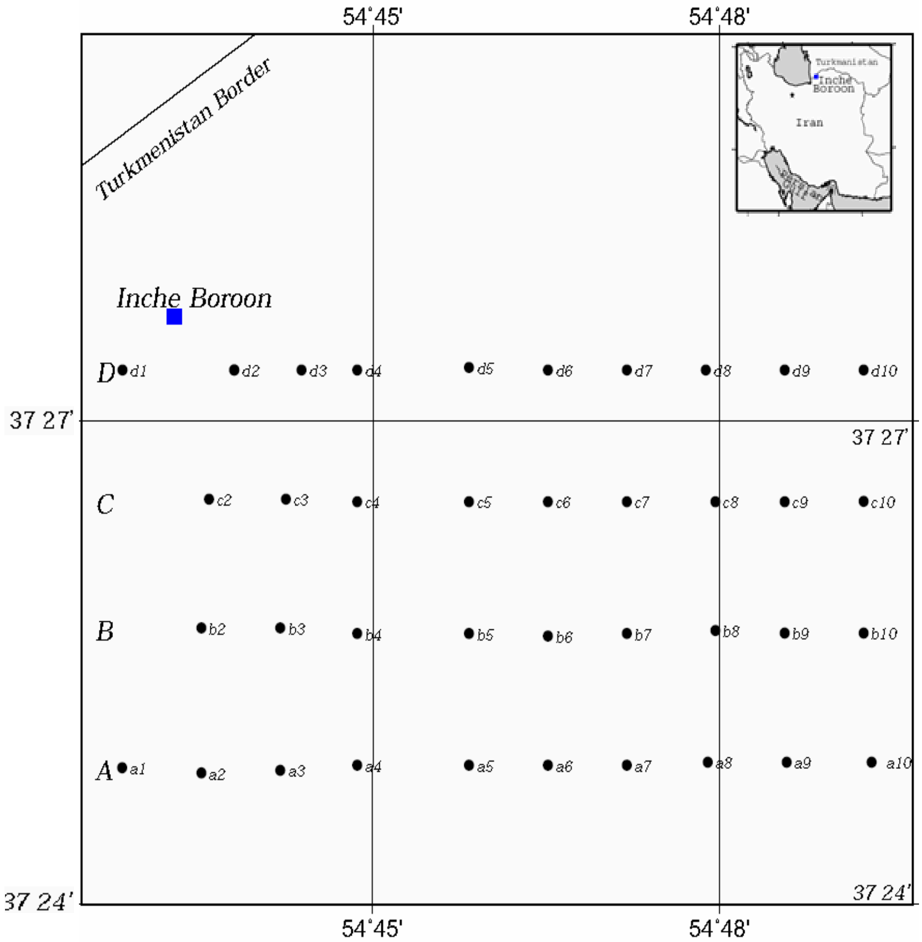


Figure 2. Location of profiles and sites

2. Magnetotelluric concepts

Measurements of the horizontal components of the natural electromagnetic field are used to construct the full complex impedance tensor, Z, as a function of frequency,

$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

indicating the lateral and vertical variations of the subsurface electrical conductivity at a given measurement site. Apparent resistivity, ρ_a, and phase, φ, are the desired quantities calculated through the following relations,

$$\rho_{a\,i} = \frac{1}{\mu_0 \omega} |Z_i|^2 \qquad i = xx, xy, yx, yy, DET$$

$$\varphi_i = phase(Z_i)$$

Where, μ_0, is the permeability of free space, ω, is the angular frequency and , DET, denotes the determinant data. Time series measurements collected in various frequency ranges are transformed into frequency domain, and cross power spectra are computed to estimate the impedance tensor as a function of frequency.
The determinant of impedance tensor which is also called the effective impedance, Z_{DET}, (Pedersen and Engels, 2005), is defined as,

$$Z_{DET} = \sqrt{Z_{xx} Z_{yy} - Z_{xy} Z_{yx}}$$

Using the effective impedance, determinant apparent resistivities and phases are computed. The advantage of using the determinant data is that it provides a useful average of the impedance for all current directions. Furthermore, no mode identifications (transverse electric, TE mode: current in parallel with the strike; or transverse magnetic, TM-mode: current perpendicular to the strike) are required, static shift corrections are not made, and the dimensionality of the data is not considered, since the effective impedance is believed to represent an average that provides robust 1D and 2D models.

3. Dimensionality analysis

The Swift's (1967) skew, defined as, $S = \left|(Z_{xx} + Z_{yy}) / (Z_{xy} - Z_{yx})\right|$, indicates the dimensionality. Where Swift's skews are generally below 0.2, the structures can be regarded as undistorted 1D or 2D, otherwise, the structures are defined as distorted 1D and 2D structures or 3D structures. Dimensionality analysis of the MT data of the area shows that the assumption of undistorted 1D and 2D structures is correct. Figure 3 shows skew values for all sites measured across the profiles.

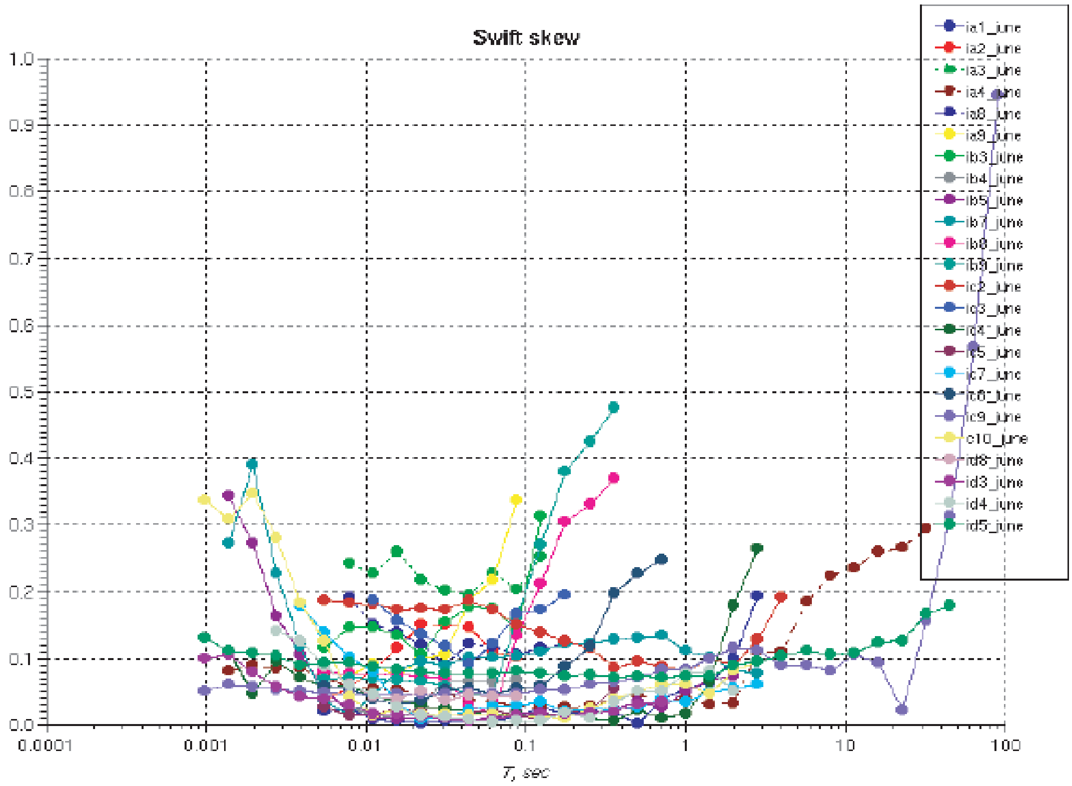


Figure 3. Swift's skew values for all sites measured across the profiles

4. Processing and 1D inversion of the MT data

Processing of the data was done using Smirnov's (2003) approach. 1D inversion of the determinant (DET) data using a code from Pedersen (2004) was performed. The MT data in apparent resistivity and phase are given as inputs to inversion program. For instance, in figures 4a and 4b these data for site C9 are shown in blue. Red symbols are 1D model responses derived from data inversion. 1D model derived from data inversion of each site shows variation in Earth's layers conductivity in sites locations. 1D model of site C9 is shown in Fig. 4d. Also, to verify structure dimensionality assumption, Swift's skew values of site C9 are shown in Fig. 4c. By study of the resistivity sections (such as Fig. 4d) of the measured sites, it is concluded that although the area is conductive, two extremely conductive layers do exist between depths from 100m to 1300m. By separation of these two layers, isodepth maps and also isopach maps of them have been derived that are shown in figures from 5a to 5d. According to the isodepth maps, depths of the top of the first and second conductive layers from earth surface are estimated from 90m to 190m and from 250m to 650m, respectively. The thicknesses of the first and second layers are also distinguished from 5m to 30m and from 10m to 120m, respectively.

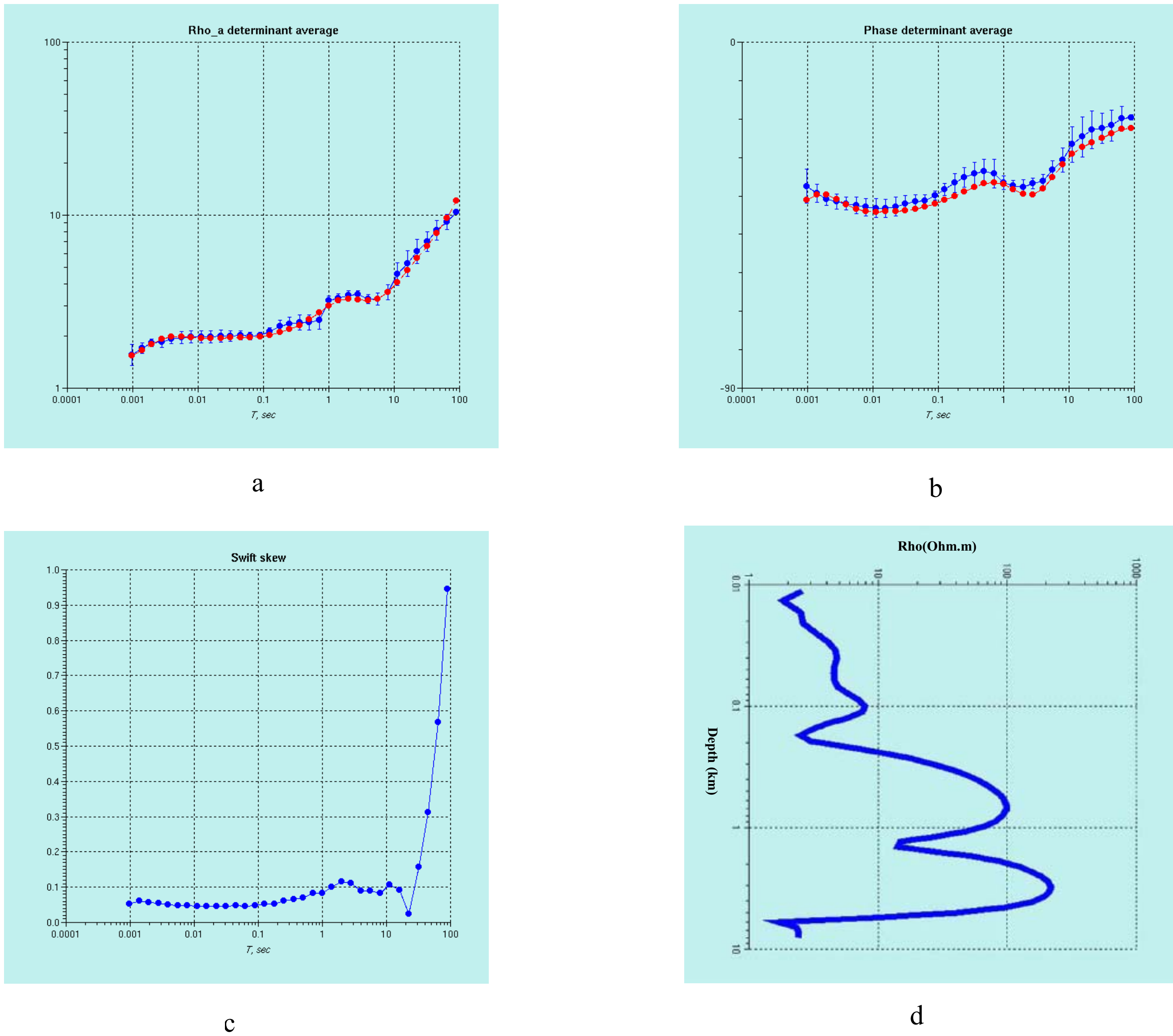


Figure 4. Data curve for site C9: a) Apparent resistivity, b) Phase, c) Swift's skew, d) 1D model

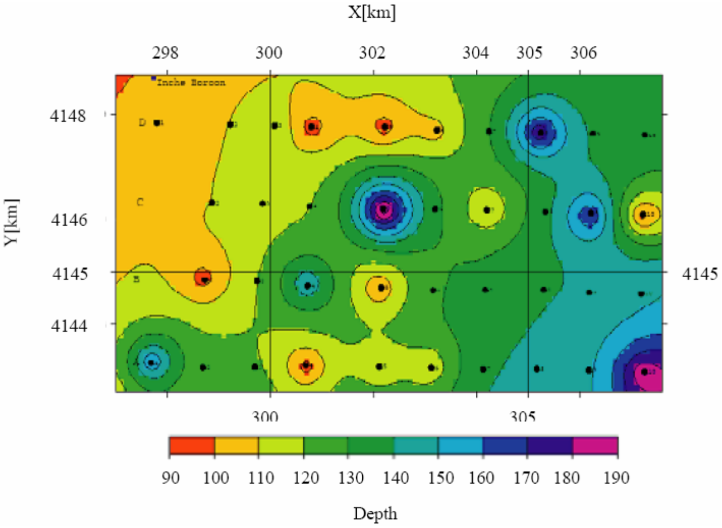


Figure 5a. Depth to the top of the first conductor

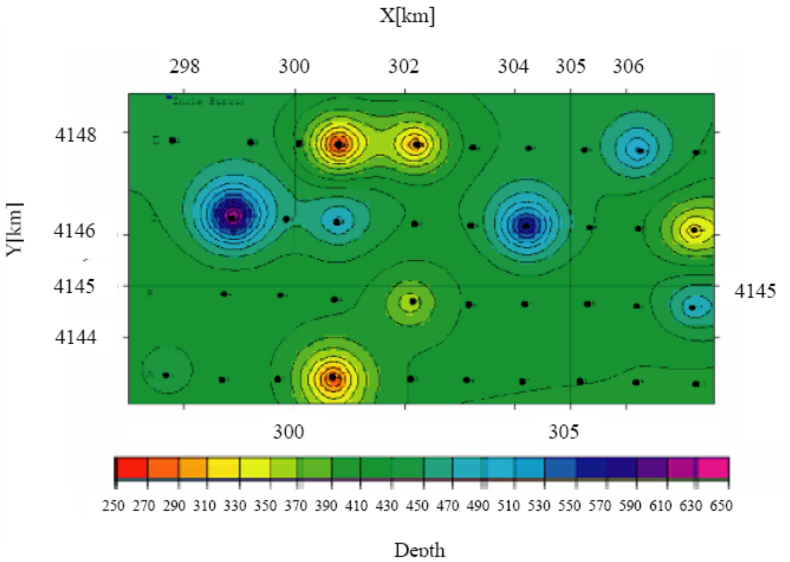


Figure 5b. Depth to the top of the second conductor

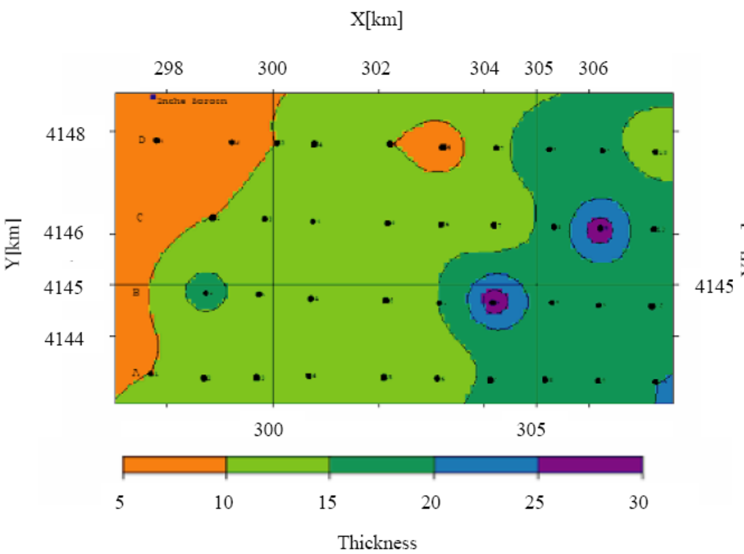


Figure 5c. Thickness of the first conductor

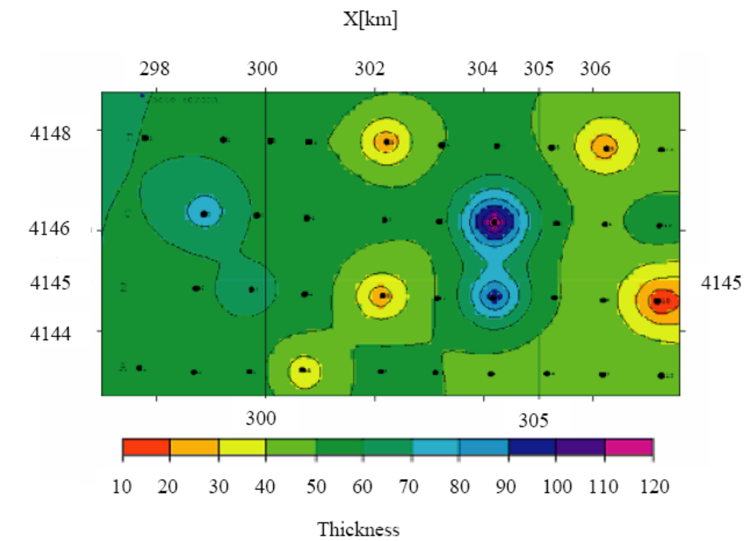
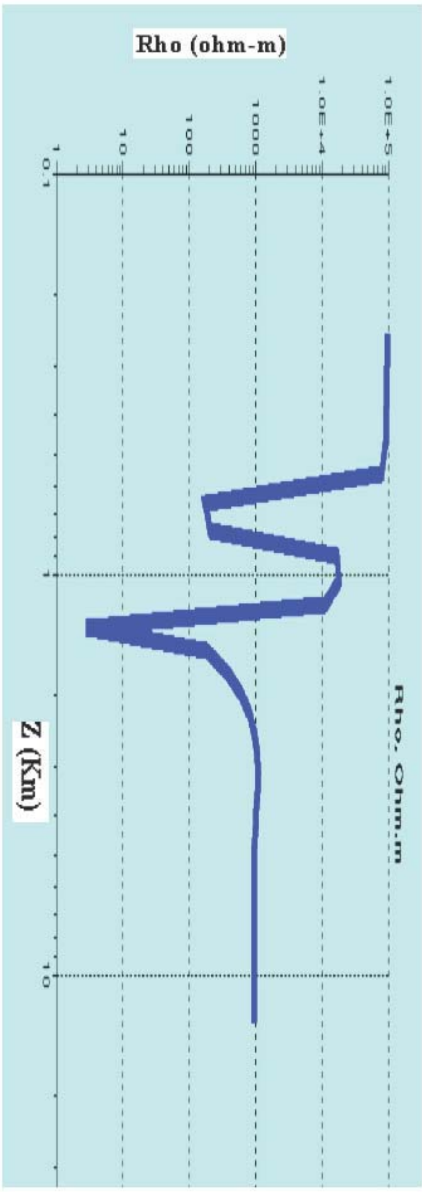


Figure 5d. Thickness of the second conductor

5. Comparison between borehole information and results of 1D inversion of the MT data

Subsurface electrical resistivity was verified by the information from a borehole in the vicinity of the area. According to the borehole log, there is a conductive layer consisting salt water at the depth of 670m to 840m. A schematic of the borehole log and the closeby resistivity section of the MT data are shown in Fig. 6.

1D model



Depth	Geological Structure	Resistivity description
0	Clay_Sand group1 (Neo Caspian formation Holocene)	Medium resistivity
122	Lime	High resistivity
125	Oelitic section Ancient Caspian Pleistocen	High resistivity
222	Lime	High resistivity
225	Clay Sand group 2 Khazar formation Pleistocen	High resistivity
310	Baku formation	High resistivity
430	Upper Asheron formation Pliocene	High resistivity
670	Lower Apsheron formation Pliocene Silt, Clay, Fine-grained sand stone, Salt water table	Low resistivity
840	Akhggl formation Pliocen	High resistivity
850	Tuff section Pliocen	High resistivity
910	Papery shale	High resistivity
960	Brown Bed	Moderate resistivity
1025	Chelecken formation Pliocene	Moderate resistivity
1550	Sarnatian formation	Increasing resistivity
1850	Sarnatian formation	Increasing resistivity
1850	Conglomerate section	Increasing resistivity
2050	Shale	Decreasing resistivity
2200	Lime	Increasing resistivity
2250	Shale and Silt	Decreasing resistivity
2400		

Figure 6. The well-log and the 1D model at the site close by.

6. 2D inversion of the MT date

A 2D inversion routine (Siripunvaraporn and Egbert, 2000) was used here to model the determinant data. We prepared initial models for 2D inversion of data based upon the results of 1D inversion. Observed, calculated and residuals of apparent resistivity and phase data along profiles are shown in Fig. 7. Final 2D resistivity models along four profiles are illustrated in Fig. 8.

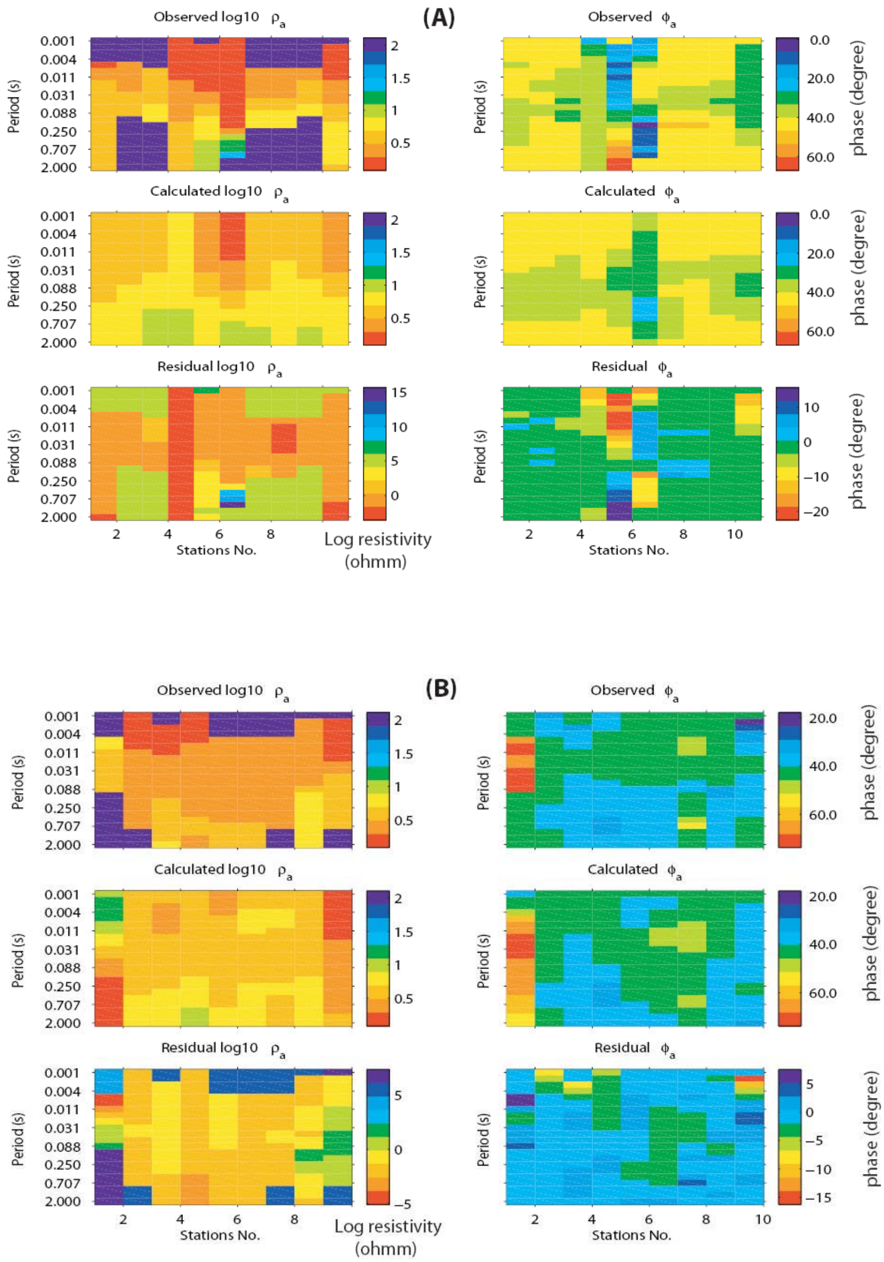


Figure 7. Observed, calculated and residuals of apparent resistivity and phase data along profiles A, B, C and D.

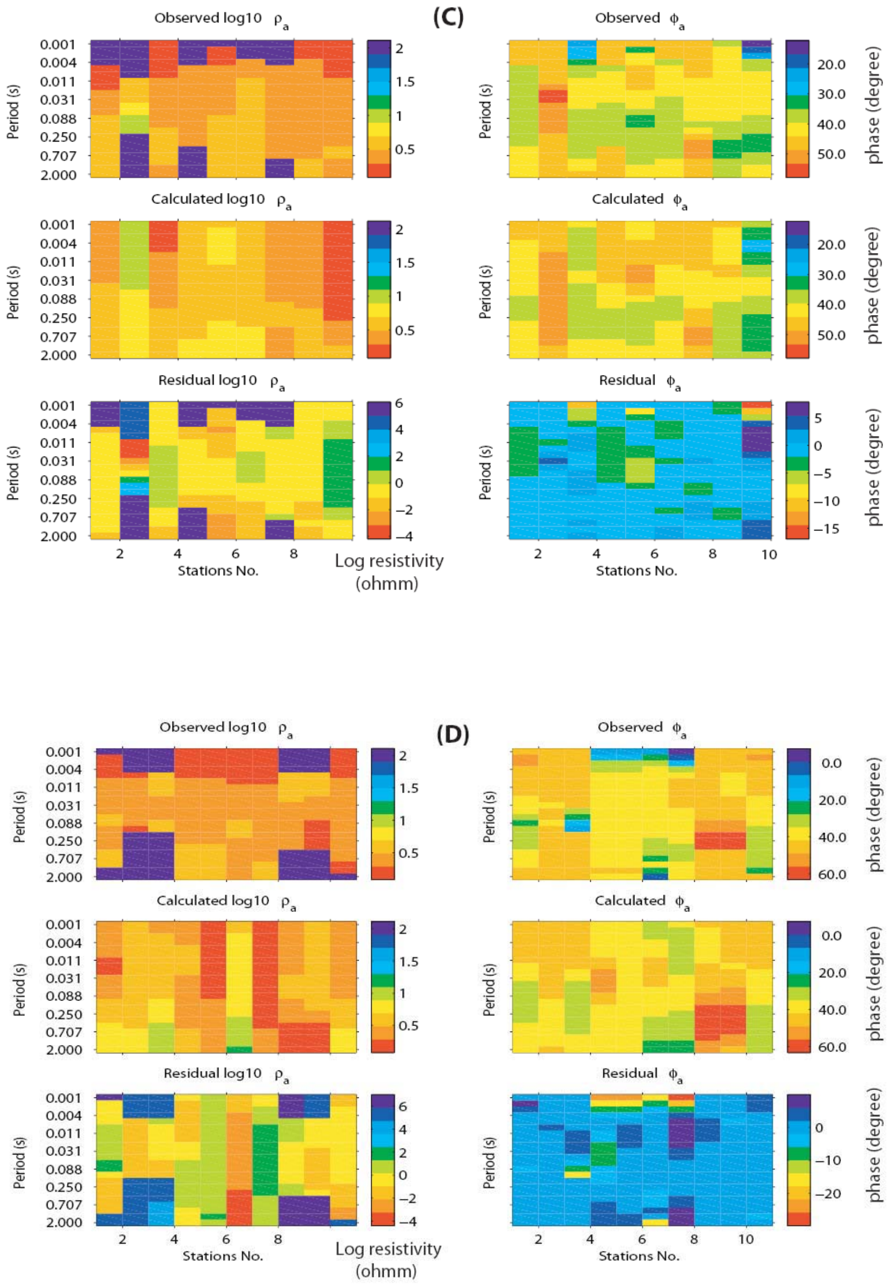


Figure 7. Continued.

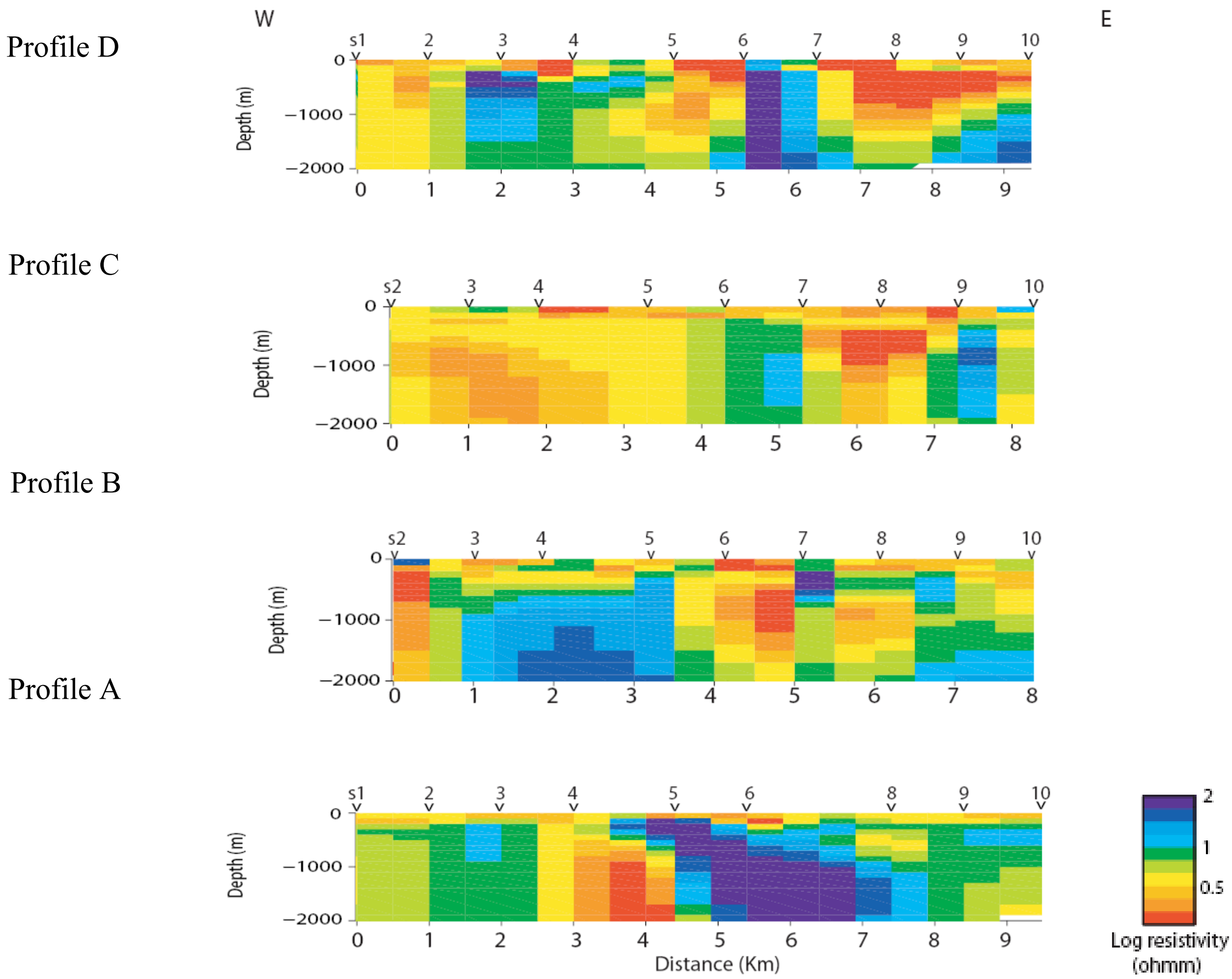


Figure 8. Final 2D resistivity models along profiles A, B, C and D.

7. Discussion and conclusions

Models of the MT data across the profiles, considerably express conductivity of the area that shows the MT advantage compared with other electromagnetic (EM) methods which aren't able to penetrate very deep in such a very conductive area. There is a good agreement between observed data and the model responses along profiles.

Derived resistivity models illustrate the presence of two conductors in the area. These layers are attributed to layers consisting salt water and are presumably reported as a reservoir for Iodine minerals.

As a final result, we suggest drilling an exploration well down to the depth of about 1000 meter at either site of c4 or c9.

8. Acknowledgement

The MTU2000 system from Uppsala University, Sweden, was used for the measurements at some sites which is acknowledged. The last version of the processing software from Maxim Smirnov is also gratefully appreciated. The Research Council of the University of Tehran is acknowledged for financial supports. We are grateful to Davood Moghadas, Alireza Babaei and Majid Zeinali for their assistance in harsh field conditions.

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