Journal of Geosciences, Osaka City University
Vol. 47, Art. 10, p. 113-126, March, 2004

Integrated geophysical exploration for sulphide minerals in the Wadi Sa'al area, south Sinai, Egypt

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Abstract

Geophysical and ore microscopic studies were carried out in the Wadi Sa'al area, south Sinai, Egypt in order to explore the sulphide mineralizations that were mentioned in previous studies. The Wadi Sa'al area is located within a large metamorphic belt and is covered by a variety of metavolcanic, metasedimentary and plutonic Precambrian rocks. The area is characterized by different structural features and has been subjected to three deformational stages accompanied by folding and thrusting. The aim of this study is to investigate the subsurface mineralizations in the area using a combination of vertical magnetic gradient (VMG), magnetic susceptibility (MS), very low frequency (VLF) and self-potential (SP) methods, with the results being interpreted in conjunction with that of the ore microscopic studies. The VMG and VLF surveys were conducted over 360 stations along 8 profiles covering the various rock units and almost transverse to the strike direction of the main geological structures in the investigated area. The field magnetic susceptibility measurements were recorded over 155 measuring points covering the different rock types in the study area. Detailed SP measurements were carried out along 6 profiles in two selected anomalous sites as interpreted from the VLF data. In addition, polished surfaces of rock samples, selected from the sites of the geophysical anomalies, were studied under the ore microscope to develop a better understanding of the characteristics of the mineralizations. The magnetic and the VLF surveys identified magnetic and conductive subsurface bodies, at several sites in the area, at depths ranging from 18 to 73 meters below the ground surface. The SP measurements showed high SP anomalies that are believed to be related to subsurface sulphide minerals indicating that the cause of the VLF anomalies is sulphide mineralized bodies. The ore microscopic study showed the presence of a variety of sulphide and magnetic ore minerals confirming the geophysical survey results. Chalcopyrite, pyrite, magnetite, ilmenite and titanomagnetite could be detected suggesting the presence of mineralizations in the study area as a sulphide minerals association. Comparison of the geophysical survey results and the microscopic study with the geology of the area showed that the basic metavolcanics and the granodiorite rocks are relatively rich in sulphide mineralizations and the junction zone of the three valleys is the most mineral-rich site in the area. The comparison showed also that the detected mineralized bodies are controlled by structural elements striking in the NE-SW direction.

Key-words : VLF-EM, magnetic, SP, sulphide minerals, ore microscopy, Sinai.

1. Introduction

The Wadi Sa'al area is located in the center of the southern part of Sinai Peninsula, Egypt (Fig. 1). It is a part of the Sa'al-Zaghera metamorphic belt. The area comprises of Precambrian igneous and metamorphic rocks of basement complex and contains many structural features as the area was subjected to three phases of deformation that are represented by sets of folding and thrusting (EL-Shafei, 1991). The area is characterized by rugged topography and high relief with altitude of about 1200 meters above sea level.

Some pervious geophysical and geological studies referred to the presence of mineralized bodies in the area. Bogoch *et al.* (1974) stated that the main cause of aeromagnetic anomalies, recorded in the Wadi Sa'al area, is magnetic bearing bodies that have relatively high magnetic susceptibilities. Soliman (1986) referred to the presence of oxidized pyrites in the granodiorite rocks at some localities in the Wadi Sa'al area. Moreover, EL-Shafei (1991) stated that some fractured mineralized bodies (mainly sulphides) occur in the hinge zone of folds related to the second phase of deformation.

The objectives of this study are to evaluate the potentiality of the mineralizations in the area and to delineate the distribution of the mineral occurrences and their relations to different rock units and geological structures through conducting an integrated geophysical survey using some efficient geophysical methods. The aim of the present study is also to carry out a micro-

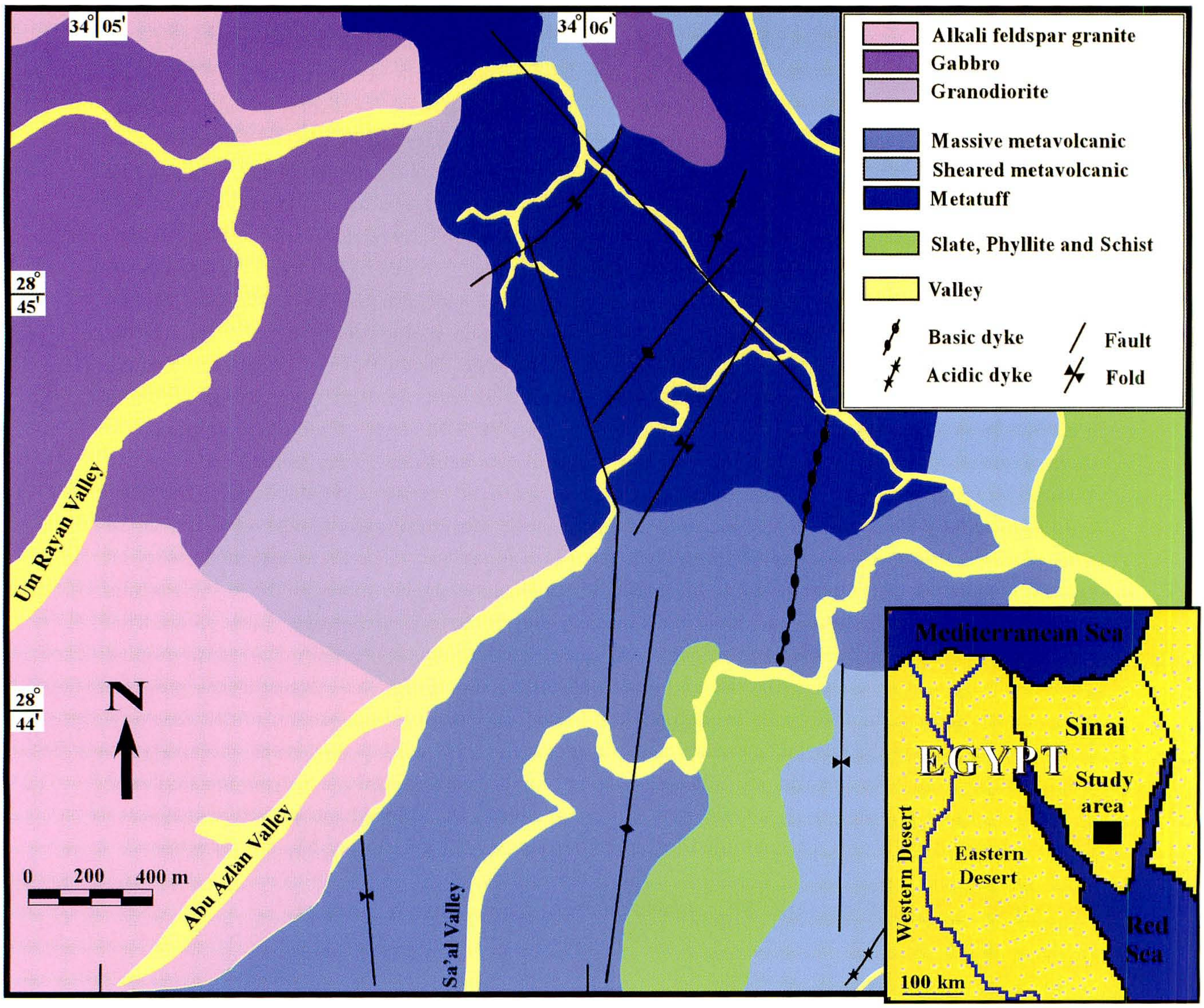


Fig. 1 Geological map of the Wadi Sa'al area, Sinai, Egypt (modified after Soliman, 1986).

scopic study to throw some light on the types and characteristics of the existing ore minerals.

To achieve these objectives, Vertical Magnetic Gradient (VMG), Magnetic Susceptibility (MS), Very Low Frequency-Electromagnetic (VLF-EM) surveys were conducted in the study area. These surveys were followed by detailed Self-Potential (SP) measurements on two sites that were selected based on the obtained geophysical results. In addition, polished surfaces of some rock samples, selected from the geophysically anomalous sites, were studied using the reflected light ore microscope. The geophysical and microscopic studies were interpreted in the light of the geological information of the area.

2. Geological setting

The Arabian-Nubian Shield is a part of the East African Orogen formed in the late Proterozoic (900-500 Ma; Bentor, 1985; Stern, 1994; Loizenbauer *et al.*, 2001) by the accretion and amalgamation of oceanic and continental magmatic arcs, with the arc-accretion being responsible for the closure of the Mozambique Ocean. The Wadi Sa'al area, being a part of southern Sinai Peninsula, is situated in the northern part of the Arabian-Nubian Shield. Most structures, in southern Sinai, are related to accretionary events during closure of the Mozambique Ocean and oriented roughly NE to ENE (Shimron, 1984; El-Shafei *et al.*, 1992). Regarding the local tectonic setting of the Wadi Sa'al area, the area is considered a part of Back-arc basin succession (El-Shafei, 1991). Shimron and Zwart (1970) concluded that the matasediments and metavolcanics of the area were involved in or close to the margin of a mature continental block. Bentor (1985) reported that the metavolcanic rocks are related to the calc-alkaline younger volcanics of the central Eastern Desert, Egypt. On the other hand, Soliman (1986) argued that the metavolcanics in the area are of immature island-arc tholeiites.

2.2. Lithology

A detailed geological map was essential to delineate the relation between the different rock units and geological structures and the expected mineralizations. Accordingly, the first step in the current research was to construct a simplified geological map (Fig. 1). Based on aerial photographs (scale = 1:10,000), a regional geological map (Soliman, 1986) and field observations, a reasonable detailed geological map could be achieved. The Wadi Sa'al area is composed of metavolcanic and metasedimentary rocks that show low grade of metamorphism compared with those located at some other localities of south Sinai. These metavolcanics and metasediments are intruded by igneous plutonic rocks. The following paragraphs are a brief description of these rock units.

2.2.1. The metavolcanic rocks

The metavolcanic rocks cover most of the area around the Sa'al Valley (Fig. 1). They are fine to very fine grained rocks, vary in composition from basic to acidic and show various degrees of shearing. These rocks are classified into three main types; the metatuffs, the sheared metavolcanics, and the massive and banded metavolcanics. The metatuff rocks are distributed along the narrow part of the Sa'al Valley. They are dark colored, fine-grained rocks. Crystals and patches of sulphide minerals, mainly Pyrite, occur abundantly as an accessory mineral, in the more basic varieties at and near the junction of the Sa'al Valley with the Um Rayan Valley and the Abu Azlan Valley (Fig. 1). The massive metavolcanic rocks show a variety of compositions in the study area that range from meta-rhyolites to meta-basalts. Disseminated sulphide minerals were frequently observed in the field associated with the basic rocks especially near and to the west of the junction of the previously mentioned 3 valleys. The sheared metavolcanics are mainly meta-rhyolites that are pink in color and highly sheared and deformed. In the highly sheared rhyolitic rocks, there are two systems of fractures striking NW and NE (Soliman, 1986). Sheared metavolcanics are also represented in the southwestern part of the area.

2.2.2. Metasedimentary rocks

The metasediments have less distribution in the study area. Slates, phyllites and schists crop out in a narrow zone in the central part of the area near the junction of the 3 valleys. These rocks are faulted, folded and show different degrees of fracturing. The phyllites and the schists show a foliation that strikes in the NE-SW direction and dips commonly to the west. These rocks are fine-grained and dark in color. Chlorite, quartz, biotite and feldspars are the most common mineral constituents (Soliman, 1986).

2.2.3. Igneous rocks

Gabbros, granodiorites, and granitic rocks are the only intrusive rocks cutting the early formed metasedimentary and metavolcanic rocks. Gabbroic exposures were recognized at several sites in the study area especially along the Um Rayan Valley. These gabbros may be related to the large gabbroic body of the El-Fringa and Shagarat area, to the north of the Um Rayan Valley (Soliman, 1997). Pyrite, in the form of cubic crystals, was observed in these gabbros and particularly conspicuous in medium-grained varieties but in most of the cases the gabbros have been strongly altered (epidotized and/or chloritized) and have developed onion-like weathering structures.

The granitic rocks constitute the most abundant intrusive rocks in the Wadi Sa'al area. They are commonly coarse to medium-grained rocks usually show porphyritic textures and contain xenoliths of mafic rock fragments. Some granodiorite rocks contain xenoliths of the metavolcanics and the metasediments as well as oxidized pyrites (Soliman, 1986). The other granitic rocks include orthoclase rich granites and quartz monzonites.

Basic and acidic dykes, in various thicknesses, grain size and trends, are widely distributed in the area. The composition of the basic dykes ranges from basalts to gabbros and dolerites. The more felsic varieties include fine-grained granite, quartz-porphyry, porphyritic rhyolites and dacites.

2.3. Structures

Many structural features were recognized in the area. Generally, it is believed that the Wadi Sa'al area had been subjected to three stages of deformation (EL-Shafei, 1991). The first stage formed a set of folds that plunge 20° due N32°W. The second stage is a strong one, characterized also by plunging folds that plunge 26° due S62°W. Because of the strong forces that pushed rocks on the two limbs of the folds, adjacent layers on the limbs must have been subjected to considerable movement parallel to one another. The mineralizations under consideration are expected to be associated with this stage of deformation. The study area is dissected by a number of faults striking mainly in the NE-SW direction. These faults are associated with the earlier two stages of deformation. Thrust faulting also exists around the central part of the Sa'al valley, representing the third stage of deformation. Foliation, cleavage and lineation with different directions are also observed in the study area.

3. The geophysical surveys

Four geophysical methods, well known in ore mineral exploration, were carried out in the study area to investigate the presence of the mineralizations in the area and to delineate their quantitative parameters as well as their relation to different rock units and geological structures. The next section describes the field surveys, results and interpretations of conducted geophysical surveys.

3.1. The Vertical Magnetic Gradient (VMG) method

The magnetic method is an old geophysical technique commonly used to investigate subsurface geology depending on the anomalies in the earth's magnetic field. The idea of measuring the gradient of the earth's magnetic field have been known since 1934 (Sermon and Roman, 1934). The VMG is an effective and rapid tool for delineating the geological structures and for mineral exploration because of its capability to detect the magnetic ores at shallow depths and to delineate their lateral extensions. Using the gradient technique, the subsurface magnetic bodies can be detected under negative gradient values and their lateral extensions can be delineated by the zero values. The gradient value of the vertical component of the magnetic field (G) can be obtained by estimating the difference between two magnetic readings (ΔV) at different sensor elevations (Δh) according to the following equation:

$$\Delta V = \Delta V / \Delta h = V_h - (V_{h+\Delta h}) / \Delta h \qquad (1)$$

The study area was covered by eight profiles striking N55°W with a profile separation of 200 meters and station interval of 50 meters. The location and direction of the profiles were chosen to cover the considered rock units and to be transverse to the strike direction of the main geological structures in the area (Fig. 2). The intensity of the vertical component of the Earth's magnetic field was measured at each station at two elevations (0.5 and 1.2 meters above ground surface) using the Canadian Scintrex MFD-4 digital fluxgate magnetometer. The vertical magnetic gradient values were calculated from the measured data and the obtained values are presented as a contour map (Fig. 3) in which, only the negative values are contoured.

Thirty one vertical magnetic gradient anomalies, with intensities ranging from −15 up to −140 nanotesla/meter, were detected from the magnetic gradient contour map. These anomalies are believed to be related to ore bodies that contain magnetic minerals with different concentrations. The depths to the top of these subsurface ore bodies were estimated from the detected anomalies using two different techniques proposed by Hood and McClure (1965) and by Barongo (1985). The interpreted depth of these bodies ranges from 25 to 67 meters.

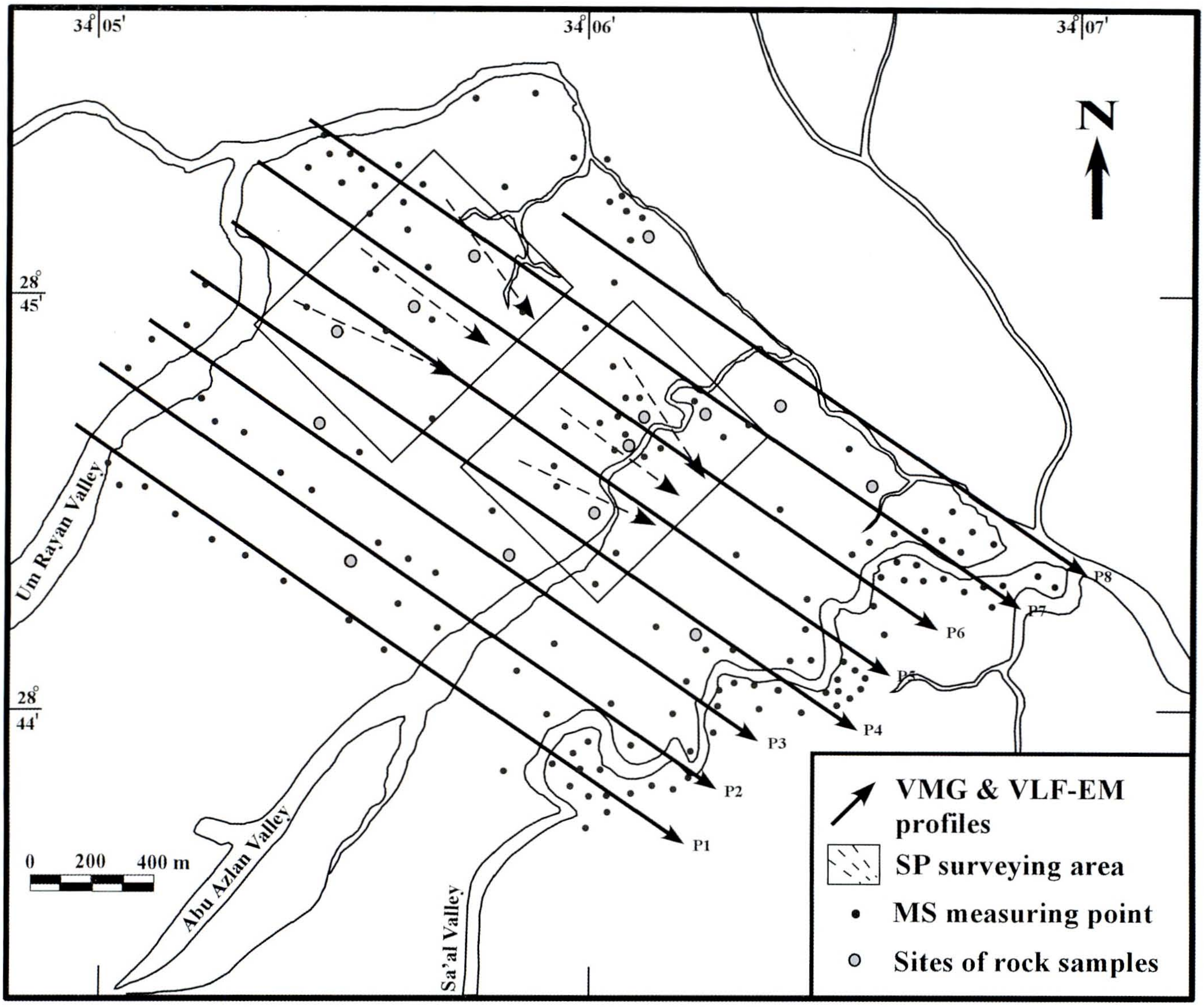


Fig. 2 Geophysical survey and rock sampling map.

Comparison of the VMG map (Fig. 3) with the geological map of the study area (Fig. 1), shows that the anomalies are continuous and covering large parts of the survey area. It is also clear that most of the anomalies are concentrated in the metatuff and granodiorite rocks with the granodiorites having the most abundant number of anomalies while the metatuffs are associated with the strong ones. The junction zone of the three valleys (Sa'al Valley with the Um Rayan Valley and the Abu Azlan Valley) shows the strongest anomaly. On the other hand, gabbro and massive metavolcanic rocks show anomalies that have moderate concentrations while the sheared metavolcanic and the meatasedimentary rocks show only a few weak anomalies. It also appears that the anomalies trend mainly NE–SW (Fig. 3). This direction coincides well with the main trend of the geological structures in the area. Some of the contacts between different rock units, such as the contact between the metatuff and the massive metavolcanic rocks, at the junction zone, and between the massive metavolcanic and the meatsedimentary rocks, show considerable anomalies.

3.2. The Magnetic Susceptibility (MS) measurements

The magnetic susceptibility of rocks is the fundamental parameter in magnetic prospecting. Apparent magnetic susceptibility values can be measured in the field using a portable magnetic susceptibility meter. The magnetic susceptibility values measured in the field are affected by the irregularities in the surfaces of rocks at the measuring points. However, corrections for rock surface unevenness can be applied to the measured data.

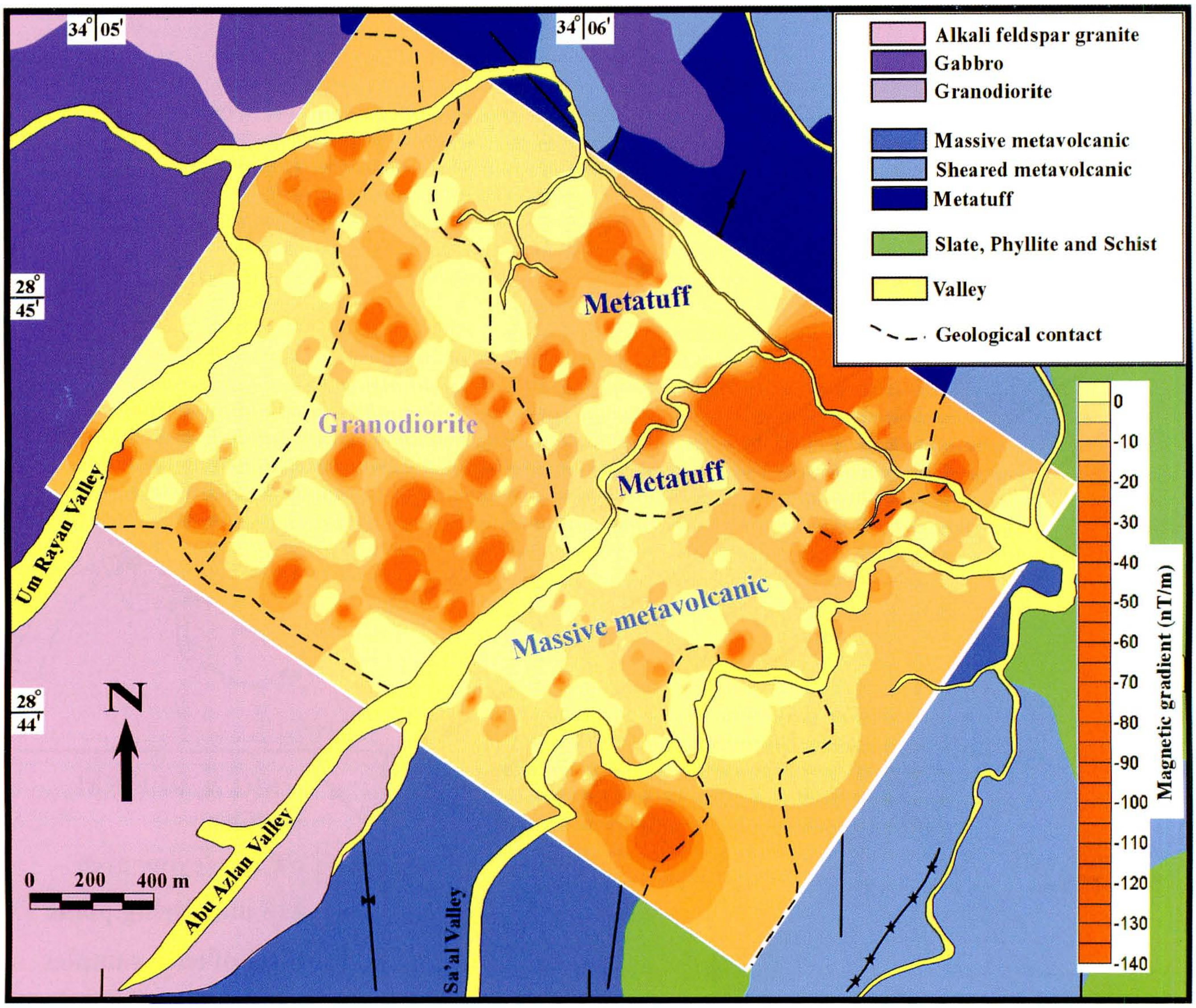


Fig. 3 Vertical magnetic gradient (VMG) anomaly map.

Magnetic susceptibility measurements were conducted in the study area using the Geofyzika KT-5 Kappameter. About 155 measuring points, covering the different rock units in the area, were acquired to assist the interpretation of the magnetic gradient data (Fig. 2). At each measuring point, the measurements were recorded up to four times and the average was calculated to minimize the error in the collected data. The obtained data were apparent susceptibility values in the (SI) units. These data were subjected to surface unevenness correction and the true susceptibility values could be calculated from the corrected data using the following equation (Geofyzika KT-5 Kappameter, 1995);

$$K = K^{\backslash} / (1 - K^{\backslash} / 2) \quad (2)$$

Where K is the true susceptibility and $K^{\backslash}$ is the apparent susceptibility.

The range and the average magnetic susceptibility values in the (c.g.s.) units, for each rock type in the study area, were calculated and are listed in table (1). A comparison between the magnetic susceptibility values of the rocks in the study area and the values recorded for similar common rock types is carried out. Figure (4) is a bar diagram showing a comparison between the average magnetic susceptibility values of the rocks in the study area and the average values of similar rock types in general. The comparison shows that some of the rocks in the study area have relatively higher susceptibility values than the common values of similar rock types. The highest MS values were recorded over the metatuff rocks (about 12 times higher than the common average). These relatively very high

Table 1 Range and average magnetic susceptibility values of rocks in the Wadi Sa'al area.

Rock type	Susceptibility range in (c.g.s.) unit x 10^3	Average Susceptibility in (c.g.s.) unit x 10^3
Gabbro	0.068 – 2.395	0.893
Granodiorite	0.255 – 1.94	0.920
Massive metavolcanic	0.018 – 4.631	0.684
Sheared metavolcanic	0.013 – 0.384	0.067
Metatuffs	0.017 – 30.160	4.392
Metsediments	0.017 –1.615	0.188

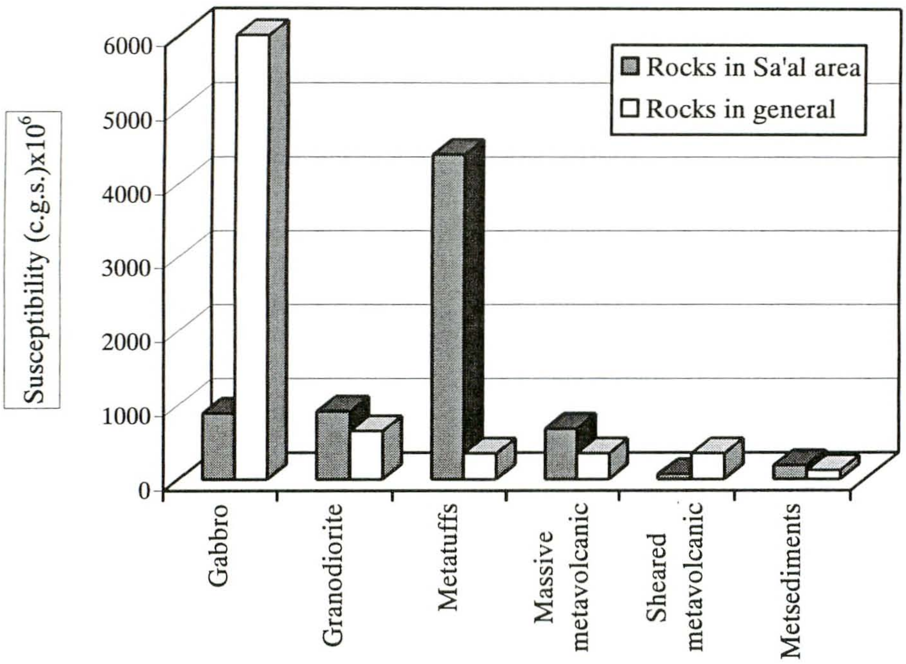


Fig. 4 Bar diagram shows the relative magnetic susceptibility values of the rocks in the Wadi Sa'al area.

values may be attributed to the presence of magnetic ore minerals with considerable concentrations. The granodiorites and the massive metavolcanic rocks exhibit relatively high MS values as well. The recorded average values are 1.4 and 2 times higher than the common average recorded for the similar rock types, respectively. Slate and phyllite rocks show moderately normal MS values. On the other hand, although gabbros and sheared metavolcanic rocks have extremely different MS characteristics, they showed significantly lower MS values than the common values.

A precise inspection of the magnetic survey results shows good match between the VMG and the MS results. The metatuff rocks that are associated with the highest amplitudes of the VMG anomalies have the highest relative MS values. Similarly, the granodiorite rocks and the massive metavolcanic rocks, that have the most abundant number of the VMG anomalies, are associated with relatively high MS values. The metasediments and the sheared metavolcanic rocks that show normal and low susceptibility values are very poor in the VMG anomalies distribution.

3.3. The Very Low Frequency-Electromagnetic method

The very low frequency-electromagnetic (VLF-EM) method is an excellent, cheap and rapid prospecting tool. It has been successfully used in locating sulphide deposits in different localities all over the world (e.g. Fraser, 1969; Paterson and Ronka, 1971; Shendi, 1988). The method uses, as a source, the electromagnetic field emitted from the powerful military radio stations in the frequency range of 15 − 25 kHz. At a very large distance from the transmitter, the electromagnetic field approximates to a plane wave. In case of the presence of a subsurface conductive body, a secondary electromagnetic field is induced with the same frequency of the primary field but differs in phase, direction and amplitude. The interference between the primary and the secondary fields produces an elliptically polarized field. The general practice in the VLF-EM prospecting is to determine the polarization parameters including the tilt angle (ϕ) of the elliptically polarized field. The subsurface conductive body is usually located directly under the crossover point along the tilt angle profile.

The very low frequency-electromagnetic measurements were carried out along the same profiles and at the same stations of the vertical magnetic gradient measurements (Fig. 2). It was possible in the study area to receive the VLF-EM waves emitted from UMS radio broad-casting station in Moscow. The frequency of these waves is 17.1 kHz and the direction of the received primary field, N85°W, was appropriate, as it is nearly perpendicular to the strike of the expected subsurface conductive bodies under consideration. The tilt angle (ϕ) values were measured using the Canadian Scintrex SE-81 single coil, phase, amplitude and strike (SCOPAS) receiver.

The VLF-EM measurements, like most of the electromagnetic methods, are highly affected by the topographic irregularities. Uneven terrains could contribute significant anomalies that destroy the measured tilt angle data. Consequently, the VLF-EM data had to be subjected to topographic corrections. Eberle's correction technique (1981) was applied to the measured tilt angle values. This technique concludes that the topographic contribution is given by:

$$\phi_{top} = \tfrac{1}{2} \tan^{-1}(2 / \tan\tau - \cot\tau) \qquad (3)$$

Where ϕ_{top} is the amount of tilt angle produced by topographic effect.

τ is the incidence angle of VLF-EM wave on the ground.

The corrected real component Rc% ($\tan\phi_c$ x 100) values were calculated from the corrected tilt angle (ϕ_c) values. A filtering technique, that was presented by Fraser (1969 and 1971), was applied to the corrected real component values in order to minimize the topographic effect and to obtain less noisy and contourable data. This technique can be expressed as follows:

$$F_{2,3} = (M_3 + M_4) - (M_1 + M_2) \qquad (4)$$

Where M_1, M_2, M_3 and M_4 are any four consecutive data points and $F_{2,3}$ is the filtered value at the mid-point between these consecutive data points.

By applying this technique, the crossover point is transformed into a positive peak very close to the top of the subsurface conductor. The corrected filtered real component Rcf % values are presented in the form of contour map (Fig. 5). On this map, 34 anomalies (with values ranging from − 20% to − 160%) could be delineated. These anomalies are interpreted as subsurface conductive bodies. The anomalies are concentrated in the metavolcanic and the granodiorite rocks. The metatuffs, the massive metavolcanics and the granodiorite rocks exhibit the highest number of the anomalies while, the metasediments and the sheared metavolcanics show the lowest. The gabbro rocks also show a considerable concentration of the anomaly distributions. Some anomalies are associated with the structural contacts, especially between the granodiorites and the surrounding rocks. The junction zone of the three valleys also shows high VLF anomalies. Most of the VLF anomalies coincide with the VMG anomalies, which may conclude that the causative subsurface bodies are conductive bodies with some magnetic characters. It is also obvious that the anomalies are oriented mainly in the NE-SW direction, the same direction as that of the VMG anomalies. This indicates that the distribution of the VMG and the VLF anomalies is controlled by subsurface structures that have NE-SW direction which is coincident with the direction of the measured surface structures in the area (faults, and axes and limbs of folds of the NE-SW direction).

The depths to the top of the expected conductive bodies are estimated using three depth estimation methods. These methods were introduced by Paterson and Ronka (1971), Baker and Myers (1979) and Milos (1981). The average depth is found to be ranging from 18 to 73 meters. This range value is close to that calculated from the VMG anomalies.

3.4. The Self-Potential (SP) method

The self-potential (SP) method is a popular, very sensitive method in sulphide mineral exploration. The high potentials are usually associated with sulphide and graphite ore bodies. Both massive and disseminated sulphides may produce distinct SP anomaly (Parasnis, 1986). The interpretation of SP anomalies is usually quantitative. The anomaly minimum is assumed to

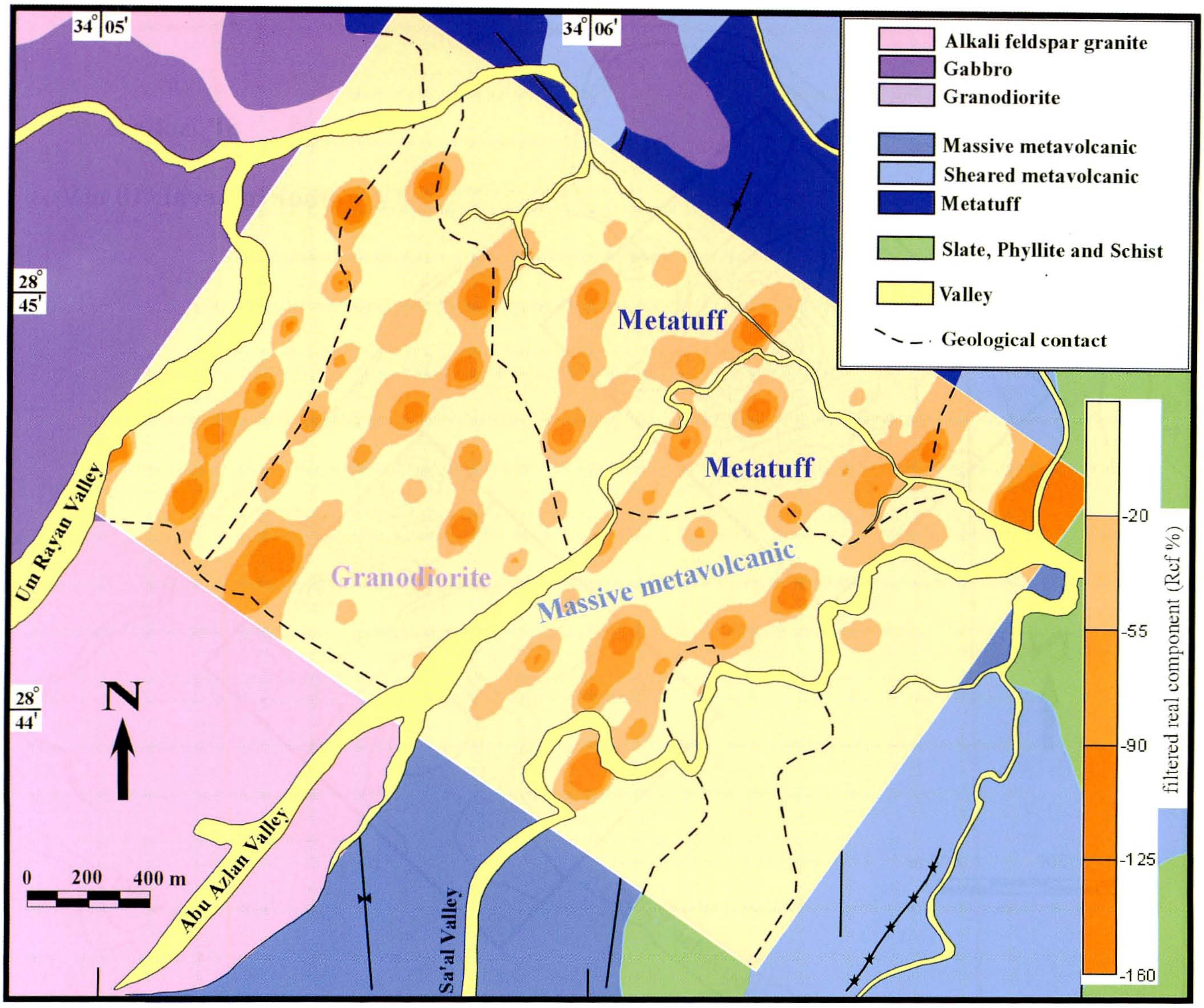


Fig. 5 Very low frequency – electromagnetic (VLF-EM) anomaly map.

occur over the center of the anomalous body (Kearey and Brooks, 1991).

Detailed self-potential (SP) measurements were carried out along six profiles in two selected anomalous sites, as indicated by the obtained geophysical results, in order to examine the VLF anomalies and to assist the geophysical interpretation. Each of the selected sites was covered by three SP profiles nearly perpendicular to the axis of the selected anomaly (Fig. 2).

Gradient SP measurements were carried out using the Canadian Scintrex RSP-6 self-potential and resistivity unit with non-polarizable copper electrodes. A fixed electrode spacing of 20 meters was kept along the measured profiles. Relative SP values were calculated from the measured gradient SP data. These values were presented as SP contour maps (Fig. 6). The self-potential maps show considerably anomalous SP values (from −10 mV up to −85 mV) over the two selected anomalies. The cause of these anomalies may be subsurface sulphide minerals with considerable concentrations. The estimated depths to the top of the SP anomalous body are found to be ranging from 12 to 60 meters, as estimated using the half-width method (Kearey and Brooks, 1991). The SP results indicate that the VLF anomalies are related to subsurface sulphide ore bodies.

4. Microscopic investigation

The geophysically anomalous sites, in the study area, were sampled for carrying out an ore microscopic study to examine the geophysical survey results and to throw some light on the types and characteristics of the

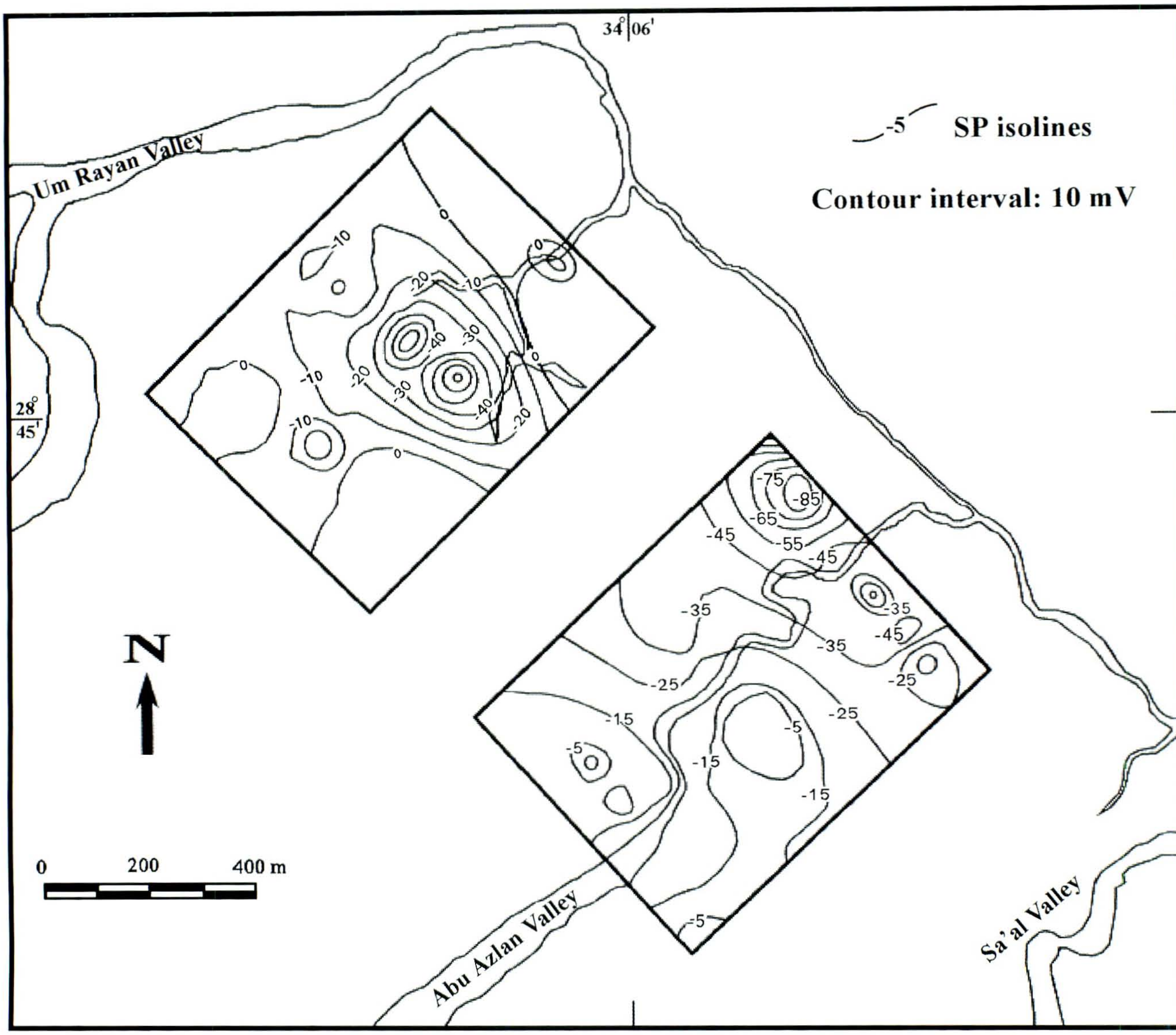
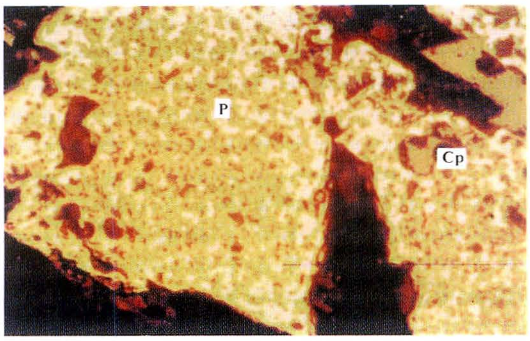


Fig. 6 Self-Potential (SP) anomalies over the two selected sites.

expected ore minerals. The rock samples were prepared, then studied using the reflected light ore microscope. The microscopic study shows that pyrite, chalcopyrite, magnetite and ilmenite are the main primary sulphide and magnetic minerals identified in the studied rock samples, while hematite and titanomagnetite are minor constituents. Pyrite is the most abundant sulphide phase and it occurs as impregnated discrete crystals, 1-3 mm across (Fig. 7a&b), or subrounded grains (Fig. 7c), and skeletal shape (Fig. 7d&e), readily identifiable by its pale brass yellow color. It is mostly epigenetic in relation to silicates, and is associated with superimposed hydrothermal alteration. Chalcopyrite is less abundant than pyrite and occurs as fine to coarse grained disseminated in the host rocks especially in the metatuff rocks (Fig. 7a&c). However, individual chalcopyrite grains are easily recognized in the granitoid and metatuff, and sometimes gabbro rocks. Magnetite occurs as euhedral coarse grains forming pseudomorphs showing various degrees of modification by limited martitization or "overgrowth" along grain boundaries (Fig. 7f). Hematite occurs as secondary aggregates after magnetite (Fig. 7f). Titanomagnetite could be identified in some rock samples as small crystals associated mostly with pyrite or chalcopyrite (Fig. 7b&g). Ilmenite could be also detected in partially altered form (Fig. 7e&h).

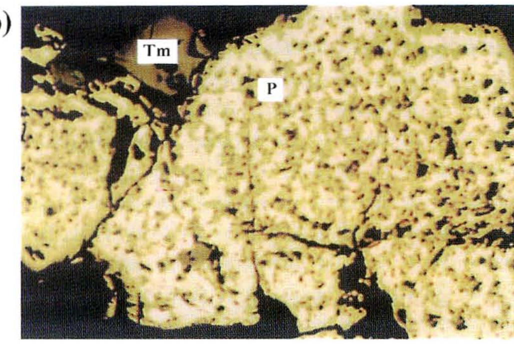
Microscopic study shows the presence of different types of sulphide and magnetic minerals in the rocks that exhibit geophysical anomalies, which coincides

(a)



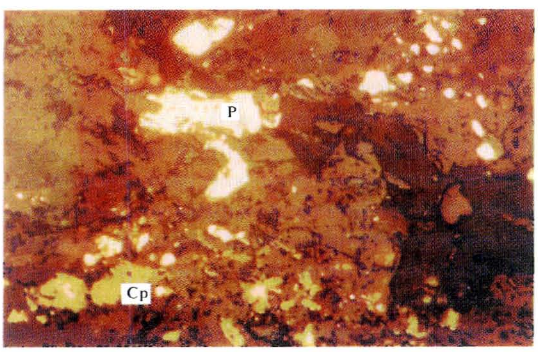
Photomicrograph showing Pyrite (P) and Chalcopyrite (Cp) crystals 200 X.

(b)



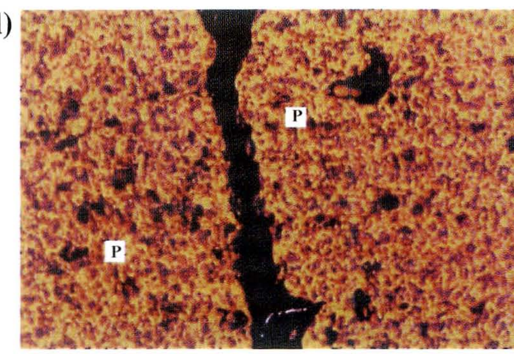
Photomicrograph showing a large crystal of Pyrite (P) with a small crystal of Titanomagnetite (Tm) 200 X.

(c)



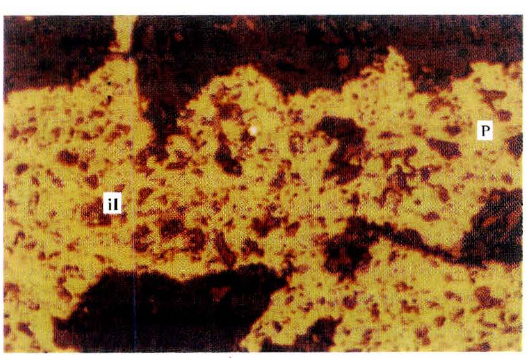
Photomicrograph showing scattered grains of Pyrite (P) and Chalcopyrite (Cp) crystals 200X.

(d)



Photomicrograph showing skeletal Pyrite (P) crystal 200X.

(e)

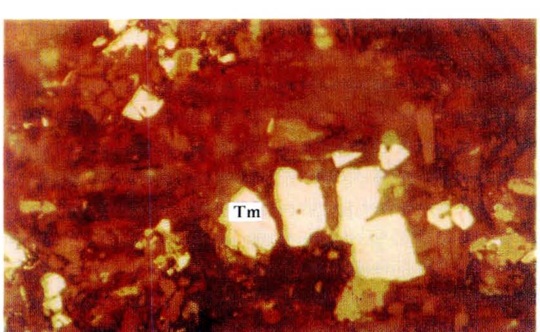


Photomicrograph showing Sieving Pyrite (P) crystal with Ilmenite (il) remainents 200X.

(f)

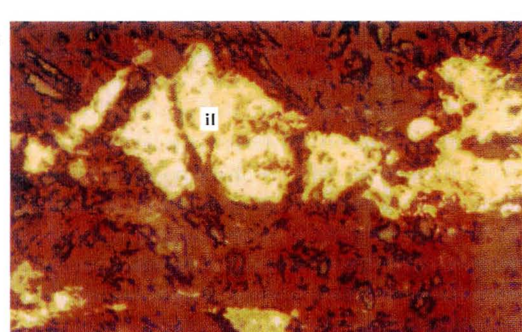
Photomicrograph showing Magnetite (M) and secondary aggregates of Hematite (H) 200X.

(g)



Photomicrograph showing a crystal of Titanomagnetite (Tm) 200X.

(h)



Photomicrograph showing partially altered ilmenite (il) 200X.

Fig. 7 Ore microscopic photomicrographs showing different sulphide and magnetic ore minerals.

with the geophysical interpretation, confirming that the detected geophysical anomalies are related to these sulphide and magnetic ore minerals.

5. Discussion

The magnetic surveys show considerable magnetic anomalies indicating the presence of subsurface magnetic bodies at depths ranging from 25 meters to 67 meters and oriented in the NE-SW direction. These anomalies are concentrated in the metatuff and the granodiorire rocks. The junction zone (at the intersection of the three valleys) exhibits the highest of the anomaly concentration.

The VLF survey confirms the presence of subsurface conductive bodies, oriented in the same direction as the magnetic anomalies. The depth to these anomalies ranges from 18 meters to 73 meters. These conductive bodies are associated with the granodiorite and the basic metavolcanic rocks. The junction zone also shows an abundance of VLF anomalies. Most of the VLF anomalies coincide with the magnetic anomalies concluding that the conductive bodies are the same/or associated with the magnetic bodies.

The detailed SP survey over the selected VLF anomaly sites indicates that the SP and VLF anomalies are generated by the same source, which is a significant concentration of sulphide minerals. Generally, the geophysical signatures suggested that the causative subsurface bodies are sulphides-bearing bodies with some magnetic characters. Figure (8) shows the distributions of the interpreted subsurface bodies. The delineation of these subsurface bodies is based on connecting the anomalies having similar characteristics along consecutive profiles acquired using different geophysical methods.

The ore microscopic study shows a variety of sulphide and magnetic minerals (pyrite, chalcopyrite, magnetite, titanomagnetite and ilmenite). However, the studied rock samples represent only the outer zone of the mineralization, which is expected to be poor in the sulphides, and massive bodies may be still preserved at depth. Study of the microfabrics of the detected minerals provides important information on the mineralizations. It indicates that metamorphism, tectonic deformation as well as the epigenetic hydrothermal activity might have significantly contributed to the concentration of the mineralization. Brittle minerals such as pyrite, and chalcopyrite, commonly show cataclastic deformational fabrics, while the more ductile minerals, particularly magnetite, and ilmenite, were subjected to, corrugation, and intragranular deformation. Hydrothermal fluids are possibly resulted in mobilization, transportation, and reprecipitation of the pre-existing primary minerals forming a mineralization network controlled by structures in the area (fold hinges, shear zones, fissures, and cleavages).

Comparison of the distribution of the expected mineralized bodies (Fig. 8) with the geology of the area shows that the basic metavolcanic rocks and the granodiorite rocks are richer in the mineralizations suggesting that the source materials of these rocks may be the same source of the mineralizations. The contacts between the different rock units exhibit considerable geophysical anomalies, indicating that these contacts might have contributed to circulating and concentrating the mineralizations in the study area.

The comparison also shows that the distribution of the mineralized bodies is controlled by subsurface structures that have NE-SW direction that is the same direction of the axes and limbs of folds of the second stage of deformation. This relation may indicate that the continuous deformation, caused by folding and resultant sliding of adjacent layers in the limbs, could have created an open system through which fluids could move and concentrate the mineralizations. The occurrence of high anomaly concentrations associated with the junction zone of the three valleys, a highly deformed zone, confirms that the deformation process played an essential role in concentrating and controlling the mineralizations. The relation between the surface structures and the distribution of the mineralization may also indicate that the surface structures have subsurface extension controlling the distribution of the mineralizations and that the surface mineralizations are mirror images of subsurface mineral occurrences with considerable concentrations.

Furthermore, the mineralogical and geophysical characteristics of the upper and lower parts in the area suggest that the mineralizations must have occurred in a compositional gradient because of the progressively increasing degrees of deformation at high levels in the area. Thus, it can be concluded that the sulphide mineralization in the Wadi Sa'al area may have occurred prior to the deformation mechanism, then the folding process was responsible for concentrating and redistributing these mineralizations along the fold axes and limbs.

6. Conclusions

Integrated geophysical surveys and microscopic studies were carried out in the Wadi Sa'al area, south Sinai, Egypt to investigate the potentialities and the

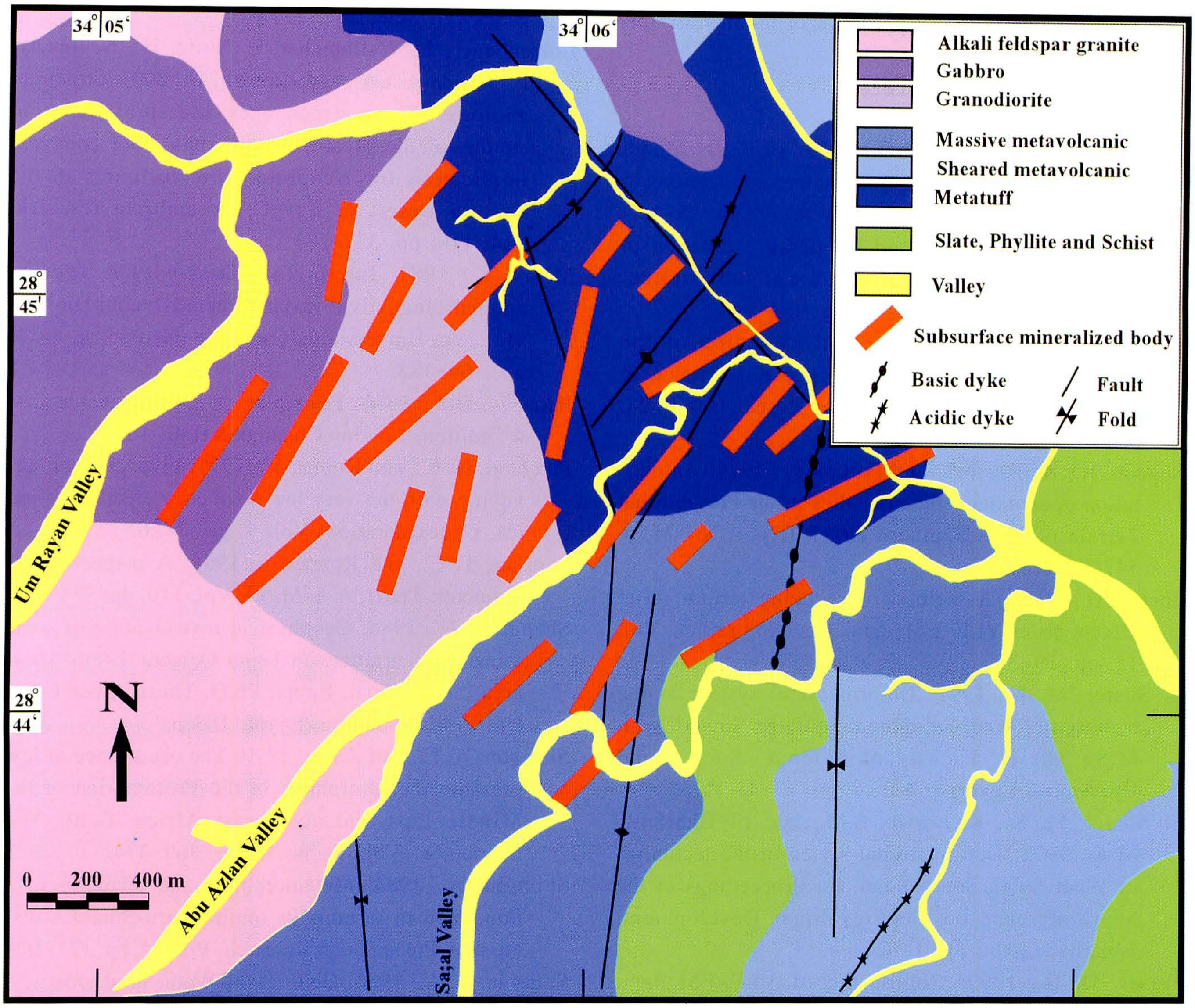


Fig. 8 The expected mineralized bodies in the Wadi Sa'al area, as interpreted from the geophysical surveys.

characterizations of the sulphide mineralizations in the area. The geophysical surveys were conducted using the very low frequency-electromagnetic method, the vertical magnetic gradient method, the magnetic susceptibility method and the self-potential method. The sites of the resultant geophysical anomalies were sampled for carrying out the ore microscopic study.

The interpretation of the geophysical data in the light of the geological information and ore microscopic study reveals the presence of subsurface sulphide minerals in the study area with different concentrations. The results show that the metatuffs, the granodiorites and the basic varieties of the metavolcanic rocks are relatively richer in sulphide minerals with the junction zone of the three valleys being the most promising site.

The interpretation of the geophysical data also shows that the distribution of the subsurface mineralizations is controlled by the structural elements striking NE-SW developed at the second stage of deformation.

The present study shows that the use of VLF-EM, VMG, MS and SP methods, in combination, is an effective tool for detecting and tracing subsurface sulphide mineralizations in areas with similar geological conditions.

Acknowledgments

The authors would like to express their great thanks to Mr. Mohamed Rashed for his kind assistance. We also express our deep appreciation to Mr. Mohamed Mostafa for his help with the microscopic description and for his valuable comments. The authors also express their deep gratitude to Dr. Nemoto Hiroo for his helpful suggestions and useful review of the manuscript.

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Manuscript received August 26, 2003.
Revised manuscript accepted December 15, 2003.