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VLF-EM FOLLOW UP OF THE EXPECTED SUBSURFACE OCCURRENCE OF SULPHIDE MINERALIZATION IN WADI ISBAIYA AREA, SOUTH SINAI, EGYPT

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تتبع تواجد تمعدنات الكبريتيد التحت سطحية المتوقعة باستخدام موجات كهرومغناطيسية ضعيفة التردد فى منطقة وادى اسباعية، جنوب سيناء مصر

الخلاصة: أجري مسح جيوفيزيائى أرضى باستخدام طريقة الموجات الكهرومغناطيسية ضعيفة التردد فى منطقة وادى اسباعية، جنوب سيناء، مصر لاستكشاف اماكن تواجد تمعدنات الكبريتيد. نتيجة لصعوبة المنطقة لا يوجد اى مسح جيوفيزيائى أرضى سابق فى هذه المنطقة. نتائج المسوحات الجيولوجية و الجيوفيزيائية السابقة التى اجريت فى الاماكن السهل الوصول اليها و التى تحيط بمنطقة الدراسة حددت العديد من الشذوذات الناتجة من تواجد تمعدنات النحاس الكبريتيدية و الموجودة فى صخور الكوارتز مونزونيت. تهدف الدرسة الحالية إلى تحديد أماكن التمعدنات المتوقع تواجدها فى منطقة وادى اسباعية، من خلال تحديد اتجاهاتها وامتدادها و استنتاج علاقتها التركيبية بتواجدات التمعدنات الأخرى الموجودة فى المناطق المجاورة (مثل: منطقة أم قيصوم، أم علوى وسانت كاثرين). طريقة الموجات الكهرومغناطيسية ضعيفة التردد المستخدمة تمكنا من تحديد الشذوذات الموصلة المختلفة. جدير بالملاحظة ان هذه الشذوذات المختلفة لوحظت بوضوح فى الجزء الأوسط من منطقة الدراسة. أماكن تقاطع الاتجاهات التركيبية تمثل المناطق الواعدة لتواجد التمعدنات الفلزية. اكدت الدراسات الميكروسكوبية للقطاعات المصقولة لبعض عينات الكوارتز مونزونيت السطحية التى أخذت من أماكن الشذوذات الجيوفيزيائية تواجد التمعدنات الكبريتيدية المتمثلة فى البيريت و الكالكوبيريت بالاضافة لكميات قليلة من الذهب و الفضة و تمعدنات الحديد المتمثلة فى الماجنيتيت، الأليمينيت و البيروتيت. تركيزات هذه التمعدنات تزداد بزيادة العمق الذى يصل إلى ٢٠٠ متر و تتحكم بها التراكيب الجيولوجية الرئيسية و الثانوية مثل الصدوع. هذه الدراسة تؤكد أهمية العوامل التركيبية التى تتحكم بتواجد التمعدنات ذات القيمة الاقتصادية.

ABSTRACT: *Ground geophysical survey, using the Very Low Frequency Electromagnetic method (VLF-EM), has been conducted in Wadi Isbaiya area in order to investigate new occurrences of sulphide mineralization. The area is situated on the outcropped basement plateau in the mid-southern Sinai, Egypt. Due to its rough terrain, almost no previous ground geophysical surveys had been conducted at that location. Results from previous geological and geophysical surveys, conducted at the easily accessible localities surrounding the area of study, delineated several anomalies resulting from the presence of copper - sulphide mineralization and distributed in the quartz monzonite rock units. The current study aims to trace the expected subsurface mineralization potentialities at the area of Wadi Isbaiya, delineate their trends and extensions as well as deduce their structural relationship with other mineralization occurrences found within its vicinities (ex: Umm Qeissum – Umm Alawi – Saint Catherine). The utilized VLF-EM method enabled us to detect various conductive anomalies. Noticeable superimpositions between these different anomalies were clearly observed at the central part of the study area, which asserts the existence of metallic mineralization causative sources. Integrating the interpreted results of this VLF-EM survey allowed us to delineate the lateral extensions of these causative mineralization sources and estimate their depths, which exceed 200m. Locations of the intersection of the structural trends represent the most promising sites for metallic mineralization occurrences, and were always accompanied by significant VLF-EM anomalies. Microscopic examinations and microprobe analysis techniques confirmed the presence of anomalous sulphide mineralization, in the form of pyrite and chalcopyrite, in addition to minor traces of gold and silver. These results may confirm the importance of structural factor, which may control the occurrences of mineralization of economic value.*

1. INTRODUCTION

Exposed basement, which covers almost the whole region of the southern Sinai, provides an important resource of industrial minerals in Egypt. Currently, the Egyptian governments encourages researchers to investigate for new mineral resources in the southern Sinai, in order to provide new jobs and establish sustainable developed communities for nomads habiting the southern Sinai District. The current work aims to investigate the area bounded by latitudes 28º 32′ 10″ and 28º 34′ 10″ N, and longitudes 33º 59′ 22″ and 34º 01′ 22″ E which covers about 6 Km^2. The area is a part of the basement complex exposed in Saint Catherine, South Sinai Peninsula (Fig.1).

El-Ghawaby et al. (1989) outlined several copper - sulphide mineralization zones, distributed within quartz monzonite rock at Umm Qeissum and Umm Alawi areas, the easily accessible localities surrounding the area of study. Due to its rough terrain and high topographic relief, no ground geophysical surveys have been conducted at Wadi Isbaiya. The current work conducted ground VLF-EM method at the area of Wadi Isbaiya in order to detect the subsurface occurrences of conductive mineralization. In addition, several rock samples were collected from the geophysical anomalous zones for further microscopic investigations and microprobe analysis in order to know the types of mineralization causing the geophysical anomalies.

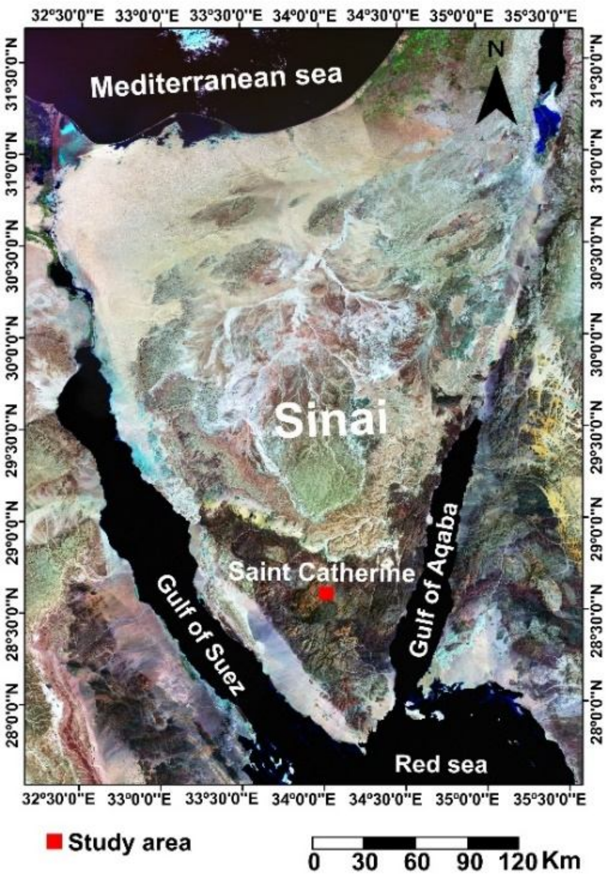

Fig. (1): Location map of the study area.

2. GEOLOGICAL SETTING

The area of study occupies an extensive terrain of rugged mountains of basement exposure rocks, bounded on the west by fault of N-S trend delimiting Wadi-Isbaiya and on the east by the accurate segment of the Catherina ring dyke intrusion at Umm-Alawi Mountain. Rocks distinguished by calc-alkaline and alkaline suits cover the study area. The former comprises quartz diorite, quartz monzonite and syenogranite, in addition to Wadi filling deposits, felsic and mafic dykes (Fig.2), (El-Shishtawy, 1994; Niazy et al., 1995). Quartz monzonite is a dominant rock unit exposed in the core zone of the study area, (Azer, 2007; Salem and El-Fouly, 2000). Quartz monzonite cuts also the NE- and NW-trending dykes of predominantly felsic composition. Xenoliths of older quartz diorite are frequently enclosed in the quartz monzonite (Arnous, 2000). (Hassan, 1987) detected several surface alteration zones in the quartz monzonite rocks at the Umm Qeissum area (NE of the study area). Umm Qeissum – Umm Alawi zone is characterized by the occurrence of disseminated pyrite and chalcopyrite associated with intense argillic - phyllic alteration in the quartz monzonite at the central part of Wadi Umm Qeissum, which was defined as porphyry copper mineralization (El-Ghawaby et al., 1989). Shendi, (1988) deduced subsurface occurrences of sulphide mineralization in Umm Qeissum – Umm Alawi area, based on magnetic and VLF-EM measurements.

3. STRUCTURAL LINEAMENTS

It is well known that, in most of the mineral exploration programs, the structural lineaments especially faults play a significant role in the mobilization, distribution and deposition of the mineral deposits. Accordingly, this part of the study is directed to the investigation of the prevailed surface structures, and their role in the distribution of the mineralization in the study area. Lineaments are used to describe the linear topographic features of regional extent that are believed to reflect crustal structure. Structural lineament maps are, generally, used to ascertain such relationships and emphasize the role of the structural elements in the concentration and distribution of mineralization. To achieve this target, a surface structural lineament map, for the study area has been produced by reviewing the previous geological and structural maps of the study area and its surroundings (e.g. Hegazi, 1998; Arnous, 2000; El-Ghawaby et al., 2001), studying the available satellite image, (Fig. 3), using appropriate software, beside the geological field observations.

The resulted surface structural lineament map, (Fig. 4) showed that the main trends in the study area run in the N-S, NE-SW, NNE- SSW and NNW-SSE directions.

The main types of these lineaments are dykes, fractures and faults which cut along the quartz monzonite rock of this map have been used to carry out trend analysis of the detected structural features because of their significant in the quantitative interpretation of all types of data; topographical, geological or geophysical. This method of analysis could reveal the directions (trends) of forces and their strengths, as well as the mineralization emplacement and their structural controllers.

The detected surface tectonic trends, (Fig.4) have been plotted on a rose diagram, (Fig.5) in order to get some information about the prevailed tectonic features in the study area and its surroundings. The analysis of this rose diagram shows that the N-S (Nubian or East-African), NNE (Aqaba) and NE (Tibesti or Aualitic or Bukle) trends are considered as major trends in the study area.

4. METHODOLOGY

One of the most common applications of the VLF-EM method is to search for massive metallic ores. The method can also be utilized to verify the presence of conductive bodies along vertical, or semi vertical, geological structures such as dikes, faults and shear zones. Several VLF transmitting stations, distributed all over the world, broadcast EM radio waves with frequencies ranging between 15: 30 KHz. VLF receiver

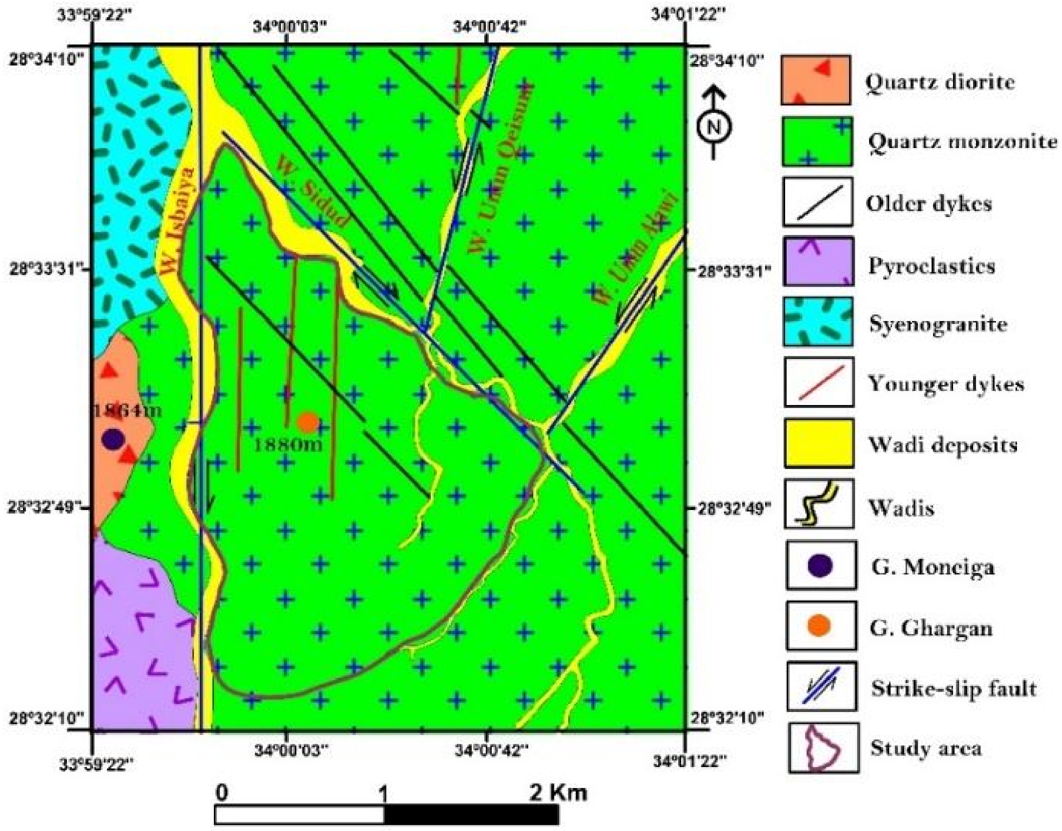

Fig. (2): Geological map of the area of the study (after Soliman, 1992).

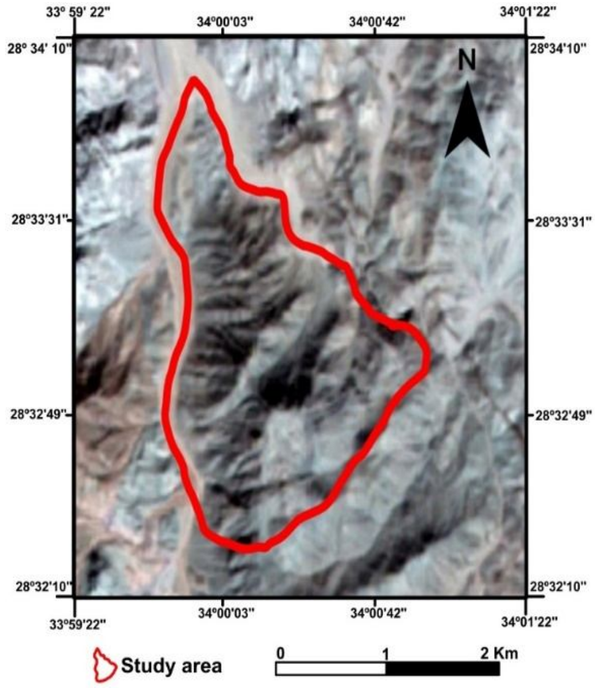

Fig. (3): Aster image (2002) of the study area and its surroundings.

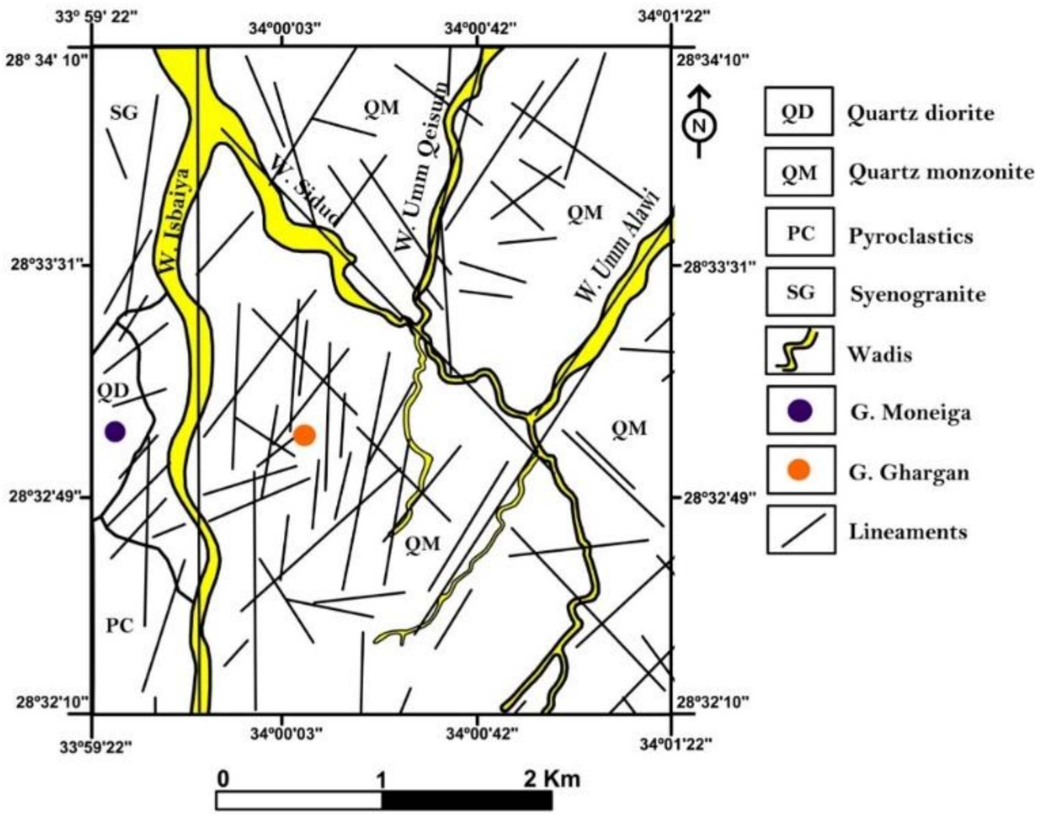

Fig. (4): Surface structure Lineament map of the study area and its surroundings, based on Aster image analysis.

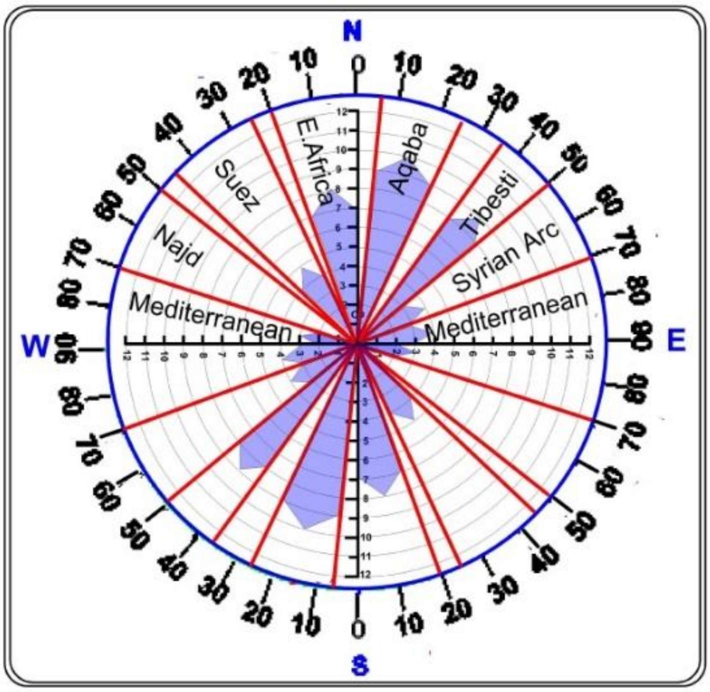

Fig. (5): Rose diagram showing the Frequency of major trends detected from the surface structure lineament map of the study area.

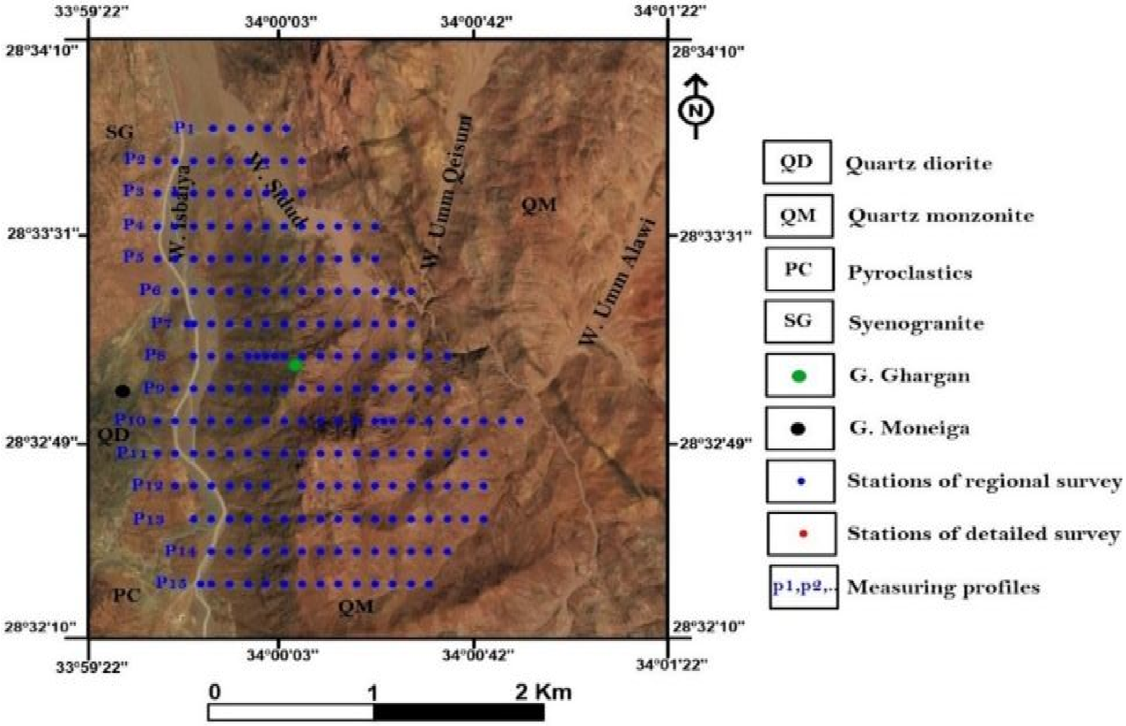

Fig. (6): Surveyed profiles during the regional VLF-EM survey.

antennas are able to pick up both the primary wave and the distortion occurred due to the presence of any conductive bodies underneath the measuring stations. The secondary field is then resolved into its in-phase (real) and out-of-phase (imaginary) components based on the phase lag of the secondary field from the primary wave (Palacky et al., 1981). Practically, the in-phase component is much more sensitive to conductive bodies, while the out-of-phase component responds to the variation of the earth's electrical properties (Jeng et al. 2007).

5. FIELD WORK, DATA PROCESSING AND PRESENTATION:

The (VLF-EM) survey was conducted along fifteen profiles trending W-E, spaced by 200 m with station interval of 100 m along each profile, were surveyed to cover the whole area of study, 6 Km^2 using SCINTREX ENVI geophysical system. Figure (6) show the location of the measured stations.

The main powerful transmitting station picked up at the area of study was broadcasted from Italy at a frequency of 20.3 KHz. The VLF receiver antenna, used in the current survey, records the field total signal strength, the tilt of the magnetic field, Tilt angle, In-Phase (real) and Out of Phase (imaginary) components for each measured station.

The measured data were corrected for the topographic effect using Eberele's (1981). Fraser filter technique has been applied (Fraser, 1969 & 1971) only for the tilt angle and in-phase (real) component to remove the noise and convert the crossover anomalies into positive peaks directly over the conductor. The filter is based on a simple function expressed as F2,3 = (M4 + M3) − (M1 + M2), where F2,3 is the new filtered value that will be recorded at the midpoint between every four successive measurements M1, M2, M3 and M4 along the surveyed profile.

The tilt angle measurements have been filtered using the KH filter (Karous and Hjelt, 1983) in order to invert the tilt angle readings into a pseudo-section which depicts the subsurface distribution of apparent current densities (I_a). The following formula is used to calculate the filter:

$$(\Delta x/2) = \frac{2\pi}{\Delta z}(-0.102H_{-3} + 0.059H_{-2} - 0.561H_{-1} + 0.561H_1 - 0.059H_2 + -0.102H_3)$$

Where H_{-3} to H_3 are six equally spaced tilt angle measurements, along a VLF surveyed profile. (I_a) is the apparent current densities, which will be re-plotted spatially at the mid distance ($\Delta x/2$) between stations $H_{-1}$and H_1, and at a depth level (Δz), equal to the separation between the stations, used in the calculations. Repeating the process for various depth levels (i.e. 1*x*, 2*x*, 3 …), one can depict a pseudo-section of the conductive subsurface geological features that caused the detected VLF anomaly along the measured profile. After applying the necessary corrections, the VLF-EM measurements were presented in the form of contour maps using the Golden Software Surfer (V.13), profiles using Golden Software Grapher (V.8.1.388), pseudo-sections using the KHFFILT program (V.1.1) and stacked profiles.

6. RESULTS AND INTERPRETATION

6.1. VLF-EM contour maps:

The filtered VLF tilt angle and in-phase (real) component maps (Figs.7&8) have displayed a similar distribution of anomalies but different in amplitude, that there are several positive and negative anomalies. The most interesting zone of positive anomalies is occupying the central part of the map which expresses the existence of intersection between the trended anomalies in AA′ and BB′ directions.

The VLF-imaginary component (out of phase) map (Fig.9) shows several positive and negative anomalies. The inflection or cross over point between the positive and negative anomalies is more interesting.

From the VLF-EM maps, it is noticed that the central part of the area is the zone of interesting which indicates the intersection between the trended anomalies related to the subsurface structures in the NNE-SSW and N-S directions. This intersection zone is considered to be an area where the hydrothermal solutions take place and mineralization accumulate. So, these anomalies are expected to be associated with sulphide minerals association.

6.2. VLF-EM pseudo-sections:

In order to quantitatively interpret the VLF results, tilt angle measurements have been filtered using the KH filter (Karous and Hjelt, 1983), forming the VLF pseudo-sections which are fast and accurate in depicting the subsurface structures. We have used this imaging technique to produce apparent current density cross-sections in the present study. For the interpretation of the subsurface geometry, apparent current density cross-sections with depths were made using the acquired VLF data along all the profiles.

Pseudo-sections were constructed for all of the surveyed VLF profiles of which only four pseudo-sections are represented for explanation (Figs.10-13). The pseudo-sections are attached with the actual measured tilt angle, in-phase, out-of-phase, Fraser filtered tilt angle (F.F-tilt angle), and Fraser filtered in-phase (F.F-in-phase) curves. In the following, four of these pseudo-sections are described in details:

Profile (6)

The tilt angle anomaly plot along this profile indicates the presence of one strong anomaly which is located on the inflection point at the distance between stations 800 and 1100 m and extending to a depth of about 200 m on the VLF pseudo-section (Fig.10). A similar conversion occurred to the in-phase data but stronger in amplitude. The (F.F-in-phase) curve shows a higher anomaly resolution than that shown on the (F.F-tilt angle) curve which implies that the detected conductive ore mineralization is accumulated along fractures or fault zones.

Profile (7)

Profile P7 (Fig.11), is located to the south of P6 and separated from it by 200 m.The tilt angle in-phase (real) anomaly plots along this profile indicate the presence of a high conductive anomaly at the center of the profile on the inflection point, between distances 700 m and 900 m. The VLF pseudo section also depicts the same result, showing the presence of high conductive body occurring between stations 700 m and 900 m and extending to a depth more than 200 m. similarly the peak of Fraser filtered (in-phase and tilt angle) corresponding over the inflection point (station 750 m) of the in-phase and tilt angle profile.

Profile (8)

The in-phase (real) anomaly plot along this profile indicates the presence of one strong anomaly, located at the surface between stations 800 m and 900 m on the inflection point and extending to a depth of about 200 m to become between stations 700 m and 1050 m as shown in the VLF pseudo-section (Fig.12). Also, the tilt angle values along this profile are higher than the background throughout the profile, with a peak between 800 m and 900 m. The peaks of Fraser the filtered (in-phase and tilt angle) are corresponding over station 850 m and over the inflection point of the in-phase and tilt angle profile.

Profile (10)

In this profile, (Fig.13) The in-phase (real) plot indicates the presence of a strong anomaly, located between stations 900 m and 1500 m and extending to a depth of about 300 m to become between stations 900 m and 1500 m as shown in the VLF pseudo-section. Also, the tilt angle values along this profile are higher than the background throughout the profile, with a peak between 900 m and 1500 m. The peak of Fraser filtered (in-phase and tilt angle) is corresponding over station 1200 m and over the inflection point of the in-phase and tilt angle profile.

In figure (Fig.14), it was tried to superimpose the deduced apparent current density cross sections along twelve measured profiles on the geologic map of the study area as they are measured in the field. It is noticed that the highly conductive bodies (red colors, which are due to the occurrence of sulphide mineralization) are controlled by the NE-SW and NW-SE faults. Profile, P10, represents the location of the intersection of these two main faults where the conductive body occupies as a great surface area.

The first three profiles P1, P2 and P3 did not have the adequate number of stations along them to run these calculations and construct their full depth pseudo-sections.

6.3. stacked profiles:

Stacked profiles for the VLF components (Figs.15&16) were represented in order to get some information about the anomaly distributions and their relations with the prevailing geological structures. Stacked profiles for in-phase, out of phase and tilt angle have the same trends of anomalies ((i.e. NE-SW and NW-SE, white dashed lines).

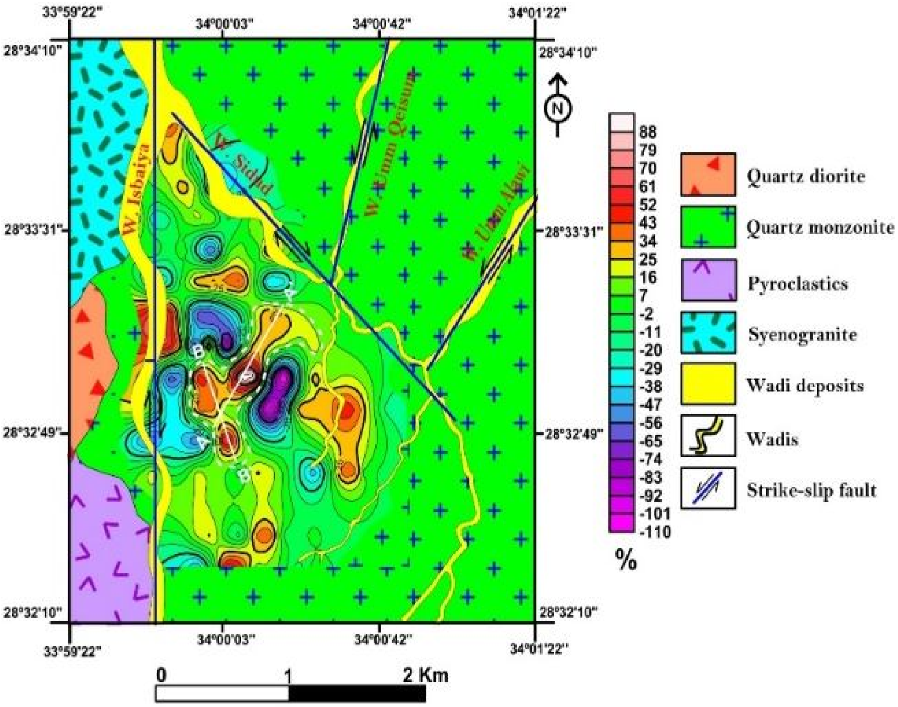

Fig. (7): VLF-EM tilt angle map of the study area.

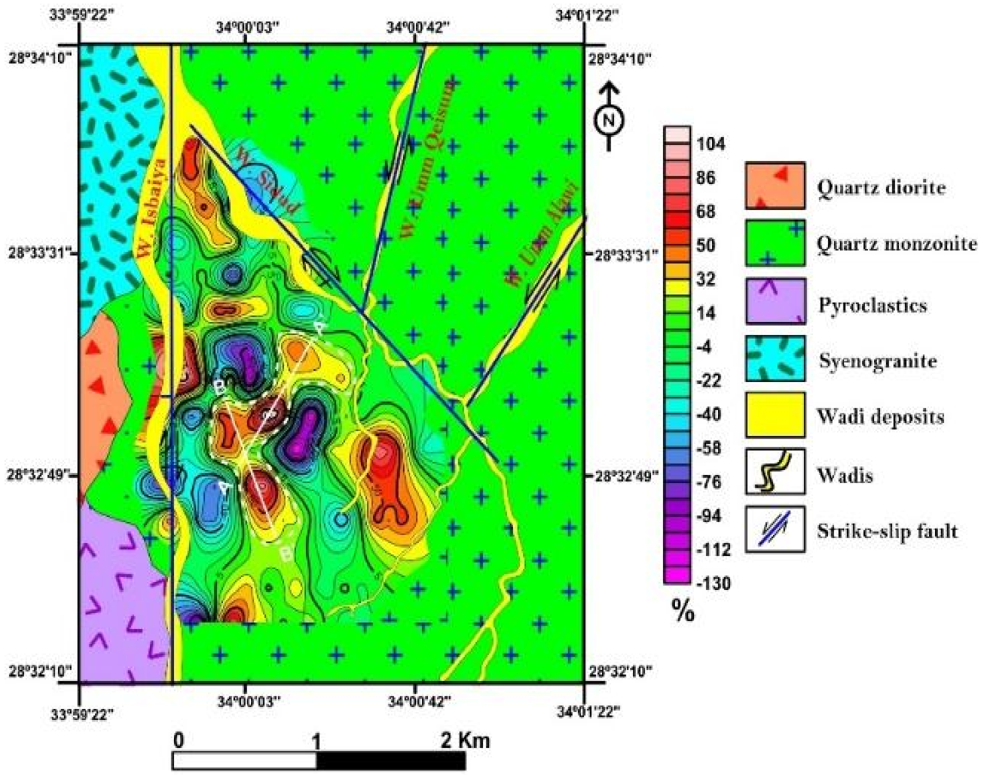

Fig. (8): VLF-EM in-phase (real) component map of the study area.

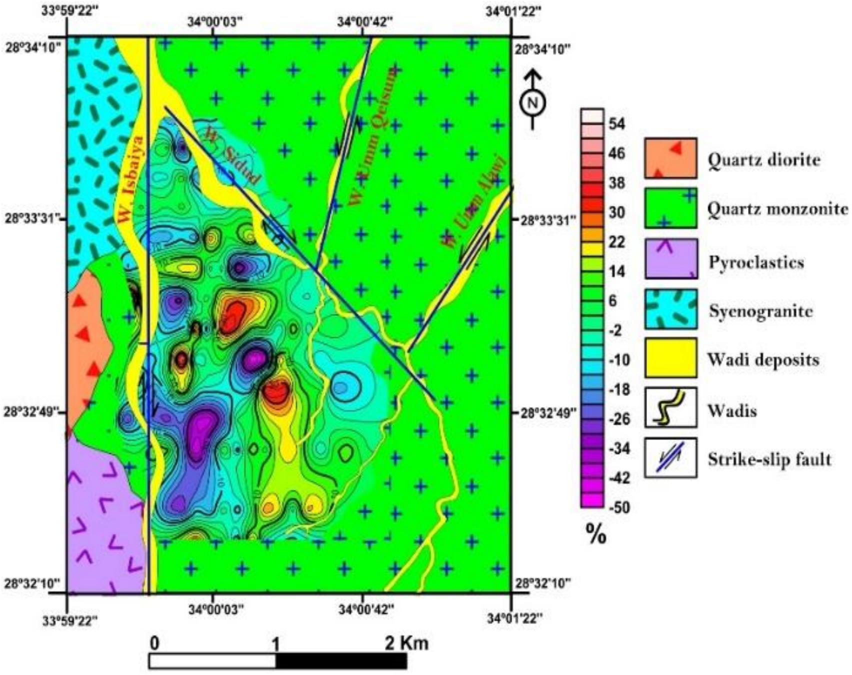

Fig. (9): VLF-EM Out-of-phase (imaginary) component map of the study area.

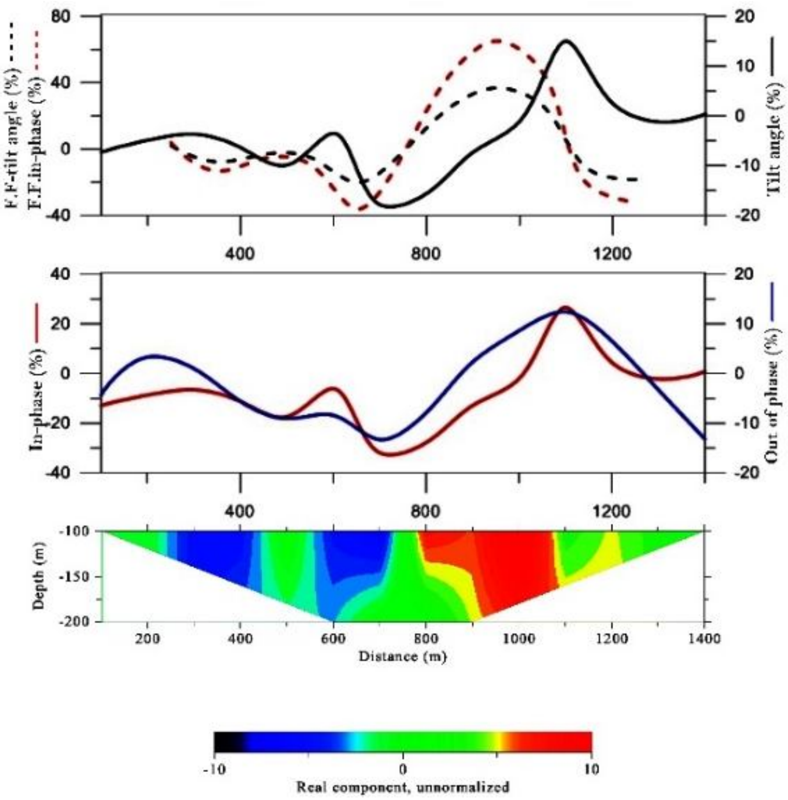

Fig. (10): VLF pseudo-sections, in-phase, out of phase, tilt angle, Fraser filtered (in-phase & tilt angle profiles at p6.

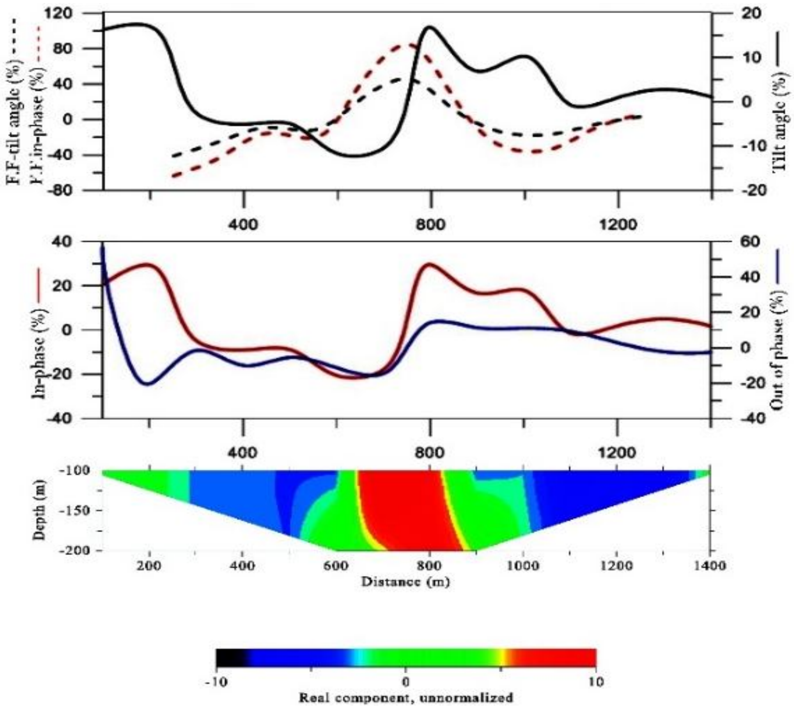

Fig. (11): VLF pseudo-sections, in-phase, out of phase, tilt angle, Fraser filtered (in-phase & tilt angle profiles at p7.

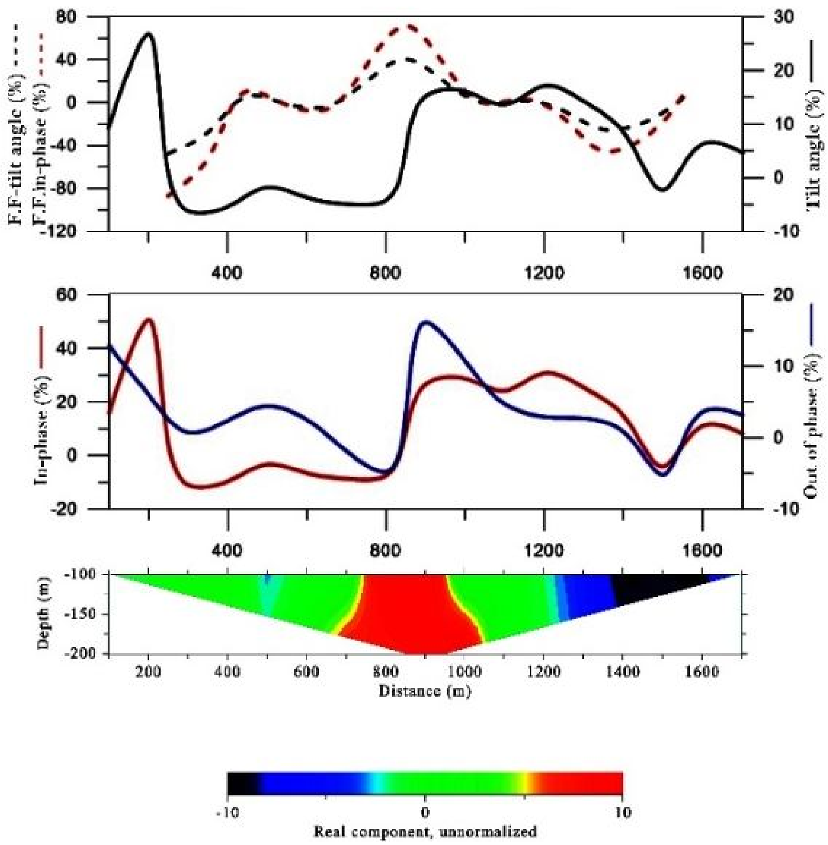

Fig. (12): VLF pseudo-sections, in-phase, out of phase, tilt angle, Fraser filtered (in-phase & tilt angle profiles at p8.

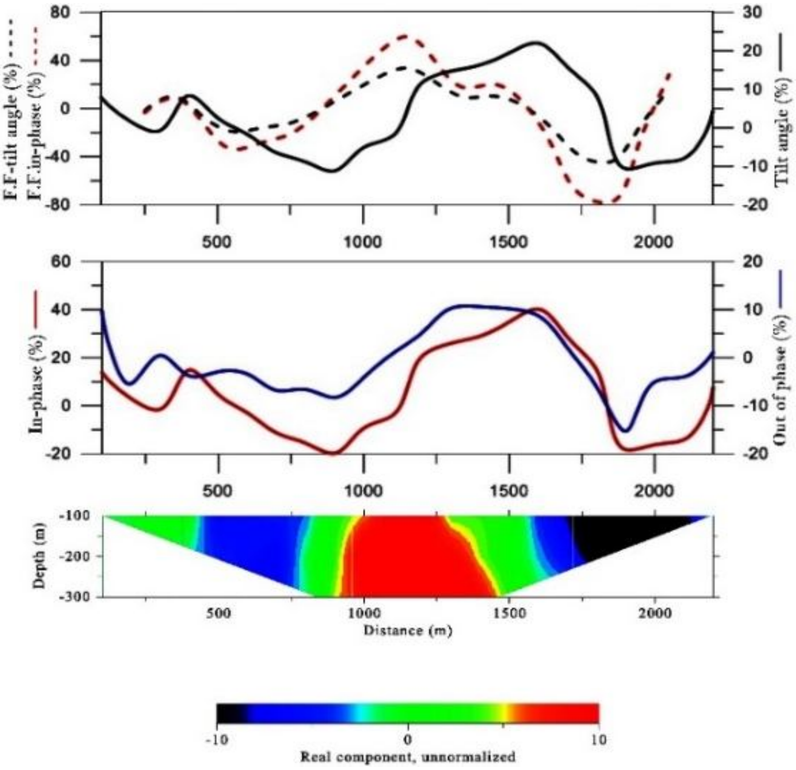

Fig. (13): VLF pseudo-sections, in-phase, out of phase, tilt angle, Fraser filtered (in-phase & tilt angle profiles at p10.

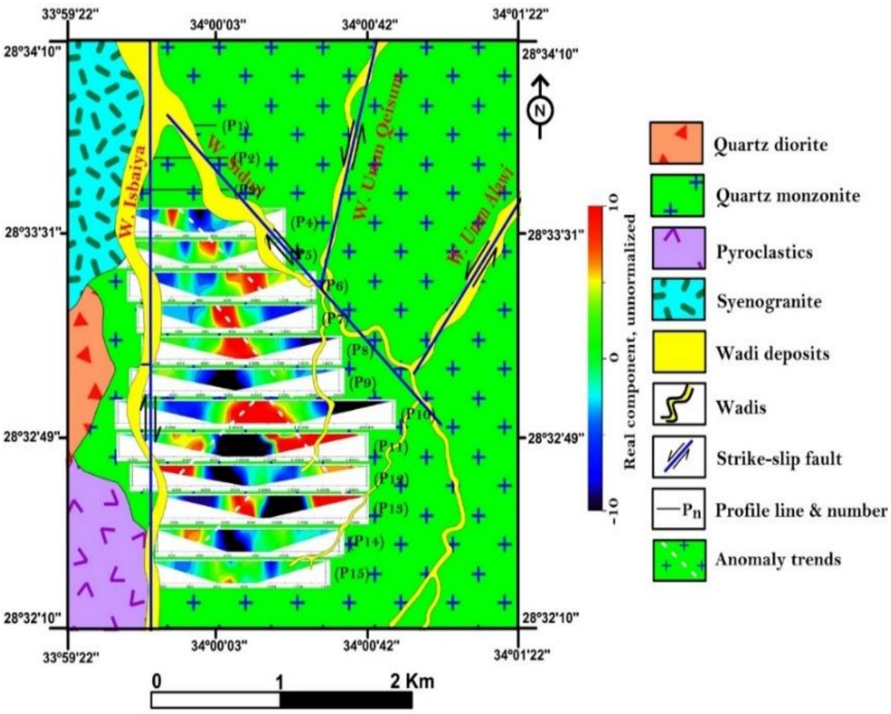

Fig. (14): Karous-Hjelt pseudo-sections superimposed on the geologic map of the study.

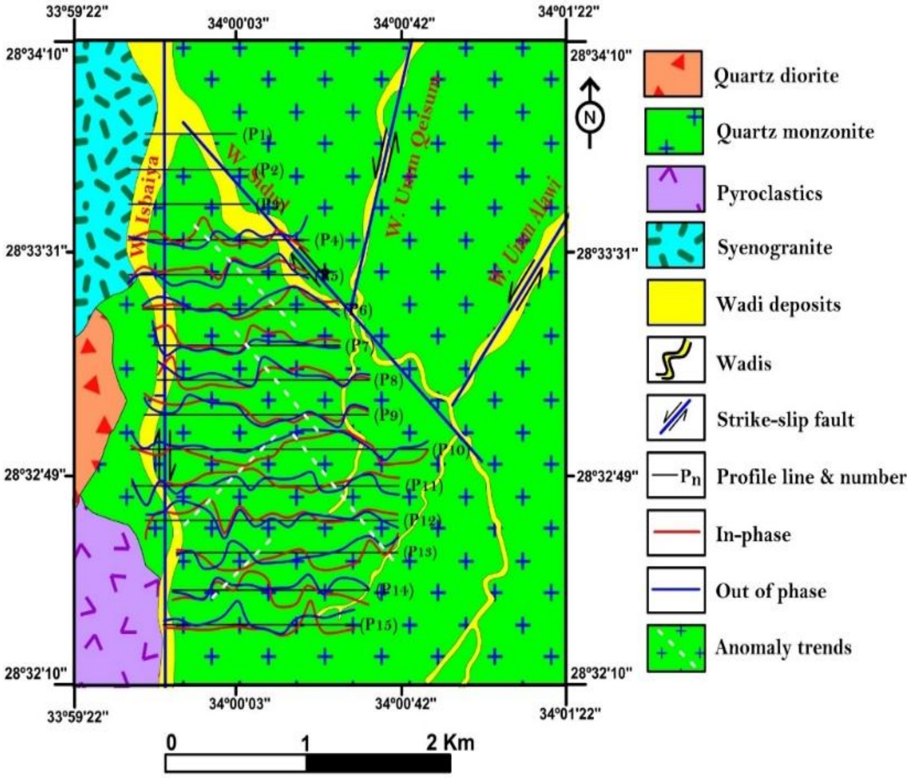

Fig. (15): Stacked profiles for in-phase & out of phase in the study area.

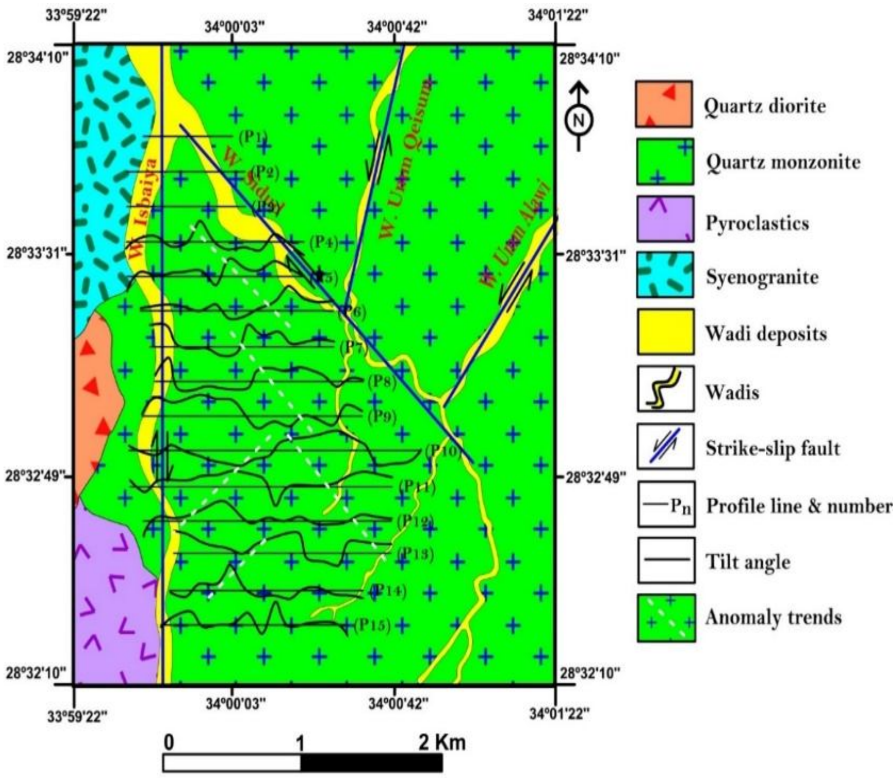

Fig. (16): Stacked profiles for tilt angle in the study area.

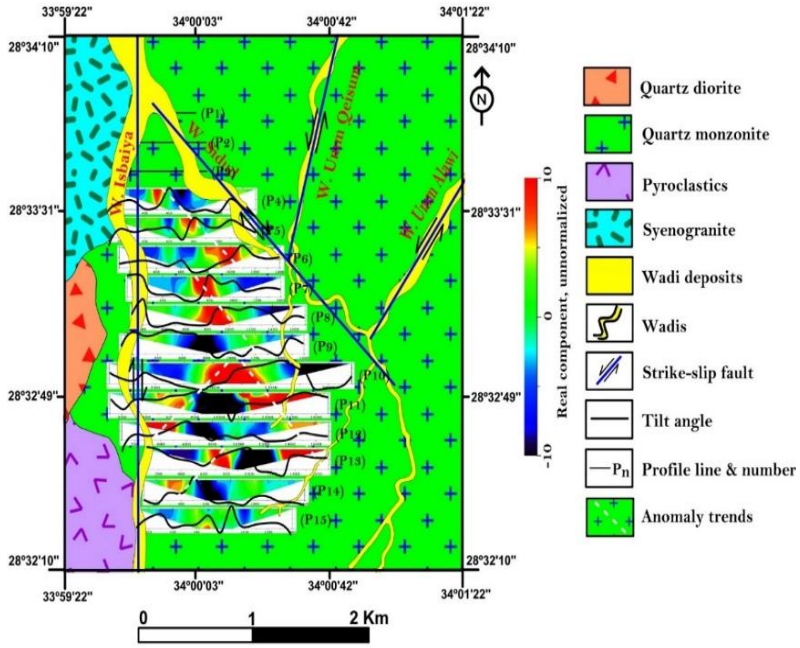

Fig. (17): VLF pseudo-sections with stacked tilt angle profiles in the study area.

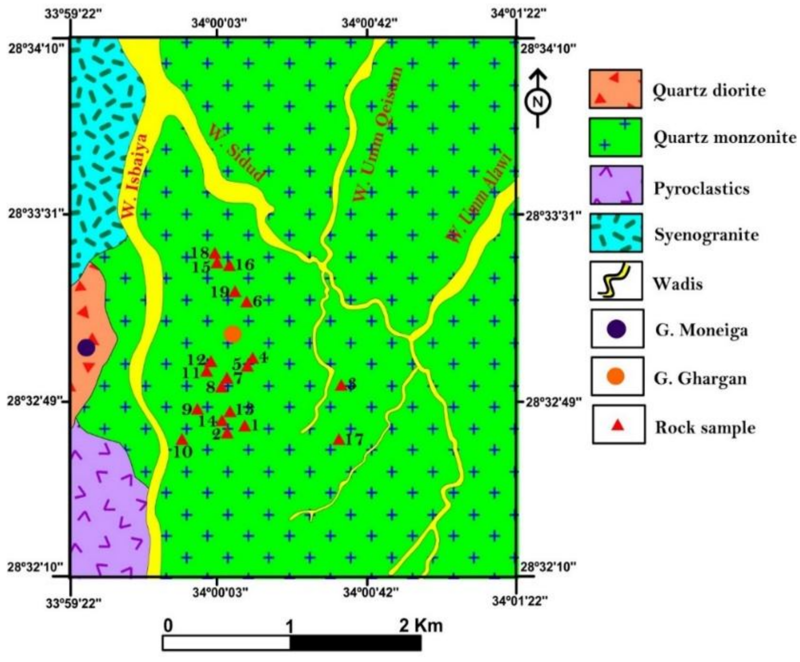

Fig. (18): Sample location map of the study area.

Figure (17) shows the relationship between the VLF pseudo-sections and stacked profiles of the VLF tilt angle in order to construct a 2.5-D interpretation model. They have the same trends of anomalies, where the cross-over point of the tilt angle profiles is corresponding over the high positive anomaly on the VLF pseudo-sections.

From Figures (15, 16 & 17), we concluded that there are two predominant structural trends controlling the occurrence of sulphide mineralization in the study area which are NE-SW and NW-SE.

6.4. Microscopic examination and mineral analysis:

According to the ambiguity in the interpretation of the geophysical measurements, it is intended to know the types of mineralization causing the geophysical VLF anomalies. For that, nineteen bedrock samples have been collected from the sites of the detected VLF-EM anomalies in the study area (Fig.18). These samples are subjected to polishing then microscopical examination and microprobe analysis techniques.

The polished surfaces have been examined by using the reflected light ore microscope, which proved the presence of sulphide minerals in the form of Pyrite, and Chalcopyrite as well as Iron oxides in the form of magnetite, ilmenite and pyrrhotite (Fig.19a, b, c, d, e&f). They occur in the form of bockets and micro fracture-fillings within the samples. However, minor traces of gold and silver could be detected.

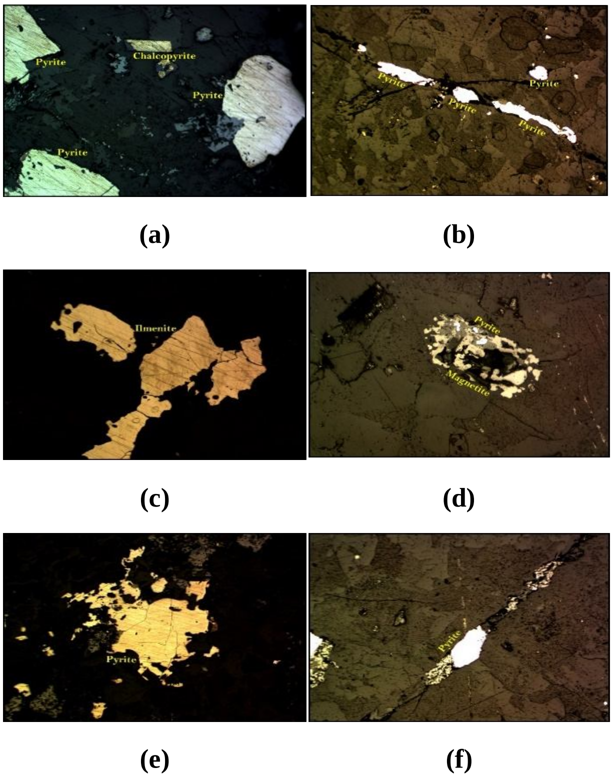

Fig. (19): a) Pyrite, Chalcopyrite and Iron oxides crystals, Quartz monzonite, x100, XPL, b) Fracture filling with Pyrite and Iron oxides crystals, Quartz monzonite, x25, XPL. c) Ilmenite crystals, Basic dyke, x 100, XPL. d) Pyrite and Magnetite crystals, Quartz monzonite, x 100, XPL. e) Pyrite crystals, Basic dyke, x 25, XPL. f) Two set of fractures filling with Pyrite, Quartz monzonite, x 50, XPL.

Now, it could be proved that the VLF-EM anomalies are due to the occurrence of sulphide minerals in the form of pyrite, chalcopyrite and minor traces of gold and silver. It is expected that the concentration of these mineralization increases with depth, which may reach to an economic ore.

7. DISCUSSION AND CONCLUSION

Through integrating the interpreted VLF maps, it can be concluded that the N-S, NNE-SSW, NE-SW and NW-SE are the main geological structural trends which control the conductive mineralization occurrences at the area of study. The resemblance between the conductive anomaly trends, deduced from the VLF maps, and the surface structural trends deduced from the structure analysis, increases the possibilities of the association of these anomalies with the presence of sulphide mineralization. Tilt angle stacked profiles attached to the pseudo-sections of each of them, were plotted at their exact position on the geological map of the area of study, in order to construct a 2.5-D interpretation model. Locations of the conductive sources were determined precisely along each profile individually. The horizontal extensions of these conductive sources across other adjacent surveyed profiles are delineated.

Points of intersection between different geological structural trends are always accompanied by the very high VLF-EM anomalies represent the zones of weakness, where hydrothermal solutions can transport a huge amount of their ore mineralization through them. These areas are considered to be the most promising sites for mineral exploration.

Ground geophysical very low frequency electromagnetic survey has been carried out at the area of Wadi Isbaiya, south Sinai to derive more information about the economical mineralization occurrences concluded the following items:

1. Integrating the interpretation of the geophysical results with the laboratory examinations confirmed the presence of various sulphide mineralization and iron oxides.
2. Subsurface pseudo-sections showed the lateral and depth extensions of the conductive mineralization zones. It was clearly indicated that the depth of these conductive accumulations can range from 200m to 300m.
3. A 2.5D VLF interpretation model was successful in determining the distribution of the subsurface sulphide mineralization across the whole area.
4. Spatial coincidence between the structural trends deduced from the VLF and surface lineament maps, showed that the preferable structural trends which contain conductive ore mineralization are NNE-SSW, N-S and NE-SW.
5. Laboratory examinations of the rock samples confirmed the presence of sulphide minerals in the form of Pyrite and chalcopyrite, and iron oxides in the form of magnetite, Pyrrhotite and a few shows of ilmenite and minor traces of gold and silver. This mineralization occurs in the form of pockets and fracture-fillings in the quartz monzonite bedrock.
6. The presence of pyrite, magnetite, and chalcopyrite and lack of other sulfide minerals is similar to the starting stage of the porphyry copper-gold mineralization in Umm Qeissum area in South-eastern Sinai, Egypt.
7. Ultimately, the study asserts the important role played by the major tectonic structural trends of Aqaba, Suez and East Africa, affecting the area of study, in providing pathways for hydrothermal solutions to accumulate economical mineralization along them. Locations where these trends are intersected are the

most promising sites for copper mineralization, which can be traced within other areas in south Sinai.

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