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Horizontal Loop Electromagnetic and Self-Potential Signatures of Mineralized Structures: A Case Study from Abu Rusheid Area, Southeastern Desert, Egypt

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Abstract. Horizontal-loop electromagnetic (HLEM) and self-potential (SP) surveys were carried out at Abu Rusheid area, southeastern Desert, Egypt, to follow the extension of the exposed mineralized shear zone at depth and to detect any possible subsurface mineralization and its probable extension, as well as to reveal its structural setting, which may affect the distribution of radioactive and other associated minerals.

The HLEM data were collected using four frequencies (110, 440, 3520 and 14080 Hz) and two coil separations (80 and 140 m). The interpretation of these data indicates the presence of two strong conductive zones trending in the NNW-SSE and NW-SE directions. These strong conductors are dissected by a moderate conductive zone trending in the NE-SW direction. The target parameters, as estimated from the HLEM data suggest that their widths range between 10 and 80 m, depths to the top are shallow and vary from 13.6 m to 58 m, dip angles range between 36° and 82° to both the east and west, and conductance (σt) changes from 18.4 to 135.2 Siemens (S). A small area was selected for an SP survey to follow observed radiometric anomalies at depth. The results indicated the existence of a series of conductive zones corresponding, in many places, to the previous identified radiometric zones.

The integration of the results revealed that, the SP and HLEM conductive anomalies are related to shear zones and faults, as well as lamprophyre and quartz veins. Most of these anomalous zones are open towards the north which may attract the attention to the continuity of mineralization northwards. In addition, the NNW-SSE, NW-SE and NE-SW trending structures are of prime importance and can be considered as significant targets for further field investigations.

Keywords: Egypt, Electromagnetic, self-potential and conductive zones.

Introduction

Abu Rusheid area is located in the southeastern Desert of Egypt, between latitudes 24° 37' 34" & 24° 38' 12" N and longitudes 34° 46' 00" & 34° 46' 35" E (Fig. 1). It is surrounded by a famous ancient mining area for emeralds. Recently, the Nuclear Materials Authority (NMA) launched a comprehensive exploration program in the Wadi Al Gemal basin, which has two important sites of valuable nuclear minerals. Two important resources occur in this basin; the ancient mine dumps, which contain large reserves of beryllium, and the precious metals resource of the Abu Rusheid area.

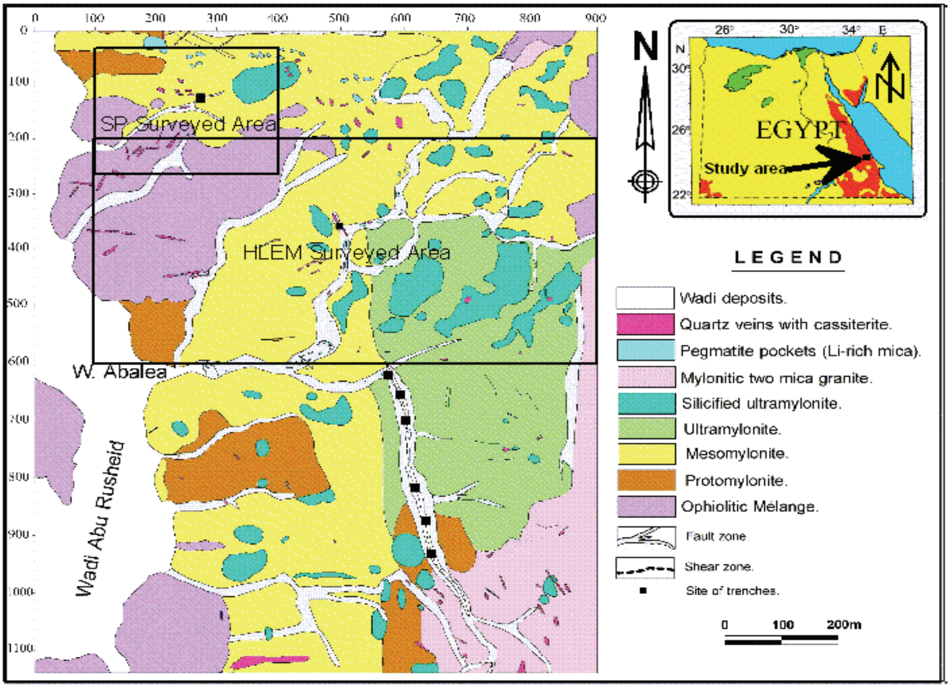

Fig. 1. Geologic map of Abu Rusheid area, Southeastern Desert, Egypt. (after, Ibrahim *et al.*, 2002).

The previous geological, geochemical and radiometric studies (Hassan, 1973; Sabet *et al*., 1976; Soliman, 1978; Hegazy, 1984; Ibrahim *et al.*, 2000 & 2002 and others) showed precious metals deposits and several anomalous radiometric zones in the study area. The strongest mineralization zones were observed along the main shear zone located at the southeastern part (Fig. 1). Most of them were trenched and we found a relative increase in the uranium mineralization and some sulphide minerals with depth. A ground geophysical survey was executed over the shear zone area (Assran and Mansour, 2004); the results suggested further geophysical work at the northern part of the study area, in a test to discover any subsurface extensions of the mineralizations.

HLEM and SP methods are used mainly to prospect for conductive materials. Such materials are commonly found in, or near fault and shear zones. If these zones contain conductive materials such as sulphides or ground water, they may be detectable by these methods. The present work focuses on the application of these methods at the northern part of the study area to follow the extension of the exposed mineralized shear zone with depth, to detect any possible subsurface mineralization, its probable extension and to reveal its structural setting which may control the distribution of radioactive and other associated minerals.

Geologic Setting

The geologic setting of the area and the potentialities for mineralizations in Abu Rusheid area and its surrounding have been discussed by various workers (Sadek, 1952; El Shazly and Hassan, 1972; Krs, 1973; Sabet *et al*., 1976; Abdel Monem and Hurley, 1979; Ibrahim *et al*., 2002 & 2004). The study area is characterized by low to moderate topography. According to Higgins (1975), Ibrahim *et al*. (2002) and Kurt and Martin (2002), the tectono-stratigraphic sequence of Abu Rusheid Precambrian rock units are: 1) An ophiolitic mélange, consisting of ultra-mafic rocks and layered metagabbros set in a metasediment matrix; 2) A mylonitic group, including proto-mylonites, meso-mylonites, ultra-mylonites, silicified ultra-mylonites and augen mylonites; 3) Mylonitic two mica granites; and 4) Post-granite dykes and veins (lamprophyre, pegmatite and quartz). The mylonitic rocks of the study area are cross-cut by many shear zones, which trend mainly in the NNW-SSE and ENE-WSW directions. These shear zones are considered as discontinuous brecciated ductile and completely altered.

Several mineral deposits have been found in the study area (Mansour, 2005), which can be grouped into two groups as follows: 1) An ore minerals group, which contains pyrite, brochanite, pyrolusite, Mn-franklinite, casseterite, kasolite, thorite, thorianite, columbite-tantalite and zircon, and 2) An associated gangue minerals group containing fluorite, mica, garnet, amazonite, tourmaline, goethite, hematite, magnetite, jarosite and thuringite.

Geophysical Survey Methods

1. Self-Potential (SP) Method

A small area was selected for the SP survey (Fig. 1) to follow the observed radiometric anomalies (Ibrahim, *et al*., 2002) with depth. This area is characterized by the presence of a lamprophyre vein running longitudinally through a narrow shear zone trending NNW-SSE and cutting through the sharp contact between two different rock types (Fig. 1). Non-polarizable (copper-copper sulphate) electrodes were utilized and a high-input impedance voltmeter was utilized to measure the potentials. Electrodes (porous pots) were placed in 5 cm deep wet holes to reduce the source of noises from the topsoil. One electrode was left as a reference at a fixed point and the second (rolling electrode) was moved over a grid with 10 m station interval and 10 m line spacing. SP readings in millivolts were taken with respect to the base station throughout the selected grid area.

2. Horizontal-Loop Electromagnetic (HLEM) Method

The horizontal-loop electromagnetic (HLEM) method can be used to infer the subsurface conductive zones at various depths by changing the spacing between the transmitter and receiver coils (Tx – Rx) or the frequency of the transmitted field (Won, 1980, and Keiswetter and Won, 1997). The method requires that a sample of the transmitted signal is sent along a wire to the receiver, where it is used to synchronize the phase of the receiver with the transmitter. This permits the receiver to remove the effect of the transmitter signal (primary field) and to split the remaining secondary field into two components. One phase with the primary field (in-phase component) and the second component is the portion of the secondary field, which lags the primary field by one-quarter cycle (90º-quadrature component). The real (in-phase) and the quadrature (out-of-phase) components of the resultant secondary electromagnetic field are recorded at several frequencies by a receiver coil, and their values are recorded as a percentage of the primary field. The midpoint joining the transmitter and receiver coils is considered as the point at which the conductivity is measured.

HLEM data were acquired using the APEX MAX-MIN I-8 instrument, a multi-frequency induction sensor developed by Parametrics Limited, Canada. The instrument and its uses in mineral prospecting have been described by Betz (1975 and 1976). In all measurements, four frequencies were used; 110 Hz, 440 Hz, 3520 Hz and 14080 Hz. In-phase and out-of-phase components were recorded with 140 m and 80 m Tx-Rx spacing and with station interval 20 m along the survey line.

Interpretation

1. Self-Potential (SP)

The SP map (Fig. 2) acts by itself as a high-cut filter, so that only the long-wavelength anomalies remain. The structure to be detected is generally 3-D, therefore it is better to interpret a contour map rather than profile data (Thanssoulas and Xanthopoulos, 1991).

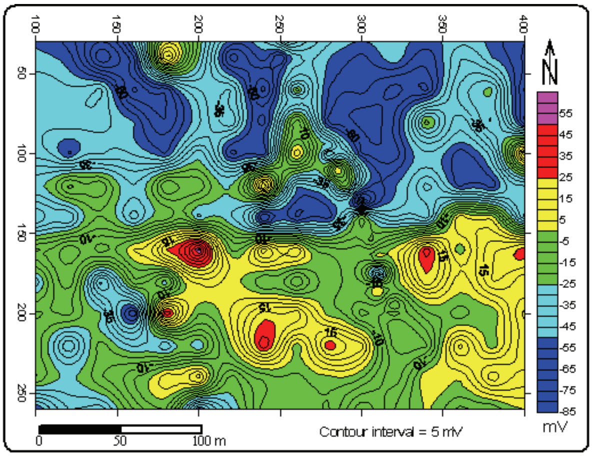

Fig. 2. Self-potential contour map.

The examination of the SP contour map (Fig. 2) shows that the area can be separated into two parts (northern and southern) by steep gradient contour lines, which run in an E-W direction. A sudden change in the magnitude and sign of the anomalies was observed along these steep contour lines, which likely represent a sharp geologic contact. The northern part is characterized by relatively moderate to strong negative SP anomalies that trend NNW-SSE, NW-SE and E-W. These anomalies appear related to the shear zones and faults, as well as the lamprophyre and quartz veins. Most of them are open towards the north; this may attract attention to the continuity of mineralization northwards. Meanwhile, the southern part is characterized by relatively weak negative and strong positive SP anomalies that are associated with the ophiolitic mélange (Fig. 1). Some of the SP anomalies appear to correlate with the identified radiometric anomalies (Ibrahim *et al*., 2002), whereas the other SP anomalies that do not coincide with any radiometric anomalies may be due to soil moisture and depth of penetration of the radiometric method (30 cm).

Figure 3 illustrates the structural lineaments that were deduced from the SP data. These lineaments may be useful for defining the locations of fault zones affecting the underlying rocks, which may act as pathways for the mineralizing solutions to form both vein-like and stratiform mineral deposits. The most conspicuous feature is the well-defined SP response associated with the outcrop of lamprophyre vein (marked A). Other narrow conductive zones were detected and traced (marked B, C and D) on the interpreted structural lineaments map (Fig. 3). Also, this map shows that, the area under consideration has been affected mainly by four sets of structures trending in the NNW-SSE, NW-SE, NE-SW and E-W directions.

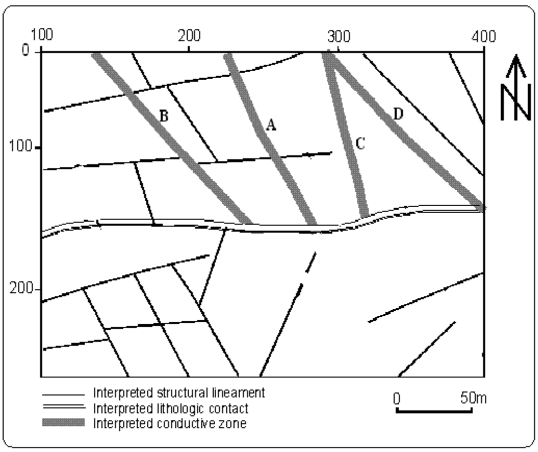

Fig. 3. Interpreted structural lineaments map as deduced from the self-potential map.

The stated four sets of faults are familiar tectonic trends in the Egyptian basement rocks and mainly reflect the strike lines of elongated intrusive and/or extrusive igneous features, faults, shear zones and lithologic contacts. However, it is very noticeable that the NNW-SSE direction is much more prominent and shows distinct and well-developed structural lineaments allover the area.

2. Horizontal-Loop Electromagnetic (HLEM)

Six HLEM profiles (coded 200, 280, 360, 440, 520 and 600) with 140 m-coil separation were conducted in 2003 from west to east (Fig. 1), nearly normal to the strike of the main structural lines and shear zone which affect the distribution of the radioactive minerals in the study area. The survey was also extended in 2004 with two more profiles (coded 60 and 140) of 80 m coil separation to follow the identified conductive bodies that have 16-58m depth.

2.1. Qualitative Interpretation

In the field survey, the out-of-phase response is normally used only to infer the ground conductivities in a resistive ground, and is not normally used to detect conductive bodies, whereas the in-phase component, while generally not responsive to the changes in bulk conductivity, is especially responsive to discrete the highly conductive bodies (Won and Keiswetter, 1997). In mineral exploration, contour maps are useful means for tracing the lateral extent of conductive units. As a result, four maps, representing the in-phase components with 140 m Tx-Rx separation, are generated for each frequency (Fig. 4 to 7).

A conductor will show up as negative in-phase values and a good conductor will respond on progressively lower frequencies, whereas poor conductor is observed only at the higher frequencies (Won and Keiswetter, 1997).

Two significant conductive zones (marked A and B) are clearly defined by linear NNW-SSE and NW-SE trending troughs on the utilized frequencies (Fig. 4 to 7). These two strong conductive zones are intersected by a moderate conductive zone (marked C) trending in the NE-SW direction. Zone (A) is observed at the extension of the previously identified EM anomalies (Assran and Mansour, 2004) associated with the main shear zone of the Abu Rusheid area (Fig. 1). This indicates that the exposed mineralized shear zone at the southern part continues with depth in the northern part of the area (Fig. 1). The observation of these conductive zones at the lowest and highest frequencies indicates that the causative bodies of these zones are good conductors located at shallow depths.

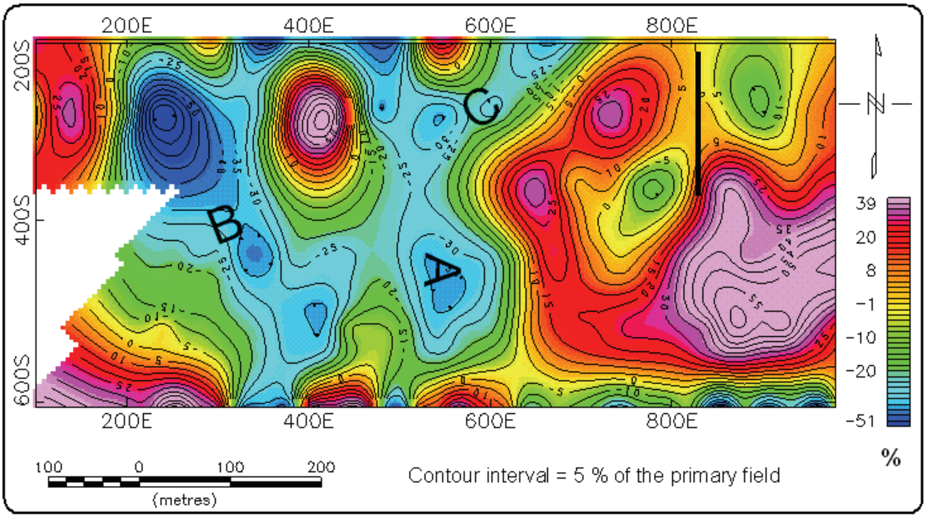

Fig. 4. In-phase EM component map with coil separation of 140m and frequency of 110 Hz.

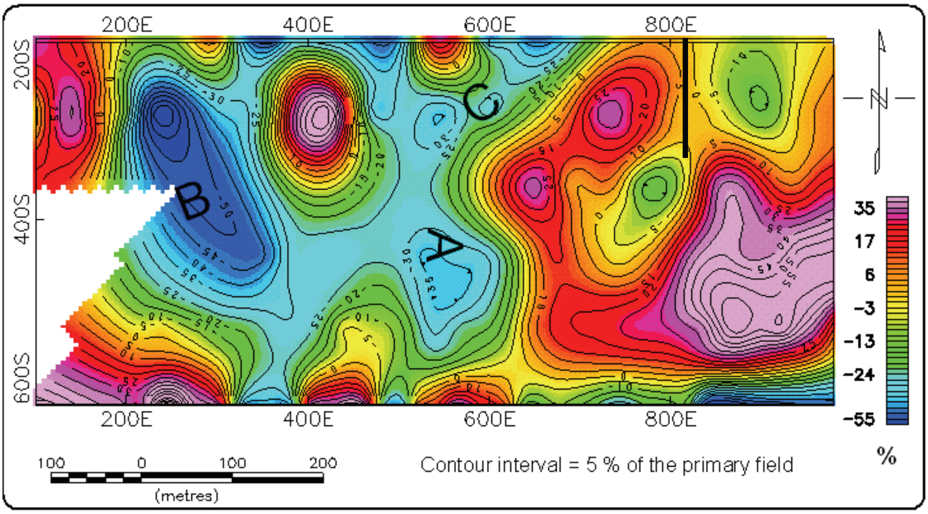

Fig. 5. In-phase EM component map with coil separation of 140m and frequency of 440 Hz.

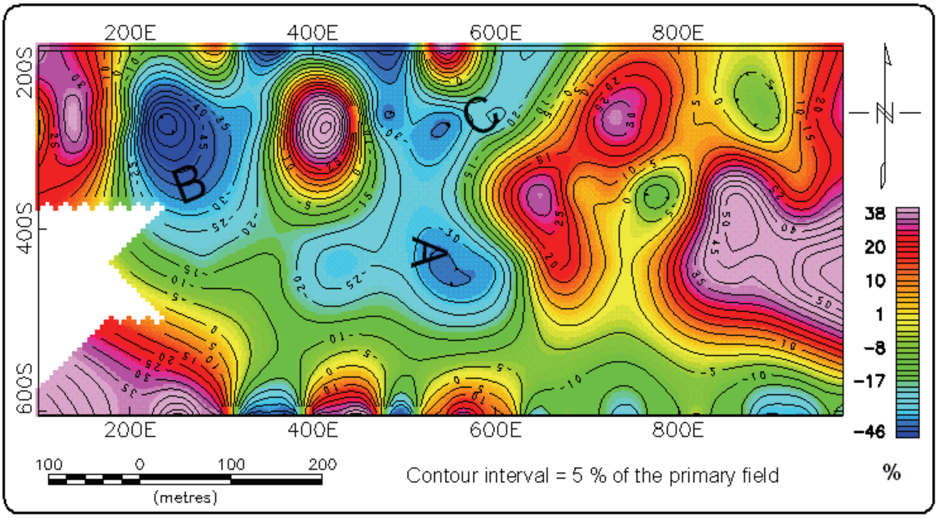

Fig. 6. In-phase EM component map with coil separation of 140m and frequency of 3520Hz.

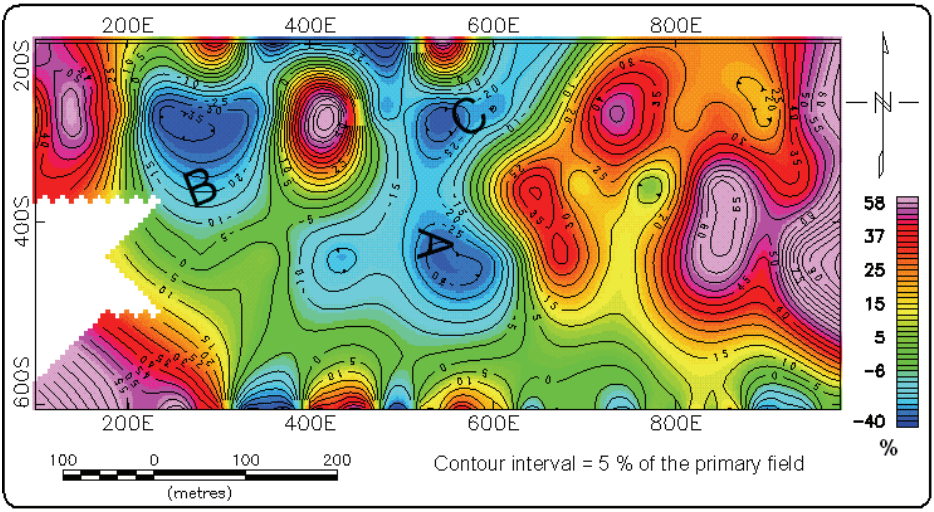

Fig. 7. In-phase EM component map with coil separation of 140m and frequency of 14080 Hz.

The strongest EM anomaly is observed at the northwestern part of the area (northern part of zone B) and clearly pronounced on the four frequencies (Fig. 4 to 7). This anomaly agrees with the high radiometric zone (Ibrahim *et al.*, 2004), and therefore it is considered as a target of higher priority for uranium exploration. The extreme north central part indicates strong EM anomalies that opened toward the north (Fig. 4 to 7). Accordingly, two additional HLEM profiles (lines 60 and 140) with 80 m Tx-Rx were conducted at the northern part, to follow the extension of these strong anomalies. The results of these profiles (Fig. 8) revealed that strong EM anomalies extend from previous EM anomalies. This may indicate the existence of another two strong conductive bodies in this part of the study area.

By correlating the SP map with the HLEM data of lines 60 and 140 (Fig. 2 and 8), it was found that at each of the EM anomaly locations there are a coincident SP anomalies. Additional anomalies can also be seen on the SP map, which may be related to disseminated sulphides. The coincidence between the SP and HLEM features, with the radiometric anomalies in some places, provides good evidence that the SP method could be used as a reconnaissance tool for uranium mineralizations in an environment associated with sulphides.

The northeastern part shows a relatively weak conductive zone (Fig. 4), which is separated into two EM anomalies by a N-S fault. The western one is elongated in the NNE-SSW direction and is observed at all frequencies (Fig. 4 to 7). This may indicate that the source body is relatively shallow. Meanwhile, the eastern anomaly is recorded on the lower frequencies (110 Hz and 440 Hz) as a weak anomaly (Fig. 4 and 5) and on the highest frequency (3520 Hz) as a very weak anomaly (Fig. 6). But this anomaly disappeared (Fig. 7) on the very high frequency (14080 Hz). This may reflect that the source body of this anomaly is located at deeper depth.. Also, the in-phase component contour maps of 14080 Hz, 3520 Hz, 440 Hz and 110 Hz indicate a comparable change in the depth to the conductive bodies from frequency 14080 Hz to frequency 110 Hz at the southeastern part of the area and thus the four maps are felt to be semi-quantitative representations of the conductive bodies to different depths.

2.2. Quantitative Interpretation

The aim of an EM survey is to estimate the geometrical and physical properties of the causative conductor. The main parameters of the HLEM interpretation are: The location, dip (θ), width (W), depth of burial (h) and conductance (σt). These parameters can be estimated by using a family of response diagrams and curves, which were designed by Nair *et* *al*. (1974). Our data were corrected for topographic effects and the cleanest curves of the in-phase and out-of-phase components of the four used frequencies were selected to derive the parameters of the conductors (Fig. 8 and 9). The first step in interpreting the HLEM data is to establish the background in-phase and out-of-phase values away from the anomaly to be interpreted. The results of quantitative interpretation of the HLEM data for the cleanest anomalies are shown in Table 1.

Table 1. The results of quantitative interpretation of the HLEM anomalies

Line	Station	Width	Depth	Dip	σt.
600	360	____	32.2 m	60º W	50.7 S
600	500	____	22.8 m	82º W	18.4 S
360	680, 760	10 m	46.2 m	82º E	40.6 S
280	240	30 m	16 m	78º E	101 S
280	500	60 m	21 m	62º W	67.6 S
280	880	80 m	58 m	80º E	36.2 S
200	360, 480	60 m	17 m	65º E	127 S
140	340	80 m	13.6 m	38º E	135.2 S
60	400	60 m	36 m	36º E	112 S

The visual inspection of the anomaly curves (Fig. 8 and 9) shows that the amplitudes of in-phase component (IP) are much larger compared to the out-of-phase component (OP) suggesting that the conductivity anomalies are caused by massive metallic bodies. The positions of the peak values of the IP and OP components differ markedly, which may suggest that the observed anomaly represents the combined effect of two or more sources. Also, the shape for most of the EM anomalies suggests two or more conductors close to each other or the source body has irregular shape. Thus a shorter coil separation and station interval might isolate the response due to the main conductor.

The width of the negative peaks of the EM anomalies on line 600 is less than the coil separation, and thus may be due to thin conductors. The negative EM anomalies on the other profiles suggest changing in the width of the conductive bodies from 10 m to 80 m (Fig. 8 and 9). A considerable increase in the conductance (σt) estimates was observed to the north from 18.4 to 135.2 S, which implies a northerly increase in the mineralization content. This conclusion is also supported by the observed surface radiometric anomalies (Ibrahim *et al.*, 2002).

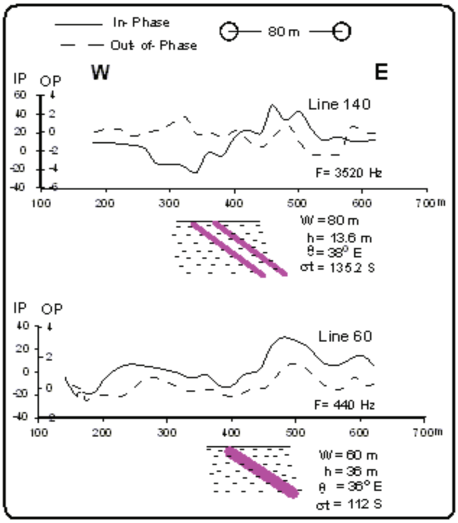

Fig. 8. Horizontal-loop electromagnetic profiles with coil separation of 80m along lines 140 and 60.

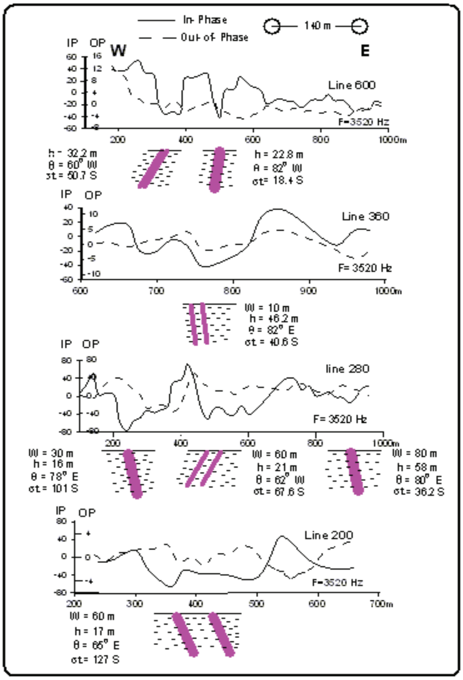

Fig. 9. Horizontal-loop electromagne profiles with coil separation of 140m along lines 600, 360, 280 and 200.

Conclusions

The HLEM data indicated that the exposed mineralized zone at the southern part persist at depths in the northern part of the area. Moreover, the data suggest the occurrence of many conductive zones that are mainly associated with shear zones and faults, as well as lamprophyre and quartz veins. The target parameters, which were estimated from the HLEM data reveal that their widths range between 10 m and 80 m, depths to the top are shallow and vary from 13.6 m to 58 m, dip angles range between 36° and 82° to the east and west, and the conductance (σt) varies from 18.4 S to 135.2 S.

The contour maps of the in-phase component for the four used frequencies (110, 440, 3520 and 14080 Hz) define the lateral extent of the conductive bodies. These maps appear to image the shear and fault zones and give a good indication about the nature of these zones (conductive or resistive). Moreover, the frequency-dependent signatures of the conductive zone, isolated anomalies, and geological variations clearly suggest the need for a broadband EM surveying. The coincidence between the SP and HLEM features with the radiometric anomalies in some places suggests that the SP method could be used as a reconnaissance tool when searching for uranium mineralization in a sulphide environment.

The following recommendations are proposed:

a) Shorter coil separations and station intervals should be used, to isolate the response due to anomalies that are caused by combined effect of two or more sources.

b) The induced polarization (IP) technique should be conducted at the locations of the strongest HLEM and SP zones in order to confirm the obtained results and explore the mineralization extensions in the deeper levels.

c) It is recommended that the NNW-SSE, NW-SE and NE-SW structural trends are of prime importance, and can be considered as significant targets for future field investigations for the study area and its surroundings.

d) Exploration drilling is recommended to test the thickness, depth extent and grade of mineralization at stations 400, 340, 240 and 360 on lines 60, 140, 280 and 600, respectively.

Acknowledgement

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بصمات الكهرومغنطيسية أفقية الدائرة والجهد الذاتي للتراكيب المتمعدنة: حالة دراسية لمنطقة أبورشيد بجنوب الصحراء الشرقية لمصر

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هيئة المواد النووية – ٥٣٠ بريد- المعادي – مصر

المستخلص. تم إجراء المسح بطريقتي الكهرومغنطيسية أفقية الدائرة (HLEM) والجهد الذاتي (SP) وذلك لتتبع الامتدادات السطحية لنطاق القص المعدني إلى أسفل، وكذلك لاكتشاف أي تمعدنات تحت سطحية محتملة وتتبع امتدادتها. بالإضافة للوضع التركيبي وتأثيره على توزيع المعادن الإشعاعية ومصاحباتها في منطقة أبورشيد بجنوب الصحراء الشرقية لمصر.

أخذت بيانات الكهرومغنطيسة الأفقية باستخدام أربعة ترددات مختلفة (١١٠، و٤٤٠، و٣٥٢٠، و١٤٠٨٠ هرتز) وكذلك استخدمت مسافتين مختلفتين بين المرسل والمستقبل (٨٠م، و١٤٠م) وأوضحت هذه البيانات وجود نطاقين قويين للتمعدنات لهما الاتجاهان شمال شمال غرب، وشمال غرب. كما وجد نطاق يقطع النطاقين السابقين وله الاتجاه شمال شرق. كما حسبت المعاملات للأجسام المكتشفة حيث وجد أن الاتساع ما بين ١٠م، و٨٠م وزاوية الميل تتغير من ٣٦ إلى ٨٢ درجة ناحية الشرق والغرب وأن عمق السطح العلوي لهذه الأجسام يتراوح مابين ١٣,٦ إلى ٥٨م. أما التوصيلية فتتراوح بين ١٨,٤ إلى ١٣٥,٢ سيمنز.

كما اختيرت مساحة صغيرة تعطي قراءات إشعاعية عالية لمساحتها بطريقة الجهد الذاتي، وذلك لتتبع هذه الشاذات الإشعاعية تحت السطح. وأوضحت النتائج وجود مجموعة من النطاقات المعدنية مصاحبة في معظم الأحوال للشاذات الإشعاعية المكتشفة على السطح.

ومن تكامل البيانات السابقة وجد أن الشاذات الجيوفيزيائية مصاحبة لنطاقات القص، والفوالق، وكذلك عروق اللامبروفير والكوارتز، كما أن معظم الشاذات مازالت تفتح للشمال، وهذا يؤكد أن التمعدنات لها استمرارية ناحية الشمال. أيضًا وجد أن التراكيب المتجهة شمال غرب، وشمال غرب، وشمال شرق لها مرتبة أولى من ناحية الأهمية، وأنها تعتبر أهدافًا مهمة للدراسات الحقلية المستقبلية لمنطقة الدراسة وماحولها.