# Application of Magnetotelluric Geophysical Technique to Study the Subsurface Structural Setting in Marsa Alam, Eastern Desert, Egypt

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# Application of Magnetotelluric Geophysical Technique to Study the Subsurface Structural Setting in Marsa Alam, Eastern Desert, Egypt

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**ABSTARCT:** *It is important to explain the subsurface geological structures in some active regions in Egypt, especially to estimate the fault activity. The present work is aimed to delineate the subsurface structural setting in Marsa Alam region, Eastern Desert, Egypt. In this research, magnetotelluric (MT) method will be applied to investigate the active subsurface structures. MT technique can detect the crustal fluids along active faults due to their high electrical conductivity anomalies. For this study, we conducted MT data using ADU-07 instruments in a net concentrating around the active faults in Marsa Alam area. The major strike direction of the studied area was determined based on the advanced analysis techniques of MT impedance tensor such as polar impedance plots, tipper, skew and two-dimensional inversion. The analysis and interpretation of MT data gave reasonable results about the subsurface structure of the selected studied active area.*

**Keywords:** Magnetotelluric (MT); polar impedance; skew and 2D modeling

## 1. INTRODUCTION

It is known that the magnetotelluric (MT) utilizes spontaneous source electromagnetic signals in order to probe the earth from shallow tens of meters to hundreds of kilometers below the surface; given measurements of the electric and magnetic field components in the appropriate period range are taken at the surface. Electric currents in the Earth are caused by fluctuations in the natural electromagnetic (EM) field. These subsurface currents produce secondary electromagnetic fields and change the total EM field near the Earth's surface. The electrical properties of the subsurface strata can be deduced from these (EM) fields [2]. This study depends on the analysis of the MT data as well as the geological information in Marsa Alam region, Eastern Desert, Egypt in order to define the significant tectonic patterns, which are responsible for the structural development of its geological units. To achieve the study, the authors acquired four MT sounding stations (the distance between each MT station was 5 kilometers) with the help of the work team of geomagnetic laboratory at National Research Institute of Astronomy and Geophysics NRIAG), Egypt. An ADU-07 (Analog Digital Unit), a five-channel, 24-bit instrument, was used to collect the MT data from all stations. Using lead-lead chloride electrodes arranged in an L-shape array with dipole lengths of nominally 100 m, horizontal electric fields were measured. The size of the measured area was about 20 kilometers. With horizontals oriented in the same direction as the electric-field array, the three orthogonal components of the magnetic field were measured utilizing permalloy-cored induction coils. With sampling rates of 128 Hz, data were collected in one band (deep depth). At the low frequencies, the MT data acquisition requires several hours. The average data collecting time is between 20 and 22 hours, while higher noise areas may need a longer measuring time. So that one instrument setup, which may require several sites when the remote reference technique is used, may be performed each day and the apparent resistivity curves have been interpreted. The analysis of apparent resistivity curves had been performed.

## 2. GEOLOGICAL SETTING OF THE STUDY AREA

The Eastern Desert province extends from the Nile Valley eastwards to the Gulf of Suez and the Red Sea. It consists mainly of high and rugged mountains parallel to, and at relatively short distance from the coast [4]. The area under consideration is located in the crystalline Precambrian basement complex in the center eastern desert of Egypt (Fig. 1). It is located in the central eastern desert of Egypt. Most authors consider the area apart of the Nubian shield. The study area is subdivided geomorphologically, into two main divisions; 1) the coastal belt, which consists of a narrow coastal plain followed inland by a series of escarpments having an average height of 40m above sea level and trending parallel to the shore-line, and 2) mountain ranges, that are made up of a series of hills and mountains with average height of 90m above sea level and striking in a NNW-SSE direction. These hills are bounded eastwards by the coastal belt and they are dissected by several wades.

The area under consideration is standing on the low hills of the red sea coastal plain and looking westwards to the Precambrian basement one can differentiate topographically the studied area into high and moderate to low relief sectors. The high relief parts include a number of conspicuous positive topographic forms such as G. El-Sibai , G. Abu Tiyur and G. Um Shaddad . G. El-Sibai (1427 m a.s.l ) G. Abu Tiyur (1099 m a.s.l) and G. El – Dabbah form together a ring complex intrusion extending further to the west beyond the limit of studied area . G .Um Shaddad (775m a. s. l ) is located in the central part of study area as an elongate ridge extending approximately E-W .most conspicuous high mountains are composed of granitic rocks .The remaining part of the area is generally of moderate to low relief. Geologically, the onshore part of the study area is part of the Central Eastern Desert of Egypt. Division of the Eastern Desert of Egypt into Northern, Central and Southern sections is based on basement type.

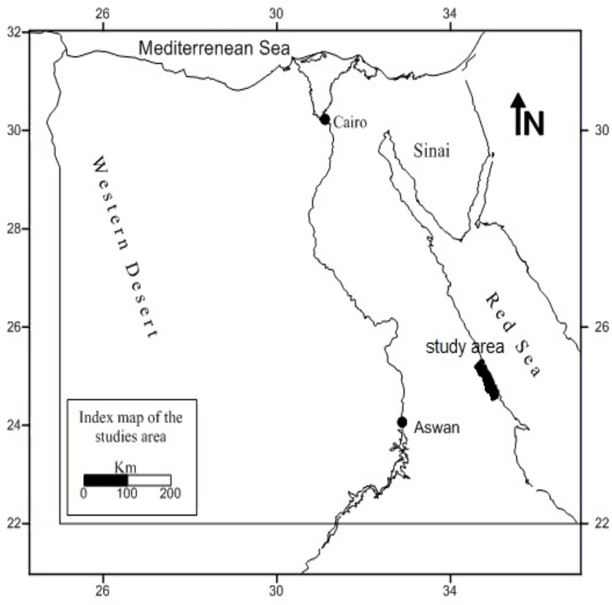


Fig. 1. Location map of the study area.

The Central Eastern Desert was formed by collapse of a small ocean basin or back arc basin. In general, the sedimentary rocks of the onshore part of study area are separable into two great divisions: the pre-rifting Cretaceous-Eocene group and the post-rifting Oligocene and later sediments group. The latter division exhibits a continuous succession from middle Miocene onward. The Cretaceous and Eocene deposits occupy the troughs of semiformal -like folds within the crystalline hill ranges. The best example of the pre-rift series outcrops in the Gebel Duwi basin, where more than 1500 m of Cretaceous and Eocene stratigraphy is exposed from the bottom to the top. The marine Upper Eocene and Oligocene deposits are absent, indicating that the region must have undergone elevation changes during these two epochs [5].

## 3. PROCESSING AND INTERPRETATION OF MAGNETOTELLURIC DATA

### 3. 1 Geoelectric Strike Direction

Before MT data are interpreted, the ideal rotational angles in relation to the main directions of impedance Z were found. Because of the importance of the analysis for the interpretation of the data, there is a number of different techniques required to analyze the dimensionality of MT data and reduce the data to the most ideal 2-D form by removing the effects of galvanic distortion since analysis is essential for the interpretation of the data. These techniques include tipper magnitude, polar plots and skew.

### 3.2 Dimensionality Analysis for the MT Data

By calculating the parameters for dimensionality and directionality, one can evaluate the electrical complexity of the subsurface. The tensor nature of the MT observations is used to generate these parameters. In this study, the tipper impedance, polar plots and skew techniques were used to analyze the MT impedance tensor and estimate the dimensionality and strike of the resistivity structure.

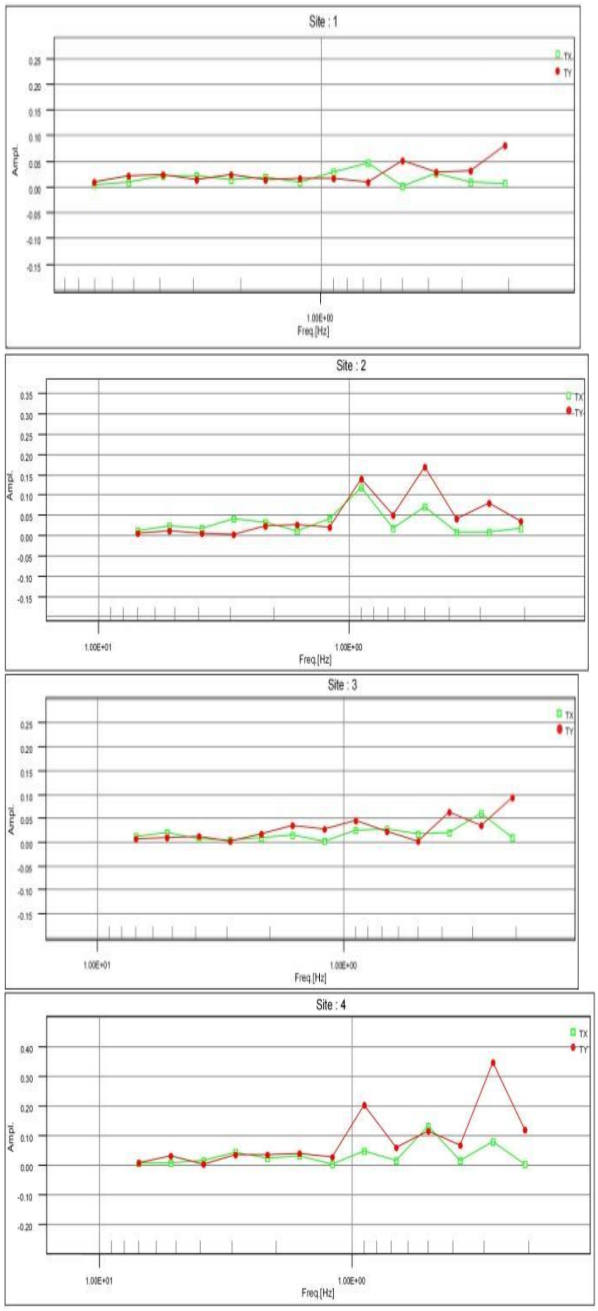


Fig.2. Shows the tipper magnitude for MT stations 1, 2, 3 and 4.

### 3.3 Tipper Magnitude

A measurement of the vertical magnetic field that has been normalized by the horizontal magnetic field is called the tipper. The vertical magnetic component in a one-dimensional earth is zero. In most cases, the vertical magnetic component of a multidimensional earth equals TXHX +TY HY, where T represents Tipper. Tipper magnitude [9] is defined by:

$$|T| = \sqrt{|Tx|^2 + |Ty|^2} \quad (1)$$

Tipper can identify the more conductive side of a contact because, close to a conductor-resistor boundary, the conductive side's near-surface current density parallel to strike is higher. Figure 2 displays tipper magnitude plots for stations 1 through 4. Vertical structure on either side of a contact is clearly defined by the representatives' stations' tipping magnitude. The tipper aids in the clarification of uncertainty in strike and aids in displaying the more conductive side of a contact.

### 3.4 Polar Impedance

The tensor MT problem is quite particular to a polar plot. It allows the display of Zxy and Zxx variation as various rotations of other data. A matrix of little plots makes up a polar plot. Each of these charts corresponds to a particular frequency. It displays Zxy and Zxx drawn in polar form as functions of rotation angle. They are presented in plain view, north up, just like on a map. Each plot shows the frequency in Hz and a vector indicating the current rotation angle for that frequency. The principal impedance polar diagrams for 1-D resistivity structures are circles [1]. Depending on whether they are a 2-D or 3-D construction, they extend in a direction that is either parallel to the strike or perpendicular to it as shown in (Fig. 3).

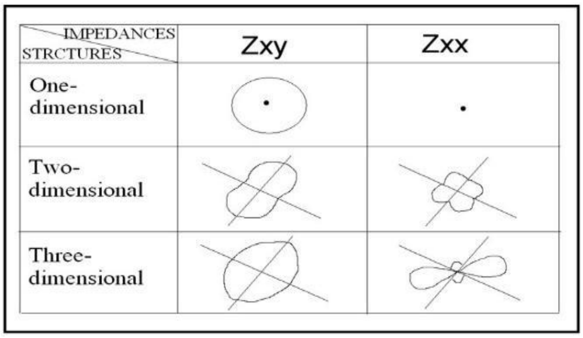


Fig. 3. Polar diagrams for impedance tensor element over 1-D, 2-D and 3-D earth structures.

At various frequencies, polar graphs display the modulus of a component of the impedance tensor as a function of the rotation angle θ ($0 < \theta < 2\pi$):

$$Zxy(\theta) = Zxy \cos 2\theta + (Zyy - Zxx) \sin\theta \cos\theta - Zyx \sin 2\theta \quad (2)$$

$$Zxx(\theta) = Zxx \cos 2\theta + (Zxy - Zyx) \sin\theta \cos\theta - Zyy \sin 2\theta \quad (3)$$

Principal impedances are Zxy and Zyx and diagonal impedances are Zxx and Zyy [3]. Polar plot analysis reveals details on the magnitude of 3-D distortion and/or noise that may exist in the data. Parallel to or perpendicular to the direction of striking, polar diagrams expand. Over resistors, the principal impedance polar diagrams are expanded parallel to the strike direction, while over conductors, they are elongated perpendicular to the strike direction. The additional impedance polar diagrams elongate in one direction for 3-D resistivity structures, and their amplitudes are similar to main impedances. In this study, we analyze the orientation of polar diagrams, which reflects the regional structure of the MT field. Figure 4 refers to the impedance polar diagrams for the representative stations. There are three curves; the red curves represent Zxy suggestions, while the blue curves represent Zxx traces. The regional strike direction, which was eventually used to define the two polarizations, is represented by the thin green line (TE and TM). We can notice that the strike direction varies with frequency, indicating variations in impedance with depth, as we move across all stations. As a result, the striking directions for stations 1 and 3 are approximately N-S. The strike direction is in the NNW-SSE direction for stations 2 and 4. According to figure 4, the magnetotelluric field appears to be more or less two-dimensional, with the major and minor axes pointing in the northeast and northwest, respectively. The later direction is in line with general trend of the area of study.

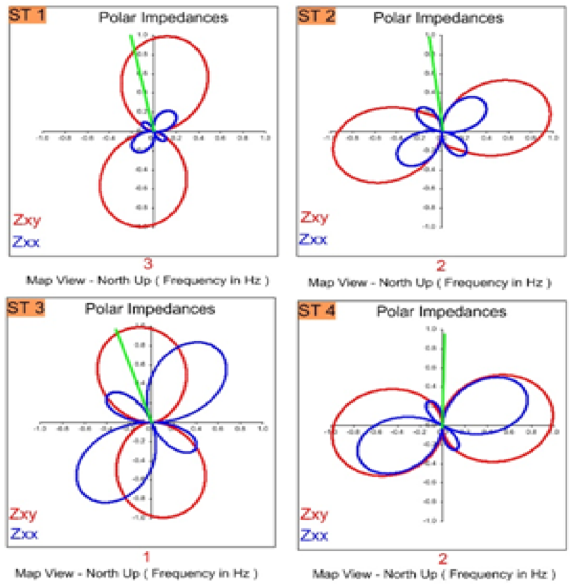


Fig. 4. Displays the typical stations on the polar plots diagram at the frequencies listed beneath each plot. The principal impedance Zxy is shown in red. The diagonal impedance Zxx is represented by the color blue. The regional striking direction is shown by the thin green line.

### 3.5 Interpretation of Apparent Resistivity Curves

For more details of the field measurements, the processed MT data, as they were used for the subsequent modeling, are obtainable in the form of apparent resistivity (ρa) and phase (φ) curves. The proportion of the strength of the electric field to the strength of the magnetic field at a specific frequency is known as apparent resistivity. On a log-log plot, the impedance phase is proportional to the slope of the apparent resistivity curve, but with a baseline of -45 degrees [9].

The components of the MT impedance tensor were derived using the vector electric and magnetic fields that were recorded at each site. These impedance components were utilized to calculate the apparent resistivities and phases in the transverse electrical (TE mode) and transverse magnetic (TM mode) directions, which are parallel (TE) and perpendicular (TM) to the anticipated strike direction for each frequency. Figure 5 displays a typical example of the apparent resistivities and phases curves for the transverse electrical (TE mode) and transverse magnetic (TM mode) measurements taken at representative sites. The data are plotted on a log-log curve, so "2" means 100, and 0 means 10. The apparent resistivity curves are not similar at all stations. This is may be due to local surface or near-surface inhomogeneities. The total features of these MT curves propose that there is a simple resistive-conductive-resistive sequence underneath variable overburden evinced by the MT response. The quality of the collected

MT data was reasonably good; however, at few MT sites and for periods around 1s, relating to the so called "dead band", the MT data were contaminated by noise and thus were finally discarded. The pattern of the apparent resistivity curves, such as the minimum at about 1 second in the apparent resistivities, indicated the presence of a shallow conductive layer beneath a thicker, more resistive cover. The MT data, on the other hand, exhibit a splitting of the curves at longer intervals, pointing to a more complicated structure.

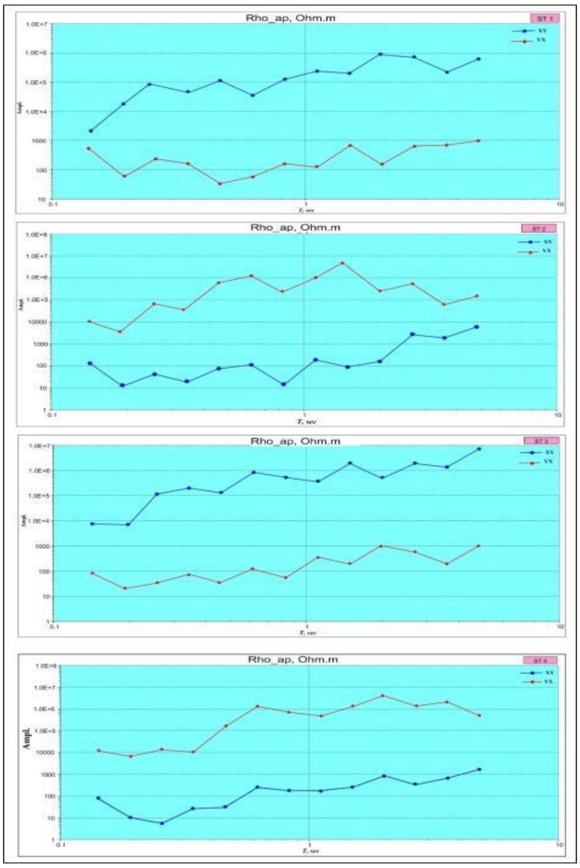


Fig.5. Displays apparent resistivity curves plots for the impedance tensor Zyy and Zyx at sounding stations.

### 3.6 Impedance Skew

Impedance skew is considered as another measure of the dimensionality for MT data [8]. It is a measurement of the proportion of its diagonal to off-diagonal parts and is used as a measure of the subsurface's complexity. Skew is given by:

$$S = \frac{(Zxx+Zyy)}{(Zxy-Zyx)} \quad (4)$$

The skew offers a measurement of the three-dimensionality of the conductivity structure close to the site [7]. The skew will be zero if the effective measured resistivity response to the geology underneath an MT station is really 1-D or 2-D. Increased skews (over 0.2) are a sign of either higher noise levels or 3-D resistivity responses to the geology. The quality of MT data can be negatively impacted by man-made electrical noise from power lines, generators, moving cars, and trains. To avoid the noise in the data, we stopped the recording during periods of active thunderstorms, lightnings, wind, and rainstorms. The magnetic induction coils were buried to reduce wind noise. From skew values for the stations, plotted in figure 6, we can notice that the value of skew is more than 0.2 for all frequencies at all sites. Skews values greater than 0.2 are an indicator of 3D geology and/or increasing noise.

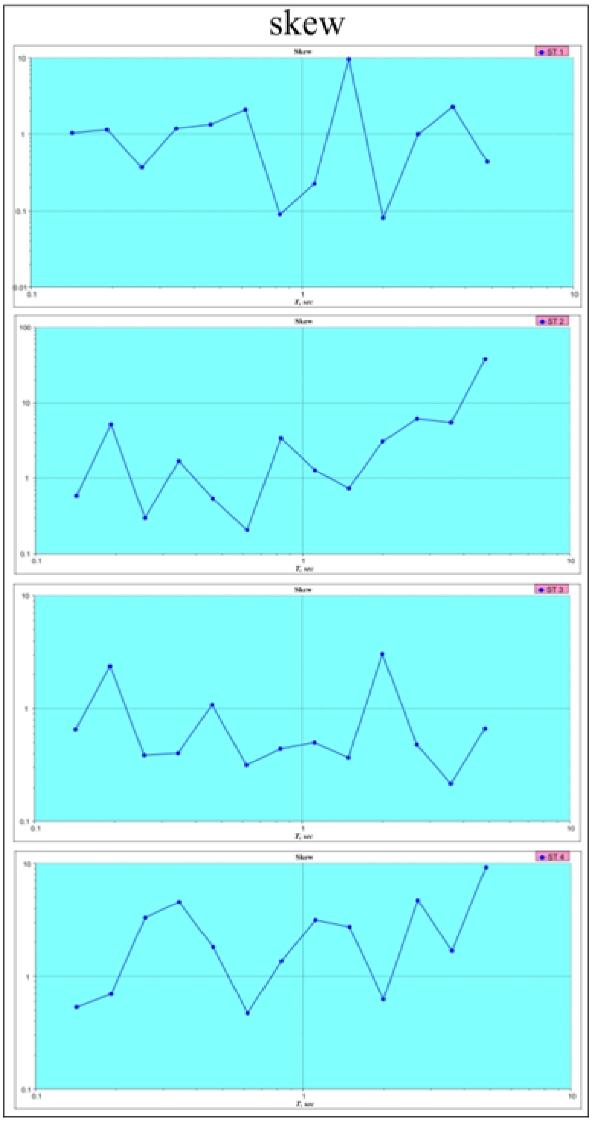


Fig. 6. Shows representative MT stations ((1,2,3 and 4) skew plots.

### 3.7 Interpretation of Pseudosections of Apparent Resistivity and Phase

Pseudosections, which are contour plots of the values of the MT function with log frequency as the ordinate and distance along the profile as the abscissa, are how the measurements are presented to provide a summary of the MT results [6]. Pseudosections can be used to identify the most significant abnormalities and to provide a succinct overview of the data. This graphic gives an idea of how resistivity varies with depth because the MT waves' ability to penetrate the earth deepens as their wavelengths get longer. In a pseudosections style, figure 7 displays the lateral variation of MT data along the MT profile. For both TE and TM modes, the apparent resistivity and phase were contoured with time on the vertical axis and distance on the horizontal axis. This graphic gives an idea of how resistivity varies with depth when the penetration of MT waves into the earth increases at longer wavelengths. In light of the behavior of the data, the pseudosections of the apparent resistivity can be separated into three zones, each of which is distinguished by the similarity in the shapes of the phases and apparent resistivities within it: A significant drop in apparent resistivity values (100 m) in TM mode is present constantly up to lengthy durations in both polarizations in Zone 1, which is located in the northern part of the section and suggests a high conductivity at deep. At the very short periods, the apparent resistivities and high impedance phases in TM mode indicate that there is shallow low - resistivity layer in the area. The conductive layer in turn overlies very resistive basement. The depth to the conductive layer appears variable. The layer gets thinner and shallower according to steeply rising apparent resistivities. Zone 2 is located in the central part of cross section, there is marked increase in apparent resistivity values (100- 700 Ω m) at moderate periods in both the TE and TM modes. Zone 3 is located in the southern part where there is a marked increase in apparent resistivity values (> 700 Ω m) in both the TE and TM modes.

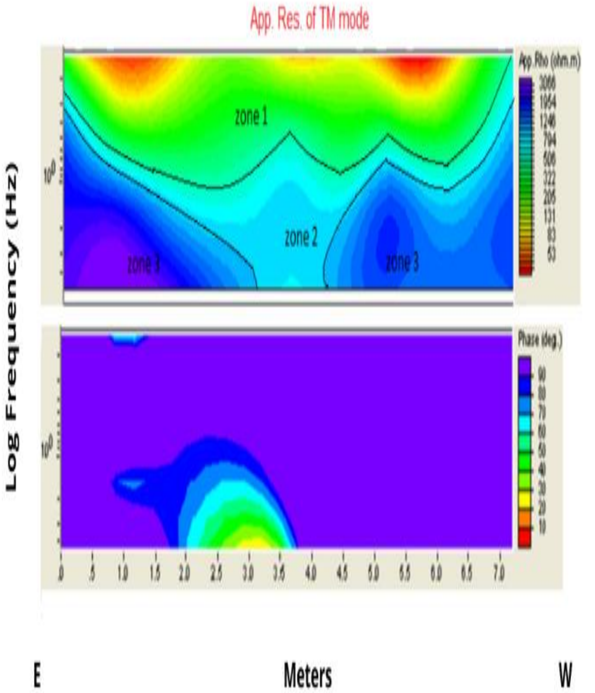


Fig. 7. Shows pseudosections of apparent resistivity mode.

### 3.8 Two-Dimensional Inversion of MT Data

The MT data were also inverted using the nonlinear conjugate gradient method with a 2-D smooth model inversion process. In order to calculate the forward model simulations, network analogs of Maxwell's equations were used to create finite difference equations. The number of stations and the station spacing, depending on the topographic relief, skin depths, and horizontal resistivity contrasts, were used to determine the input finite-difference mesh for the smooth inversion procedure. The usage of coarse mesh generation, where the rows' thicknesses increase with depth in accordance with a predetermined, set pattern, was made. For the subsurface structure of the studied area, the 2-D inversion produces reasonable findings. The shallow conductive region located above the high resistive region corresponds to a subterranean reservoir that can be distinguished using 2-D models.

The 2-D inversion (Fig. 8) shows that the MT can divide the section into three main layers according to the resistivity and geoelectrical layers that are described below:

The first layer is characterized with high resistivity (more than 1000 Ohm-m), while the second layer has resistivity ranges from 250 to 612 Ohm-m), this layer extends under all stations with depth ranges from 0 to 5000m.

The third layer has resistivity ranges from 64 to 250 Ohm-m, this layer extends under all stations with depth ranges from 1000 to 4000 m. This layer is considered as a conductive zone in the study area.

Finally from the interpretation of the previous data, we can conclude that the MT method could allow us to draw and detect the location of conductive zone.

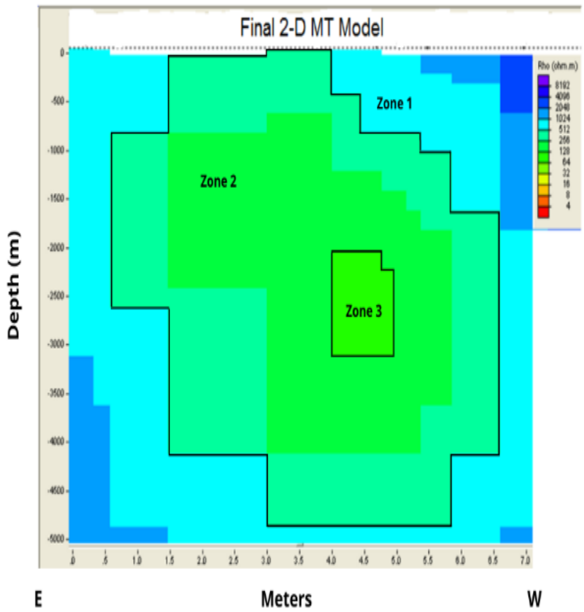


Fig.8. Two-dimensional inversion of MT data.

### 4. CONCLUSIONS

From the previous analysis of the MT data, we can conclude that, the tipper magnitude clearly defines the vertical structure on either side of a contact. It facilitates in resolving any dispute in the strike and demonstrates the more conductive side of a contact. The magnetotelluric field's structure appears to be more or less two-dimensional, with the major and minor axes located in the northeast and northwest, according to the polar impedance. The interpretation of the pseudosections of the apparent resistivity and phase shows that, there are three zones, each zone is characterized by the similar shape of the apparent resistivities. While the interpretation of the 2-D inversion gave reasonable results of the subsurface structural setting of the study area. The shallow conductive region above the high resistive region, which corresponds to the subsurface reservoir, was delineated with the help of the 2-D model. According to the resistivity and geoelectrical layers, it demonstrated that the study region may be separated into two primary layers. Finally, we can say that the MT could investigate the active geological subsurface structures which were covered by the relatively thin Quaternary layers. Also, we could conclude that the MT method could allow us to draw and detect the location of conductive zone at the study area.

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