Iron ore prospecting based on very low frequency-electromagnetic and geoelectrical resistivity at Wadi Abu Subeira, Northeastern Aswan, South Egypt

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ABSTRACT

The serious need and high demand of iron oxides in cement industry urges to carry out critical investigation in vicinity of cement factories in South Egypt Governorates. The considered area Wadi Abu Subeira lies to the north east of Aswan. The possible occurrences of hematite in the subsurface enforced to carry out some geophysical measurements in the form of very low frequency-electromagnetic and geoelectrical resistivity.

A total number of 684 very low frequency-electromagnetic and 54 vertical electrical soundings stations were executed along 9 surveying profiles arranged on three long traverses, running from west to east direction. The datasets were comprehensively and steadily inverted/transformed in terms of subsurface electric resistivity/EM-equivalent current-density. Both the vertical and lateral resistivity/current-density variations were able to image the typical shallow stratigraphic sequence of the area. The present study emphasized the robustness and cost-efficiency of applying the very low frequency-electromagnetic and geoelectrical resistivity techniques in a field like iron ore exploration.

1. Introduction

The study area (Wadi Abu Subeira) is located to the north east of Aswan, South Egypt. It lies between latitudes 24°12′08.5″ to 24°12′40.9″N and longitudes 32°55′08.7″ to 32°57′47.6″E (Fig. 1a) and covers an area of some 4.5 km². The topographic relief is clearly uneven. In the floor of Wadi Abu Subeira, the elevation increases to east direction, ranging from 96.0 m (above the sea level) in the west to 114.0 m in the east. On the flanks of Wadi Abu Subeira, the topographic relief is ranging between 140.0 m at the southern flank and 180.0 m at the northern flank (Fig. 1b).

2. Geological setting

The iron ore in the study area is hosted within Upper Cretaceous Nubian sandstone which lie unconformably on the peneplained basement complex of crystalline igneous and metamorphic rocks. Several studies have been published for Nubian Sandstone facies and its general geology, origin, lithologic character, ore deposits, beneficiations of its economic raw material (Iron ore, clay and kaolin). Concerning the origin of the ore, its estuarine origin (Bullen Newton, 1909), eolian origin (Barthaux, 1922), a marine environment under shallow water conditions, near shore lines, lagoonal, and deltaic, (Attia, 1955), and hydrothermal origin (Abd El Nasser, 1961). The thickness of the Nubian Sandstone in east Aswan has been given different values, it is 162 meter according to Attia (1955), while Hume (1907, 1962) reported a total thickness of 218 meter at Gabel Nugra east of Kom-Ombo. On the other hand, Faris and Abu-Zeid (1963) considered a composite columnar section in the east of Aswan of 89.21 meter thick.

The Nubian Sandstone series classified according to Attia (1955) into three main unit: (1) The Lower Nubian Sandstone, unconformably resting over the peneplained Basement rocks and characterized by the presence of conglomeratic and kaolin beds. (2) The Middle Nubian Sandstone, characterized by the presence of ferruginous beds and the oolitic iron ores. (3) The Upper Nubian Sandstone, characterized by presence of great thickness quartzitic sandstone. Clay bands are principally restricted to the lower parts of this series. Geological map of Northeast of Aswan area, modified after Attia, 1955, is presented in Fig. 2.

Iron ore east of Aswan is represented by two separate zones, lower

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Fig. 1. (a) Index map of east Aswan area showing the location map of the study area and (b) Topographic contour map of the study area derived from Global Mapper System V19, Global Mapper Software LLC, USA.

Fig. 2. Geological map of Northeast of Aswan area, modified after Attia (1955).
and upper zones, the lower and upper zones are termed the (A) bed “contains only one ore bed”, the (B) beds “contain two and occasionally three iron ore beds” respectively, according to Iron and Steel Company. In Wadi Abu Suberia area, the ore in surface section is represented by two iron ore beds (B1) and (B2) of upper zone separated by ferruginous sandy clay and clayey sandstone and lies under a thickness of about 80 meter of false bedding sandstone and reddish to yellowish claystone. Most of the faults are practically vertical, some of them are steeply inclined. The throw is either very small or it may reach up to 50 m, but it commonly difficult to exactly estimate because of the similarity of the sandstone beds. The majority of these faults trend in N-S or/and NNW-SSE directions; but, some of them run in NW-SE directions; and a few run either E-W or NNE-SSW.

3. Very low frequency–electromagnetic surveying technique

3.1. Conceptual background and data acquisition

Very low frequency–electromagnetic (VLF–EM) surveying techniques employ plane electromagnetic waves created by remote, land-based radio-transmitters, distributed all over the world for the purpose of marine military communication with submarines, working at
frequency bandwidths ranging from 10.0 to 40.0 kHz. These powerful transmitters radiate continuously either superimposed frequency-modulated EM wave or irregularly chopped unmodulated Morse code (dots and dashes) (Paal, 1965; Paterson and Ronka, 1971). Similar to other surface EM induction techniques, VLF–EM techniques have a key advantage over the other geophysical tools is that the induction process doesn’t need direct (or galvanic) electrode contact with the ground. Accordingly, the data acquisition could be relatively faster and cheaper than other geophysical techniques. VLF–EM techniques have an extensive range of applications in mining, hydrological, archeological, environmental and geotechnical studies (McNeill and Labson, 1991).

A VLF–EM magnetic field can be observed by a small, hand-held receiver (induction) equipped with a vertical coil in which current flow is in direct proportion to the core permeability, number-of-turns and strength of the magnetic field component(s) along its axis. Moreover, such coil reduces the self-capacitance and permits resonant tuning to the chosen frequency within the VLF–EM band-pass.

VLF–EM measurement process performed according the following steps: (1) the receiver coil is tuned to a specific frequency of the chosen radio-transmitter. (2) The azimuth of the radio-transmitter is gained by rotating the induction coil around a vertical axis until the null position (i.e. minimum pairing) is detected. (3) The coil is then rotated around a horizontal axis at right angle to that azimuth (maximum pairing) where the both real (in-phase) and imaginary (out-of-phase) components of the complex quantity (secondary/primary field ratio) are recorded as percentages through a built-in micro-processor in most common commercial measuring systems.

The real component responses are generally very sensitive to subsurface conductors (McNeill and Labson, 1991). To observe both the vertical and lateral ground resistivity variations along a profile (vertical sounding and horizontal profiling), VLF–EM measurements are made at a multiple operating frequency using a fixed and progressively-moving

Fig. 6. Transformed EM equivalent current-density contour maps using joint operating frequencies 20.3 and 26.7 kHz, (a) at depth 20 m, (b) at depth 40 m, (c) at depth 60 m. Hot colors indicate more conductive subsurface media, while cold colors indicate more resistive subsurface media.
measuring spacing (Frischknecht et al., 1991).

The measurements were carried out using the commercially available ABEM WADI™ VLF–EM system (ABEM Instruments AB, 1989). The precision of measurements depends on factors such as the ground earth model, remoteness and departure from the true azimuth of the radio-transmitters, field strength, and the ambient noises. Identifying the sources of error is critical in the ABEM WADI system because it has no tensor time series. A method to get rough weighting-error estimates is by repeating the measurements at every sounding three or four times, for each operating frequency, to confirm the data and grade the signal strength of radio-transmitters. The estimated weighted error used to assess the background noises. Also, measurements at the time of both sunrise and sunset should be avoided.

A total of 684 reliable EM induction soundings were conducted in the study area along 9 survey profiles with station interval of 20 m (Fig. 3), at right-angle to each of those azimuths, using only well-defined frequencies. The operating frequencies were 20.3 and 26.7 kHz at the measuring azimuths 315° and 340°N, respectively. Real component (Re) values at every sounding were recorded and transferred to a Laptop computer and completely analyzed. The locations of each VLF-EM sounding station was saved using the commercially available Handheld Garmin GPSMAP 64C unit.

3.2. Data treatment and interpretation

Raw data sets along all surveying profiles, real components for the used operating frequencies, were normally transferred to a Laptop computer. They have been combined with stations coordinates, viewed, validated and averaged using specially-designed spreadsheet excel files and then entered into the available software RAMAG™-2.20 (ABEM Instruments AB, 1989).
Instruments AB, 2002). The averaged real component values for joint operating frequencies (20.3 and 26.7 kHz) were typically plotted versus measuring distances and collectively presented as a single colored contour plan map (Fig. 4).

VLF–EM data filtering and transformation procedures include the application of the Fraser filter (Fraser, 1969) and the Karous-Hjelt filter (Karous and Hjelt, 1977, 1983). Fraser filter, one-dimensional linear filter-operator was applied to convert tilt-angle cross-overs into peaks and improve the lateral resolution of VLF–EM data and making them easier to identify. The Fraser filtering results presented as a single colored contour map (Fig. 5).

Karous-Hjelt filter, two-dimensional linear filter-operator, was additionally applied to improve both the vertical and lateral resolutions of VLF–EM data. The filtering results were usually stated in terms of EM equivalent current densities at specified depths which consist of both currents induced within the subsurface conductors themselves (inductive effects) and currents concentrated into the conductors from the less-conducting surrounding (current gathering). The contoured equivalent current density maxima are always occurred inside the subsurface conductors and provided depth estimates for such conductors. Transformed EM equivalent current-density contour maps using joint operating frequencies 20.3 and 26.7 kHz, at different depths 20 m, 40 m, and 60 m are presented in Fig. 6. The transformed equivalent current-densities are typically plotted as a colored contoured pseudo-depth section (Fig. 7).

4. Geoelectrical resistivity surveying technique

4.1. Conceptual background and data acquisition

The electrical resistivity survey using the Vertical Electrical Sounding (VES) technique was applied in the study area to image the

![Iso-apparent resistivity contour maps](image)

Fig. 9. Iso-apparent resistivity contour maps, progressively from AB/2 = 1.5 to AB/2 = 100 m. Hot colors indicate more conductive subsurface media, while cold colors indicate more resistive subsurface media.
resistivity variation with depth. It’s performed using popularly the Schlumberger configuration, i.e., measurements of apparent resistivity are made around a single center point with systematically varying electrode spacing. An artificially generated direct currents (DC) (I) are injected into the ground by two current-electrodes (CA, CB) and the resulted potential differences (ΔV) are measured between them by two potential-electrodes (PM, PN).

A total of 54 Schlumberger VES’s were carried out for the present measurements, with a maximum current-electrode half-spacing (AB/2) of 100 m using the commercially available Terrameter SAS–300C system (ABEM Instruments AB, Sweden). Identifying the sources-of-error is critical in the scalar ABEM™ Terrameter SAS–300 system because it has no real-time series. The method to get rough weighting-error estimates is by repeating the measurements at every half-spacing four times to validate the data and grade the signal strength. The estimated weighted error used to assess the background noise. The locations of each vertical electrical sounding station was saved using the commercially available Handheld Garmin GPSMAP 64C device. The locations of the measured vertical electrical sounding station are shown in Fig. 8.

4.2. Data treatment and interpretation

4.2.1. Qualitative interpretation

The qualitative interpretation of geoelectrical resistivity data for the present work involves the following items; (1) preparation of the iso-

![Apparent resistivity contoured pseudo sections, progressively from AB/2 = 1.5 to AB/2 = 100 m. Hot colors indicate more conductive subsurface media, while cold colors indicate more resistive subsurface media.](image-url)
apparent resistivity contour maps, where the apparent resistivity values \( (\rho_a) \) are plotted versus electrode spacing \( (AB/2) \) on maps, contoured and interpreted (Fig. 9), (2) preparation of the apparent resistivity contour sections (Pseudo-section). These sections are generally prepared by plotting the apparent resistivity values \( (\rho_a) \) for a given electrode separation \( (AB/2) \) as ordinate and the station numbers as abscissa. The obtained pseudo-sections of the apparent resistivity reflect both lateral and vertical variations of the apparent resistivity values (Fig. 10). Such sections can help prepare the geoelectrical cross sections needed for defining the geoelectric units.

4.2.2. Quantitative interpretation

The geoelectrical resistivity data sets were interpreted quantitatively in terms of 1D resistivity smoothed-earth and layered-earth models. The modeling of VES curves over horizontally stratified media were carried out by using forward filters based on the algorithms of (Koefoed, 1979; and Sandberg, 1990) and inverse modeling uses an iterative least-squares optimization approach (Kunetz and Rocroi, 1970; Zohdy, 1975; Zohdy, 1989; Loke and Barker, 1995; Pirttijärvi, 2003). The apparent resistivity data were used as a homogeneous starting model, multi-layer model, in which the number of layers is so close to the number of electrode half-spacing \( (AB/2) \). The multi-layer models were reduced manually to less number of layers and then, subjected to successive iterations till best fit between the calculated curves and the observed curves using WinSev software v6.1, 2006, (W-GeoSoft geophysical software, France). Some selected Winsev output models curves presented in Fig. 11.

A 2D smoothed-earth resistivity sections for the nine profiles were constructed by assembling and contouring inversion results of each successive 6 VES’s using the commercially available software package SURFER®-11.0/2012 (Golden Software, Inc., USA) Fig. 12.

The smoothed-earth inversion results were vertically combined and topographically corrected to build the resistivity 2D layered-earth models. The resulted 2D layered-earth models were correlated with the available geological information and used to construct final geoelectrical cross-sections (Fig. 13). The final geoelectrical cross-sections are typically reflect the actual geoelectric picture of the prevailing subsurface conditions.

5. Subsurface resistivity models

All contoured maps (Figs. 5/6 and 9) and stitched cross-sections (Figs 7 and 12/13) were usually successful in determining any vertical and/or lateral electric resistivity/EM-equivalent current-density variations present within the study area. The encountered subsurface geoelectrical units have been shown up, from upper (youngest) to lower (oldest), as follow:

1. The surface geo-electrical unit is characterized by relatively high electrical resistivity ranges, averaged as 5650 \( \Omega \)m. The thickness of this unit is ranged between 0.54 and 4.40 m. This unit was interpreted as the weathered zone which is composed of sand/silty sand, clay, graded-grained gravels and rock fragments. This layer is obviously undifferentiated on the EM-VLF cross-sections.

2. The second geo-electrical unit is characterized by intermediate electrical resistivity ranges, averaged as 326 \( \Omega \)m. The thickness of this unit is laterally varied, ranged between 2.0m and 14m. This unit was interpreted as the dominate sand/clayey-sand/sandy-clay unit. This lateral lithological variation is believed to be as a result of strong fluctuations of both short rise and fall of the sea water level.
during the deposition.
(3) The third geo-electric unit is characterized by relatively low electrical resistivity ranges, averaged as 18.5 Ωm. The thickness of this unit is laterally varied, ranged between 18.0 and 35.0 m. This unit was interpreted as the thick ferruginous clay which is well-known with occurrences of thin medium/high-grade iron ore bands/masses. Locations of these accumulated bands/masses, within the ferruginous clay, are evidently appeared as separate filtered real-component highs (very electrically conductive anomalies) within the FRASER contour map. Their vertical extensions can be roughly determined from the EM-equivalent current-density cross-sections.
(4) The fourth geo-electric unit is characterized by intermediate electrical resistivity ranges, averaged as 150 Ωm. This unit was interpreted as the dominate sandy-clay/clayey-sand/sand unit.
(5) The encountered abrupt changes of the electric resistivity values at the middle part of inverted cross-section # 8 could be interpreted as a complex faulted block (F1-F2).
6. Conclusion
The integrative use of both the VLF-EM and geoelectrical resistivity sounding techniques was found effective for imaging the typical shallow stratigraphic sequence at the study area. The obtained data sets were comprehensively and steadily inverted/transformed in terms of subsurface electric resistivity/EM-equivalent current-density. There are some direct indications for the presence of iron ore accumulations. Where, the stitched 1D layered inverted resistivity sections in 2D, below the measured soundings, could bulky imaged the relatively conductive...
ferruginous clay, whereas, the very conductive thin iron ore bands/masses, within such a dominant thick clayey layer, could be imaged from the EM-equivalent current-density cross-sections. The results could approximately differentiate between the target ferruginous clay and its fairly resistive sand/clayey sand background. From the aforementioned work, we can conclude that, the area under consideration is relatively poor with respect to iron prospecting.

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