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APPLICATION OF ELECTRICAL RESISTIVITY AND ELECTROMAGNETIC METHODS TO EXPLORE MINERALIZED VEINS (COPPER AND BARITE) IN TINEJDAD AREA (SOUTH-EASTERN MOROCCO)

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EXTENDED ABSTRACT

La catena montuosa dell Anti Atlante del Marocco si trova sul bordo settentrionale del Cratone Africano occidentale. L’Anti Atlante appare come un enorme anticlinorio ad andamento ENE-WSW. Localmente il basamento affiora come un *inlier*, ma la parte principale è costituita da una copertura paleozoica leggermente piegata. Le orogenesi eburniana (2 Ga) e panafricana (600 Ma) hanno lasciato le loro impronte nel basamento del Precambriano. Successivamente un nuovo ciclo di Wilson iniziò con la formazione di un *rift* nel tardo neoproterozoico. Dopo la sedimentazione di *syn-rift*, l’apertura del *rift* si è interrotta, ma la costante subsidenza ha consentito la deposizione di una spessa pila di sedimenti paleozoici in un ambiente di acque poco profonde. Questo bacino intracontinentale si è poi piegato nel Carbonifero medio, formando la catena a pieghe dell’Anti Atlante. La caratteristica principale di questa catena è la mancanza di un importante scollamento o struttura a *duplex*.

L’Anti Atlante orientale è ricco di depositi minerali con varie mineralizzazioni. È generalmente caratterizzato dalla presenza di vene mineralizzate di barite, piombo e rame. Queste mineralizzazioni a volte mascherate da alluvioni quaternarie, sono racchiuse in formazioni paleozoiche e neo-proterozoiche, il che rende molto complesso identificarle e localizzarle.

Nelle regioni di Gardmiyt e Banigonssa, sono stati introdotti metodi di resistività elettrica ed elettromagnetici a frequenza molto bassa (VLF) per caratterizzare la litostruttura delle regioni studiate e per esplorare vene mineralizzate in rame e barite. La scelta dei metodi geofisici utilizzati in questo studio si basa sul fatto che la mineralizzazione è associata alla calcite e al quarzo che hanno proprietà fisiche resistive. Queste anomalie di resistività si possono distinguere da un mezzo circostante meno resistivo e, secondo lo studio di Dakir *et al*. (2019), le anomalie della polarizzazione indotta e quella della resistività elettrica sono correlative e corrispondono al passaggio alle zone mineralizzate.

Nella regione Draa-Tafilalt, nel Marocco sud-orientale, la popolazione pratica principalmente attività agricole lungo i fiumi (Ziz e Gheris) e intorno a sorgenti e pozzi. Inoltre, l’allevamento del bestiame costituisce una parte significativa dell’economia della regione. La desertificazione e la scarsità di precipitazioni hanno un impatto negativo sullo sviluppo agricolo cosicchè, di recente, l’esplorazione e lo sfruttamento minerario sono diventati l’attività dominante praticata dagli abitanti utilizzando inizialmente metodi artigianali. Nel contesto di piccoli progetti minerari, la definizione del modello del sottosuolo è un passo importante nel monitoraggio e nella definizione dei programmi di lavoro nei siti prospettati.

Il geofisico deve definire il comportamento fisico del sottosuolo che potrebbe avere una relazione con le zone mineralizzate, a partire da un numero limitato di indagini geofisiche. Il problema sollevato dai cercatori minerari è duplice, da un lato avere informazioni geologiche del basamento, e dall’altro determinare la variabilità laterale e verticale delle vene mineralizzate.

Da questa prospettiva, il presente lavoro sviluppa un approccio innovativo di combinazione dei metodi elettrici ed elettromagnetici, con l’obiettivo di quantificare e localizzare le vene mineralizzate presenti nel sottosuolo.

ABSTRACT

The electromagnetic method by the measure of the angle of inclination of wide axis and the ellipticity of the ellipse of polarization can be used to prospect the maximum field and to validate the electric data. this technique is known for its speed and ease of implementation. The VLF electromagnetic results show two types of Karous-Hjelt anomalies: i) positive anomalies with an apparent current density ranging between 30 and 40%, indicating that the explored areas are affected by a network of faults. In the Paleozoic sandstone formations, the faults are generally oriented in NE- SW direction, while in the Neoproterozoic pyroclastic formations, are oriented in NW-SE direction. ii) negative anomalies with an apparent current density varying between -30 and -40% corresponding to resistant zones probably associated with mineralized veins oriented in the same direction of the fractured zones. The VLF measurements confirm the anomalies obtained by the electrical resistivity. Thus, the resistant zones correspond to the passage of mineralized veins and the conductive zones are correlated with the fractured areas. The coupling of electromagnetic and electrical resistivity methods suggest that the mineralization is controlled by three parameters (i) Structural: the mineralization is examined by two fault systems, the NW-SE family in the Precambrian basement (Banigounssa site) and the NE -SW family in the Paleozoic blanket (Gardmıyt area), (ii) Lithological: the mineralization is hosted by the Paleozoic detrital and the Neoproterozoic pyroclastic formations and (iii) Hydrothermal: the explored mineralization is related to two major hydrothermal events; a Pan-African event linked to the late Neoproterozoic extensive phase responsible for the establishment of mineralization within the Precambrian basement, and then a Hercynian event manifested by the remobilization of metals in the structures oriented in NE-SW direction.

***Keywords**: electrical method, electromagnetic method, eastern Anti Atlas, barite and copper mineralization*

INTRODUCTION

A review of processes leading to the formation of a metal deposit shows that, as with an oil deposit, a specific geological condition is required for a metal deposit to form. This implies that a good exploration strategy will first be concerned with understanding the geological context and targeting regions from their geodynamic context. In the eastern Anti Atlas many works (Abi *et alii,* 2003; Tuduri *et alii,* 2006; Gasquet & Cheilletz 2009; Mouttaqui *et alii,* 2011 and Baïdde *et alii,* 2016) revealed that the Precambrian and Paleozoic formations are known to contain many polymetallic deposits. Mineralization in this field is of the filonian type which sometimes appears on the surface and in most cases it is covered by encasing formations and by alluvial Quaternary, which makes it very complex to follow up these veins. In this sense, geophysical prospecting techniques must be used to identify buried and blind mineralization in the Tinjdad region. The objective of the present paper is on one hand, to explore/locate mineralized veins and to contribute to the mapping of their behaviour in the depth. On the other hand, the study results will be used to establish the relationship between mineralization and deep faults affecting the prospected area. The geophysical approach, using electrical and electromagnetic methods, confirm its efficiency to explore metal deposits (Bérubé, 1997; Eze *et alii,* 2004; Djroh, 2014; Gaafar, 2015; Florsh *et alii,* 2017; Jamal & Singh, 2018; Upadhyay *et alii*, 2019; Dakir *et alii,* 2019 and Dakir *et alii,* 2020). The use of the electrical resistivity method is based on the fact that the mineralization is associated with calcite and quartz. This situation allows to distinguish easily the resistant anomalies from the conductive ones. According to the Dakir et alli, 2019, in the Taroucht region, the obtained induced polarization anomalies and that of the electrical resistivity are correlated and associated with mineralized veins. The Very Low Frequency electromagnetic technique reveals considerable EM anomalies, even over poor conductors such as sheared contacts, fracture zones, and faults. Hence, this method has been a popular tool for the rapid mapping of near-surface geological structures (Parker, 1980; Phillips & Richard, 1975; Saydam, 1981; Sunmonu *et alii,* 2016).

GEOLOGICAL CONTEXT

The mountain range of the Moroccan Anti-Atlas, located on the northern edge of the West African Craton, belongs to the Pan African orogenic belt (Choubert, 1943; Choubert & Faure-Muret, 1980; Ennih & Liégeoi, 2001; Hefferan *et alii,* 1992; Leblanc & Lancelot, 1980; Thomas *et alii,* 2002). It stretches over more than 700 km along a WSW-ENE direction from the Atlantic to Tafilalt, the foothills of Algeria. It is limited to the North by the South Atlas Fault Zone which stretches from Tunisia to Agadir and extends into the sea towards the Canary Islands (Gasquet, 1992). Its southern boundary is the Tindouf Carboniferous Basin formed by the belt of the large tertiary and secondary hamadas of Drâa, Guir and Kem Kem (Fig. 1). This chain is divided into three areas: (i) The western part extending from the Atlantic to Jbel Siroua, (ii) The central part which includes the Jbel Siroua and the region of Bou Azzer, El Graara and (iii) The eastern part includes the Jbels Saghro and Ougnat. This subdivision is accentuated by an oblique accident (Choubert, 1947); the Major Anti-Atlas Accident limiting the Western Anti-Atlas of the Central and Eastern Anti-Atlas. This WNW-ESE middle-direction fault extends from the northern part of the Jbel Siroua, where it connects with the South Atlasian Fault, to Zagora. It extends over almost 6000 km to Kenya, via the Hoggar, under the name of the lineament of Tibesti (Guirau

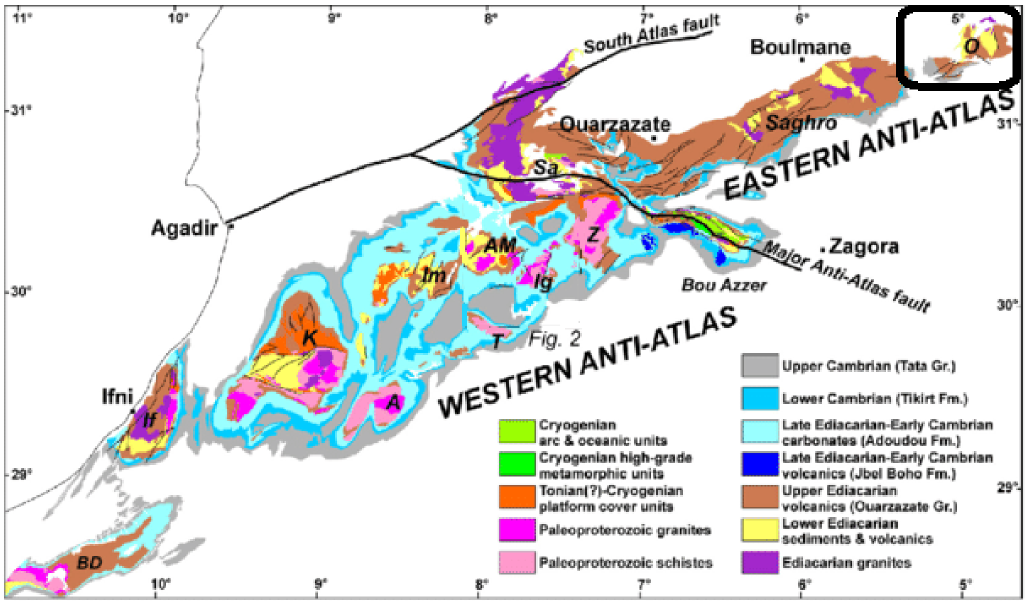

Fig. 1 - Simplified geological map of the Anti-Atlas, Walsh et alii, (2002) and Gasquet et alii, (2008)

et alii, 2000). In Morocco, it marks the western boundary of a so-called Eburnean domain (2 Ga) of a pan-African domain in the east, (Leblanc & Lancelot, 1980).

The Anti-Atlas geological province is the host of a variety of ore deposits, ranging from Paleoproterozoic to Ordovician. These deposits are mainly Cu-Au porphyry types, precious metal epithermal (Au, Ag) or polymetallic VMS base metals (Cu, Pb, Zn, Au, and Ag), while the sub- Atlas region presents an important occurrence of manganese. The map (Fig. 2) shows the location of the most important deposits in the Anti-Atlas region. In the transition area between the buttonhole of the Ougnat and Saghro the region is characterized by Barytine and copper veins.

MATERIALS AND METHODS

In Wenner array, the four electrodes with a definite array spacing "a", are moved after each measurement. In each station,

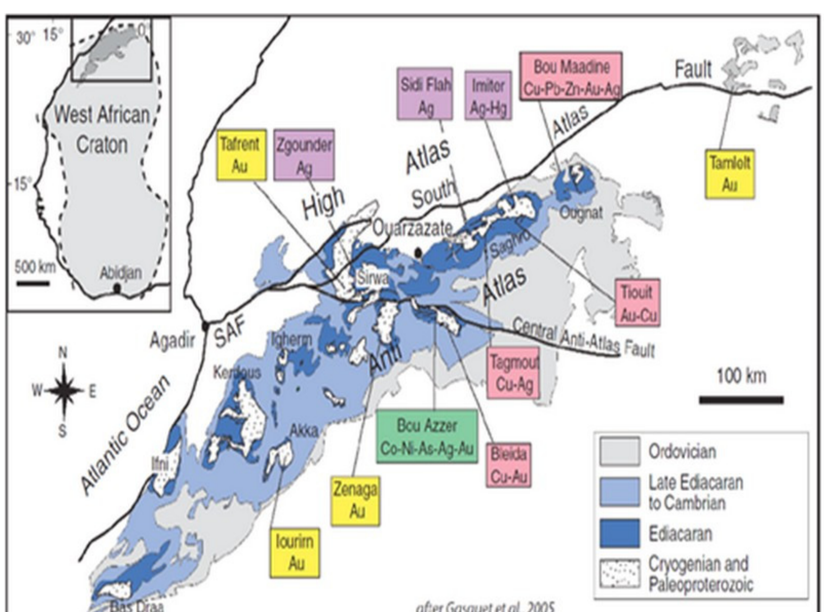

Fig. 2 - The main Anti-Atlas deposits, according to Gasquet et alii, (2008). amended by Mouttaqui et alii, (2011)

the value of resistivity is referred to the center of the array (Kunetz, 1966). The choice of this device is based on the fact that it shows contours of the sensitivity values almost horizontal in the center (Marescot, 2004), which makes it very efficient for the vertical resolution . The resistivity of the ground is measured by injected currents and the resulting potential differences at the surface. Two pairs of electrodes are required: electrodes A and B are used for current injections, while electrodes M and N are for potential difference measurements. The apparent resistivity ρa is calculated from the current I and the potential difference ΔV (Eq. 1). The coefficient K is called geometric factor. For Wenner configuration, the factor K can be calculated from the electrode spacing (Eq. 2):

$$\rho a = K \Delta V / I \quad (1)$$

$$K = 2\pi a \quad (2)$$

The instrument used in this research work is advanced geophysical instruments from Iris. The profiles, oriented in the E-W and NNE-SSW directions, were made using the Wenner-α configuration, where the voltage and current electrodes are closely spaced and fixed in the center of the array. In the field, the electrical horizontal profiles with a maximum separation of the electrodes AB=300 m (a=100 m), were carried out. For each profile, 18 measurements were taken with a spacing of 10 m. These profiles will be used to produce the resistivity maps.

A number of configurations can be used with frequency-domain EM systems. The most common is the VLF-EM method that exists as multiple-frequency systems and as ground-conductivity meters. Measurements can be taken for the real component in-phase with the transmitted signal and the out-of-phase or quadrature component. These methods offer the advantage that ground contact is not necessary, meaning that operation is fast, minimal personnel are required and continuous systems can be easily implemented. They have been widely used as profiling instruments, mainly with subsequent qualitative interpretation. They are useful to locate fault and mineralized zones. The VLF-Instrument, specially designed for high productivity surveys in groundwater and mining exploration, is lightweight and ease of use. The VLF electromagnetic method (VLF-EM) is based on the use of radio waves between 15 and 30 kHz (Müller *et alii,* 1984). The primary magnetic field Hp emitted by the VLF stations can be captured by the VLF instruments. When a conductive element is traversed by the Hp electromagnetic field, an induced current (currents of Foucault) passes through it and produces a secondary magnetic field Hs phase-shifted with Hp, oriented in any direction (Mcneïll & Labson, 1991). The Tilt and the Ellipticity of the Hs electromagnetic field are calculated by the two equations (3) and (4) (Saydam, 1981).

$$\tau = R_e / H_p \quad (3)$$

$$\varepsilon = I_m / H_p \quad (4)$$

With R_e is the Real component, and I_m is the imaginary component.

During our study, the survey was carried out using the Receiver T-VLF Iris Instruments, operating in tilt angle mode, in order to measure the parameters of the ellipse of polarization, which are the tilt τ and the ellipticity ε. In this mode, it is convenient to operate with a transmitter (VLF station) which is located in the supposed strike (±45°) of the prospected target for a maximum coupling. For detecting the supposed fractures in the study area, the GBR station located in Rugby (England) has been chosen, with a power of 750 kW, which emits a signal with a frequency of 16 kHz. On the fieldwork, VLF-EM profiles were conducted, with profile length reaches 500 m. Readings were taken respecting a spacing of 10 m. The profile lines were oriented in NNE–SSW and E-W directions.

In order to have effective electromagnetic measurements, we used two filters using KHFFILT software; the Karous and Hjelt (KH) filter applied to the real component. This filter allows to establish apparent current density cross-sections showing the driver's response at depth (Karous & Hjelt, 1983). Qualitatively, it is possible to distinguish the conductive anomalies from the resistances by using a cross-section of the apparent current density (Karous *et alii,* 1977), where a high positive value corresponds to a conductive structure and low negative values corresponds to a resistant structure (Benson *et alii,* 1997; Sharma & Baranwal, 2005).

RESULTS AND DISCUSSIONS

The present paper contributes to measure geometric and physical subsoil parameters, in order to determine the direction and the depth of fractured zones and veins in the Tinjedad area. Electromagnetic and electrical methods were carried out in two sites (Fig. 3), in the locality of Banigonssa in the Neoproterozoic outcrops, and locality of Gardmiyt in the Paleozoic cover.

Gardmiyt Area

Electrical prospecting in Gardmiyt area

Based on the horizontal prospecting results, we established electrical resistivity maps from 15 electrical lines to show the spatial distribution of the apparent resistivity in the prospected ground.

The map AB/3=60 m (Fig. 4) shows that the apparent resistivity values vary from 40 to 120 ohm.m. It highlights two distinct anomalous areas:

- an anomalous zone located in the middle with high resistivities (120 ohm.m). This zone is attributed to the passage of barite veins hosted in relatively resistant

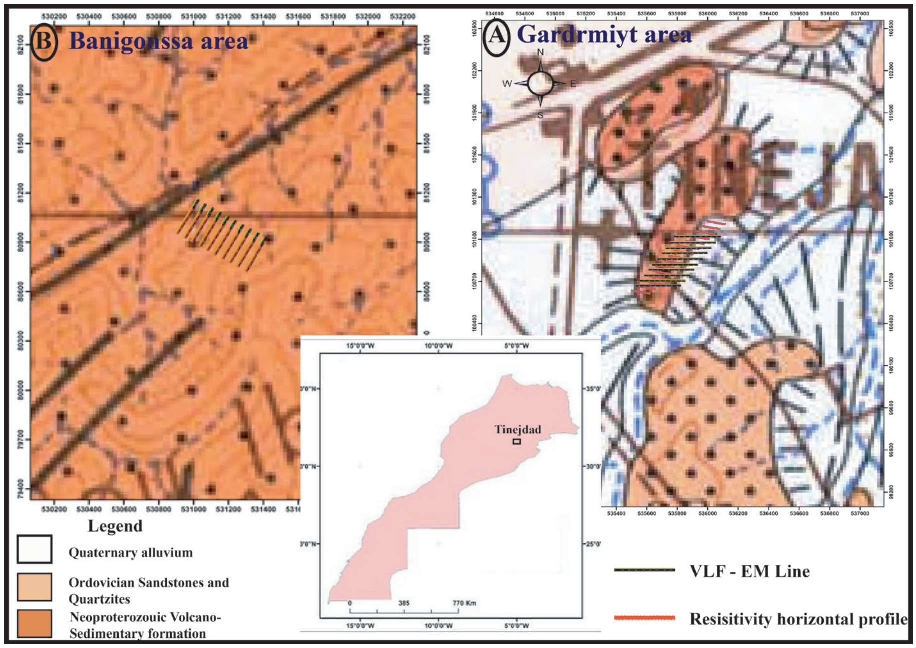

Fig. 3 - Location of the geophysical profiles A-Gardmiyt site in the Geological map 1/200000 of Todrha-Maider. B-The Banigonssa area in the 1/100000 Geological map of Taroucht

sandstone formations,

- an anomalous zone with relatively low resistivity (80 ohm.m). It is related to the presence of altered pelitic sandstones.

The map also shows a conductive anomaly (40 ohm.m) spotted in the north-eastern part. This anomaly is undoubtedly attributed to the presence of a landfill causing chemical contamination of the land at depth, resulting from leachate and the dissolution of the rejected products.

The analysis of the second map AB/3=100 m (Fig. 5) shows strong lateral heterogeneities of the prospected land:

- in the middle of the prospected area, the map reveals a

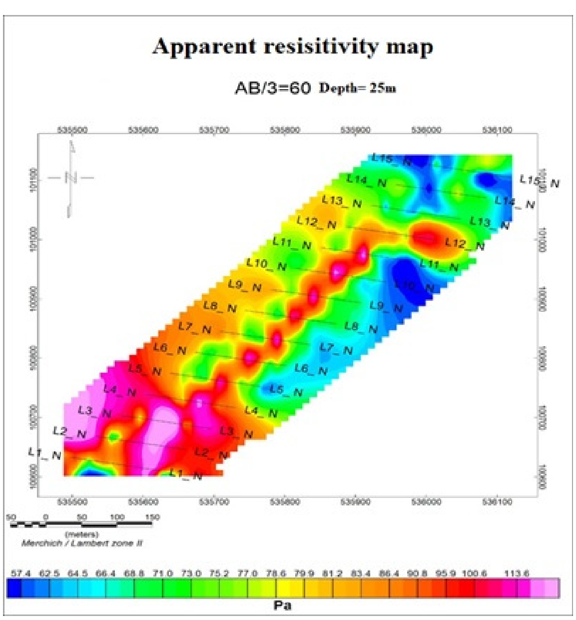

Fig. 4 - Resistivity map produced on the Tinejdad site (AB/3=60 m)

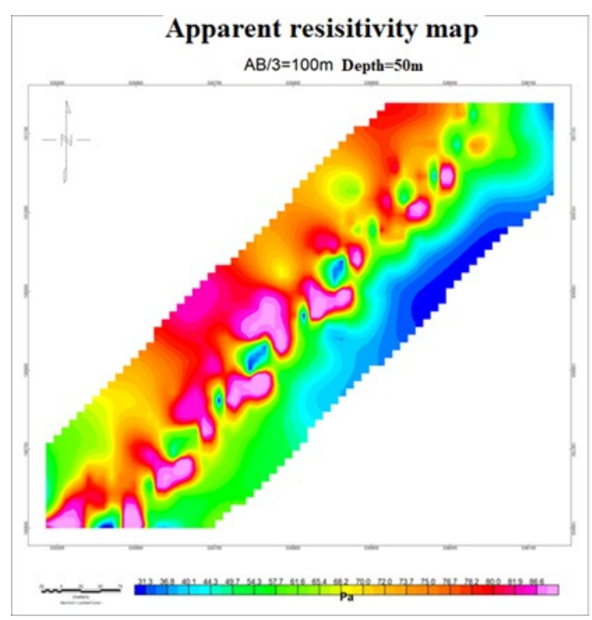

Fig. 5 - Resistivity map produced on the Tinejdad site (AB/3=100 m)

resistant anomaly with high resistivity (>90 Ohm.m). This response obviously corresponds to the passage of the mineralized barite vein oriented in NE-SW direction.

- on either side of the vein, the carbonate sandstone soils are relatively (50 ohm.m) due to their weathering accumulating high water content.
- a zone where the resistivity presents an average (value) reflects that the Ordovician sandstone formations are relatively resistant and therefore less altered.
- an area in the northeastern part, where the resistivity response suggest the presence of more conductive terrain. It is therefore attributed to the accumulations of chemicals carried by the vertical and lateral transfer from the landfill in this location.

The 3D model (Fig. 6) confirms the presence of a resistant zone in the outcrop that continue up to a depth of 30 m. This anomaly corresponds to the passage of a barite vein with a NE-SW direction.

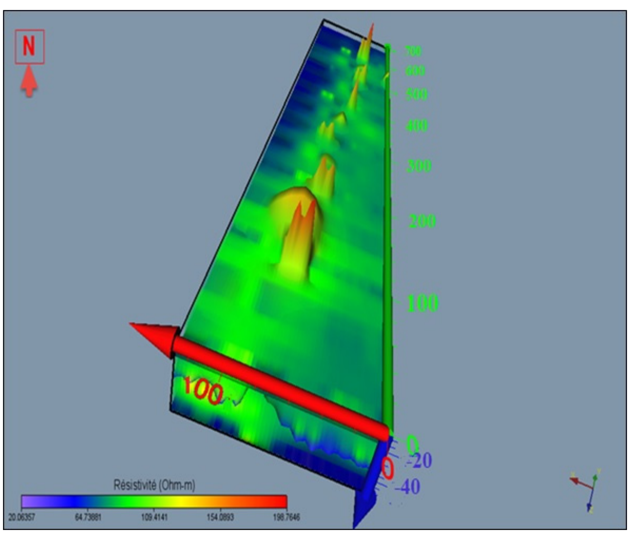

Fig. 6 - 3D model of electrical resistivity realized in the Tinejdad site

Vlf data filtering and qualitative interpretation at the Gardmiyt area

The apparent current density pseudo-sections (Fig. 7), represent lateral and vertical variation of the ground resistivity. They suggest the presence of several both conductive and resistant anomalies attributed respectively to the faults and to the passage of of barite mineralized veins. The first profile (Fig. 7-1) show that the prospected soil is largely homogeneous, except at the end of the profile at a distance of 280 m, where a resistant anomaly is detected from the surface until the depth of 20 m. This anomaly is probably associated to a barite vein. The second profile (Fig.7-2) show roughly the same apparent current density variation. However, we observe a conductive area spotted close to the resistant anomaly at a distance of 250 m. The profile (Fig. 7-4) show a conductive anomaly related to a fractured zone located at a distance of 200 m from the beginning of the profile. This anomaly continues to a depth of 50 m and corresponds to a normal subvertical dipping fault towards the East. From the cross-section, we also note the presence of the resistant zone located at a distance of 200 m. The profiles (Fig. 7-5), (Fig. 7-6) and (Fig. 7-9) reveal two anomalies: the first conductive anomaly is located at a distance of 150 m and extends to a depth of about 30 m. The second resistant anomaly spotted at a distance of 200 m and continues to a depth of 50 m. The pseudo-sections (Fig. 7-7) and (Fig. 7-8) also suggest the presence of two anomalies extending to a depth of 50 m. They correspond to resistant and conductive zones, located respectively at 145 m, 150 m and 170 m from the beginning of the profiles.

The 3D model (Fig. 8) shows that the Gardmiyt area is affected by a normal fault with subvertical dip oriented NE-SW. This fracturing seems to be continuous in the subsurface and exceeds 50 m deep It also shows the presence of the resistant anomaly oriented in NE-SW direction. Thus, the VLF results confirm the electrical resistivity results.

Banigonssa Area

The Banigonssa site is located in the SE part of Tarroucht (Cf Fig. 3). It is characterized by pyroclastic formations of Neo-Proterozoic that contain copper mineralized veins. In order to locate these mineralized veins, we executed 20 electric trails and 10 electromagnetic profiles. The results processing permit to establish pseudo sections and to realize a 3D model.

Electrical prospecting in Banigonssa area

The apparent resistivity map AB/3=50 (Fig. 9), which covers an area of 81 hectares, suggests that most of the prospected zone is occupied by conductive lands. The resistivity values vary from 40 to 93 ohm.m. It also indicates the presence of a relatively resistant zone (92.8 ohm.m) crossing the middle of the prospected ground. This anomaly is probably due to the passage of a copper mineralized vein oriented NW-SE. We also note the presence of a very conductive anomaly (39 ohm.m) located in the northern part. This anomaly is related to a fracture zone oriented in the same direction.

The apparent resistivity map AB/3=50 (Fig. 10) reveals two anomalies:

- a resistant anomaly, located in the center of the map with a resistivity of about 110 ohm.m. This anomaly is attributed to the passage of a copper vein oriented NW-SE,
- a conductive anomaly bordering the mineralized vein. It is probably attributed to the passage of a fracture oriented NNW-SSE.

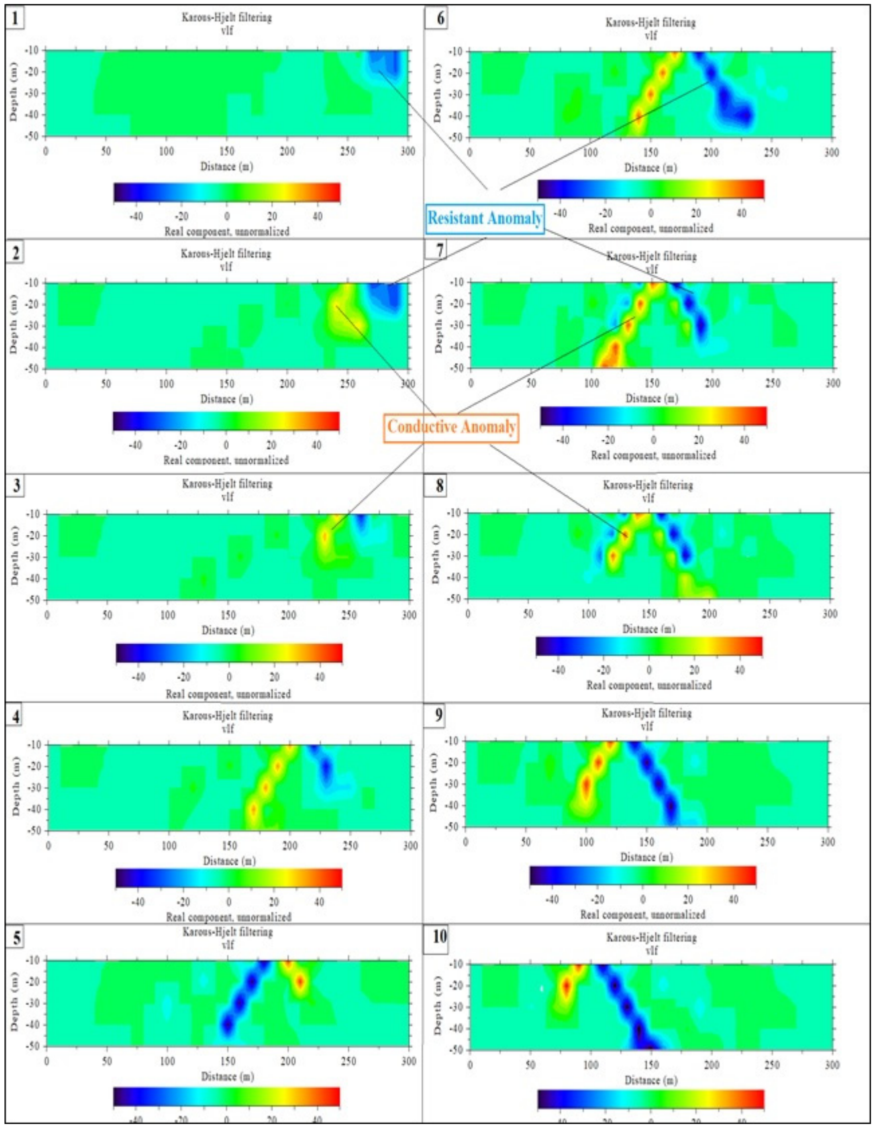

Fig. 7 - Apparent current density cross sections for all VLF lines made in the Gardmiyt region

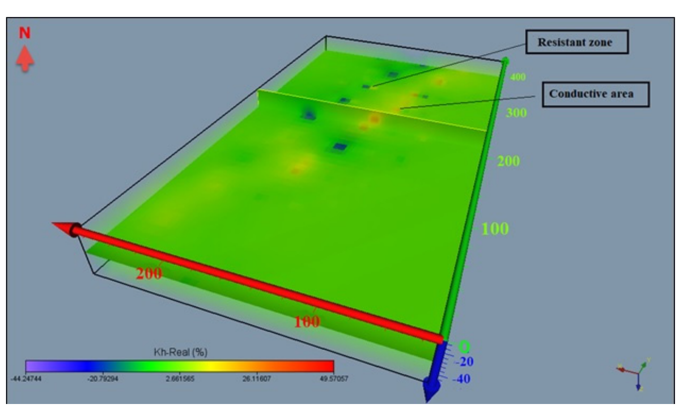

Fig. 8 - 3D model of electromagnetic data obtained at the Gadmiyt site

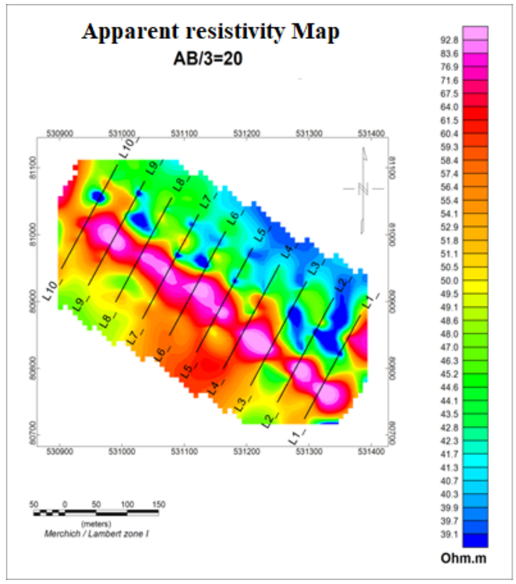

Fig. 9 - Resistivity map produced on the Banigonssa site (AB/3=20m)

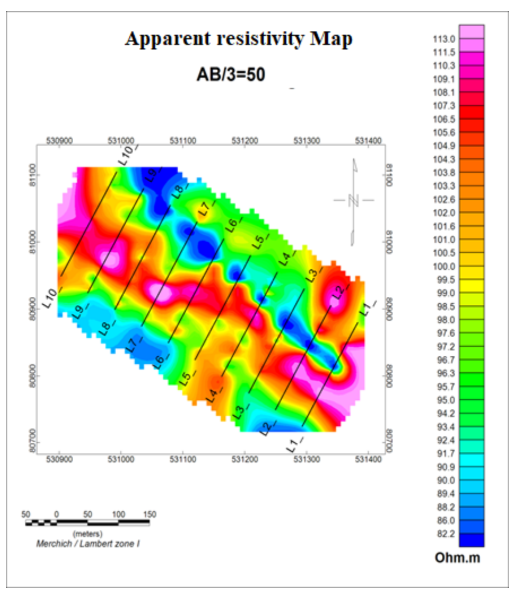

Fig. 10 - Resistivity map produced on the Banigonssa site (AB/3=50 m)

Vlf data filtering and qualitative interpretation at the Banigonssa area

The profiles (Fig.11-A) and (Fig. 11-B) identify clearly the presence of three anomalies. The resistance marked by low values of electromagnetic field is spotted at a distance of 75 m, this anomaly is probably contributed to the passage of copper mineralized vein, and the two conductors identified at a distance of 50 m and 110 m are contributed to the passage of fractured zones.

The profiles (Fig. 11-C), (Fig.11-E) and (Fig. 11-F) show the passage of the 4 anomalies. The two resistant anomalies marked by low electromagnetic field values are located at a distance of 50 m and 110 m, and two conductors are recorded at a distance of 25 m and 125 m locations. The conductive anomalies are associated to the fractured zones. The pseudo sections (Fig. 11-G), (Fig. 11-H) and (Fig. 11-J) suggest that the two veins evidenced at 50 m and 160 m are well developed in depth (about 40 m). We also note the presence of two superficial conductive anomalies which are spotted at 15 m and 180 m.

The model (Fig. 12) allows to clearly identify the alignment of the four anomalies; the two resistant zones are due to the passage of copper veins associated with granodiorite which are

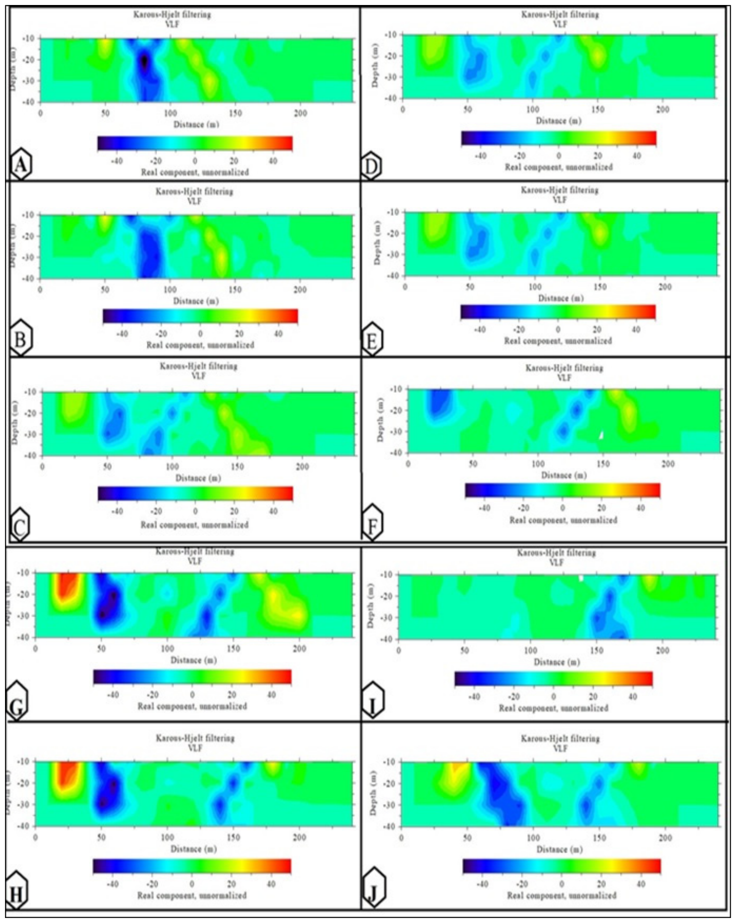

Fig. 11 - Apparent current density cross sections for all VLF lines made in the Banigonssa region

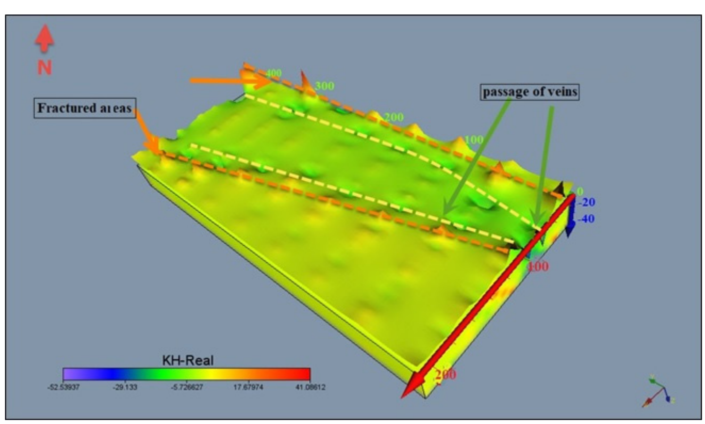

Fig. 12 - 3D map of electromagnetic data obtained at the Banigonssa site

well individualized in depth, and the two conductors are related of fractured zones. It should also be noted that the mineralized veins and the fractured zones are relatively oriented NW-SE.

CONCLUSIONS

The geophysical measurements carried out in Gardmiyt and Banigonssa regions showed that the resistivity response does not exceed 110 ohm.m, for the identified anomalies that are attributed to the mineralized veins of barite and copper. These are hosted in the sandstone formations of the Paleozoic (Barite) and pyroclastic of the Neo-Proterozoic (Copper), sometimes covered by the quaternary alluvial formations. These veins are aligned according to their locations in abandoned mining shafts and open pit mine exploited by artisanal miners. Therefore, the electrical resistivity technique confirms its importance in orienting and improving the cost of mining exploration in the above mentioned sites.

The VLF electromagnetic results showed two types of Karous-Hjelt anomalies: the first positive anomaly, with an apparent current density between 30 and 40%, indicated that the prospected areas are affected by a network of faults generally oriented in NE-SW and NW-SE directions. The second negative anomaly, with an apparent current density between -30 and -40%, revealed the presence of mineralized veins.

The results also showed that the coupling of electrical resistivity and electromagnetic methods has confirmed its efficiency in the mining exploration.

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