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Electromagnetic survey to constraints ore mining exploration in the South-East of Saghro inlier (Eastern Anti-Atlas, Morocco): application of frequency electromagnetic helicopter-borne method.

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Abstract

The Saghro Massif is considered strategic as it contains several localities with high mining indices. The Iknioen area was chosen in the present work due to its geological characteristics and pre-Cambrian dominant terrain. As well as numerous abandoned mines. To address this problem, an exploration approach based on geophysical methods is required. Geophysics occupies a crucial role in various earth exploration applications. In this paper, we typically utilize the process of pseudo-layer half-space, to determine apparent resistivity from the available electromagnetic (EM) datasets. The DIGHEMv multi-coil, multi-frequency helicopter-borne electromagnetic system was used in a geophysical study carried out southeast of the Saghro inlier. The results revealed three conductor axes, and two significant electromagnetic anomalies in the area, interpreted as indicative of metallic deposits in the subsurface. The most distinct electromagnetic anomalies were detected in the north, center, and southeast parts of the research region. Which were all previously unmined and strongly influenced by secondary faults with coverage of Ediacaran volcanic rocks. Given the established relationship between mineralization and faulting; where the degree of the anomaly is directly correlated with the amount of ore present in the hosted rocks; This location is especially worth exploring.

Keywords: Electromagnetic data, Iknioen, Apparent resistivity, Anti-Atlas, Morocco.

1. Introduction

Airborne geophysical approaches have been used more and more over the last decades, in large-scale subsurface surveys to study vast areas affordably and quickly. Magnetics, radiometric, and electromagnetism are now the most widely used in flight techniques [1, 2]. Furthermore, airborne surveys are able to provide spatial data sets, which could be linked to other spatial data sets. For example, displaying airborne geophysical results with respect to high-resolution elevation models enables us to link surface data with spatial geophysical data from the subsurface.

Because electrical conductivity depends on both the mineralization and the composition of the rock, aerial electromagnetic is a good tool for gathering data on subsurface content [3]· One

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of the main instruments of mining exploration is the frequency-domain electromagnetic system carried by a helicopter, which is used to investigate mineral reserves [4, 5]· These technologies are utilized to thoroughly examine near-surface mineralization occurrences, especially in inhabited and rugged regions· Usually, the measured variables, the secondary magnetic fields, are inverted into resistivity-depth models to indicate the subsurface conductivity distribution· The skin effect means that the penetration depths of electromagnetic fields vary according on the properties of the system; the deeper portions of the conducting subsurface are indicated by low-frequency data, while the shallower portions are described by high-frequency data· Normal maximum [3, 6, 7]

One of the primary metallogenic provinces in the Moroccan Anti-Atlas area is covered by this survey. specifically focusing on the Precambrian basement and its Palaeozoic cover in the south-eastern part of the Saghro massif[8-17]. The Ikniouen region was selected because of its attractive geological features that support the presence of mineralization deposits of both base and precious ore· Additionally, it has a number of mineral occurrences, which represent Morocco's primary natural mineral resource· Over the past ten years, the Saghro inlier has been the focus of numerous investigations due to the resurgence of interest in Pan-African metallogenic[13], [14], [15], [16], [18],[19]. In order to find further mineral resources in this area, the Moroccan Ministry of Energy and Mines, which is responsible, carried out a geophysical survey in 1999 using a helicopter and a number of techniques, including frequency electromagnetic (EM)·

The study aims to interpret the EM data to ascertain the physical parameters of the basement formations. In particular, correlate the results with the geology of the area after measuring the electrical conductivity. The ultimate goal is to create a model that connects geology, electromagnetic responses, and mining data ~~together~~. Additionally, use this model to locate potentially mineralized zones in the area for future investigation. The results could provide new geological information that can be used to direct field studies to areas where there is a higher probability of mineralization.

2. Geological setting:

The Anti-Atlas is part of the Pan-African Orogenic Belt. It extends over 750 km along a WSW-ENE direction from the Atlantic, where it reaches the Zemmour chain, to the Tafilalet. The Chain is bordered to the south by the carboniferous basin of Tindouf. To the North, it is materialized by a major tectonic lineage called the South Atlasic Fault (Figure 1). This structure extends from Gabes (Tunisia) to Agadir and continues to the sea through the Kelvin fault[19]. The chain is subdivided into three unequal parts[20]:

- The Western Anti-Atlas extends from the Atlantic Ocean to the Massif of Siroua; it mainly contains the Kerdous and Ifni formations. (Figure1);
- The Central Anti-Atlas includes the massifs of Siroua, Zenaga, and Bouazzer (Figure1);
- The Eastern Anti-Atlas includes the Saghro and Ougnat massifs (Figure1).

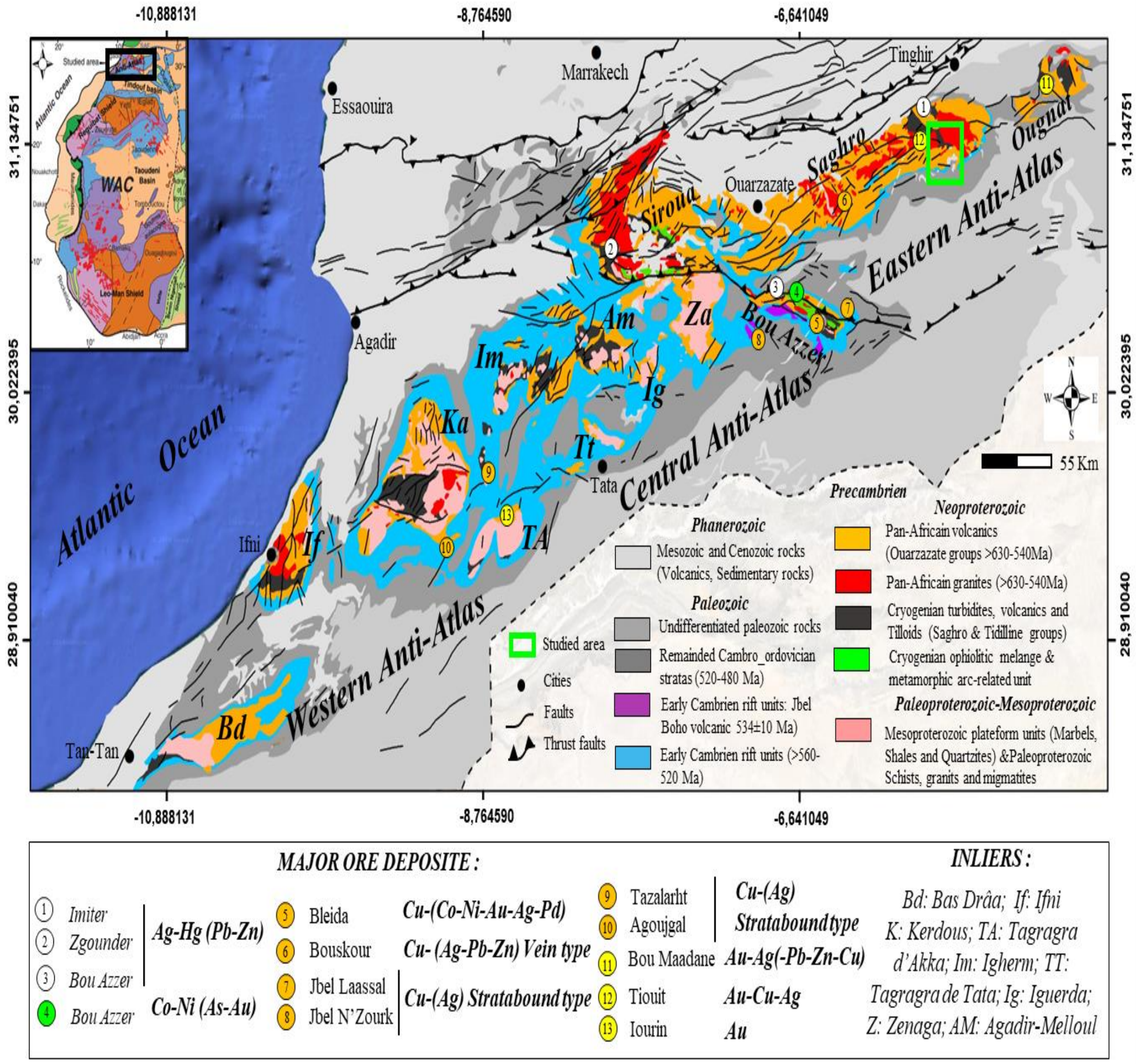

Figure 1 : Main geological units and major mining districts of the Moroccan Anti-Atlas belt [21][18, 22, 23].

2.1 Regional Geological Framework

The Moroccan Anti-Atlas was the seat of orogenesis, which relates to the Paleoproterozoic, Neoproterozoic, and Paleozoic periods, respectively[24]. The Proterozoic lands flourish in the form of erosion buttons under the cover of the Paleozoic (Figure 1). This chain is subdivided into three structural areas[25].

The Jbel Saghro Massif, which spans about 4000 km2, is stretched in the direction of ENE-WSW (Figure 1). [26, 27][13, 28, 29]. During the Pan-African Orogeny, Jbel Saghro was impacted by a series of subduction and collision events[30]. A significant deformation that is ascribed to the Pan-African orogeny [31, 32] affects the lower Cryogenian terrains and results in NE-SW-oriented folds and faults that run in the same direction. The E-W fault at ENE-WSW and the NW-SE-oriented folds were created during a second tectonic activity of the same age that also impacted the lower and upper Cryogenian lands[32],[33] , [34] The Jbel Saghro Massif is composed of Cryogenian formations flourishing at the heart of the boutonniere. According to four sectors are defined as smaller-sized buttonholes, surrounded by thick formations of the terminal Precambrian and/or the Adodounian. From west to east, we distingue (Figure 1): Sidi Flah BouSkour, Kelâa M'Gouna, Boumalne, and Imiter[13]. As in the Saghro domain, all the Neoproterozoic formations in the study area were affected by tectonic movements of the Precambrian orogeny (Pan-African orogenesis). It affects the Precambrian formations through brittle tectonics with the Hercynian orogenesis[23], [24], [25],[35].

The Iknioouen zone is situated southeast of the Boumalne boutonnière (Figure 1)[36]. These most ancient Cryogenian-age terrains are composed of a series of sedimentary sandstones and shales[37], intruded by highly potassic granitoïdes of Iknioouen and charnockite or granite of Oussilkane[12]. And covered essentially in major discordance by the rocks of rhyolites, andesite, and ignimbrites [36] (Figure 2). The Iknioouen area is known for the presence of Neoproterozoic terrains, part of the Saghro group, and the Ouarzazate series (Figure 2), which were affected by the Pan-African and Hercynian orogenesis.

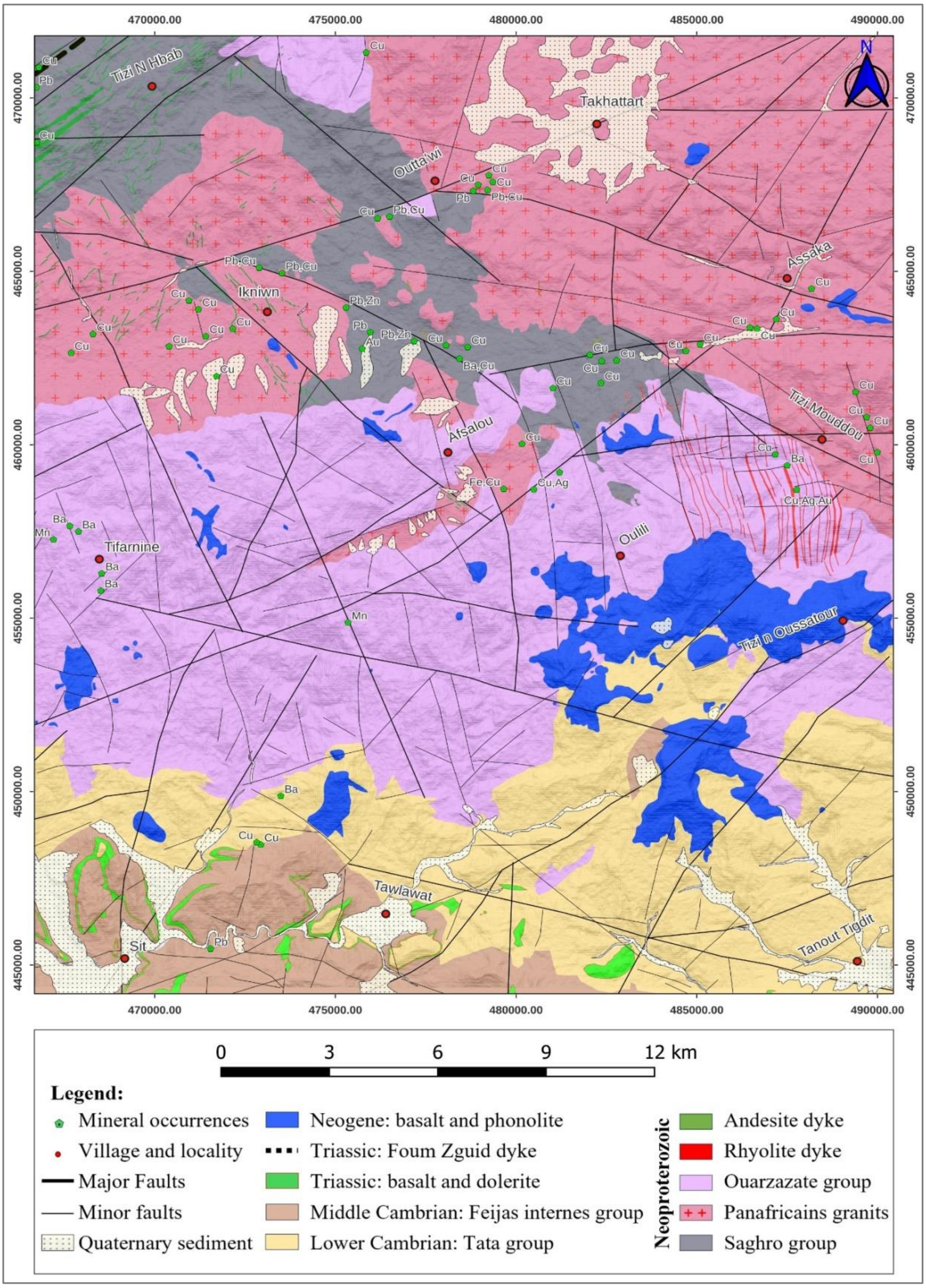

Figure 2 : Geological map of the study area, simplified from Ikniouen geological map Scale 1/50000 [38]

3. Data sets and methods:

3.1 Survey Systems: HEM system

Modern frequency-domain airborne electromagnetic systems utilize a number of (4–6) small transmitters and receiver coils having a diameter of about half a meter. The primary magnetic field is generated by a sinusoidal current flowing through a transmitter coil at a discrete frequency. The eddy currents induced in the subsurface by the primary field generate a secondary magnetic field depending on the conductivity distribution (Figure 3).

A DIGHEMV multi-coil, the multi-frequency helicopter-borne electromagnetic system made by Geoterrex was used by CGG Geoterrex in 1999 to collect the electromagnetic data for this survey· The Moroccan Ministry of Transition, Energy, and Sustainable Development donated the EM data used in this study· The Heli-ported Geophysics Companion Project covered the Saghro massif (eastern Anti-Atlas) in both the Anti-Atlas and the High Atlas· The bird measured thirty meters in height and flew at a height of sixty meters· The study area was well-covered by the network that was used, therefore flight lines were flown in a NW-SE direction with a 500 m· line separation·

The DIGHEMv geophysical system, the helicopter electromagnetic system, the function analysis, and the resistivity calculation of the electric parameters
The system's ~~brief~~ summary is given in the lines that follow:
900, 1000, 5500, 7200, and 56000 Hz are the frequencies·
Coil orientations: 3 × horizontal coplanar, 2 × vertical coaxial
Dipolar moment at 900 Hz: 225 ampere-turns/m2·
Frequency of sampling: 3 m/10 Hz
Bird height: thirty meters
Parts per million (ppm) represents the measured characteristics for the in-phase and quadrature components· Electromagnetic data were collected using a DIGHEMv magnetic system measuring the components in phase and quadrature at five frequencies with two coaxial coils and three coplanar coils.

The raw data is recorded in digital form with a step of one measure per second and is automatically corrected at the base by adjusting the phase and quadrature channels to zero level, determined by high-intensity views about three times per hour. This information is then processed digitally at a rate of 10 samples per second in order to eliminate spherical and all other residual noises.

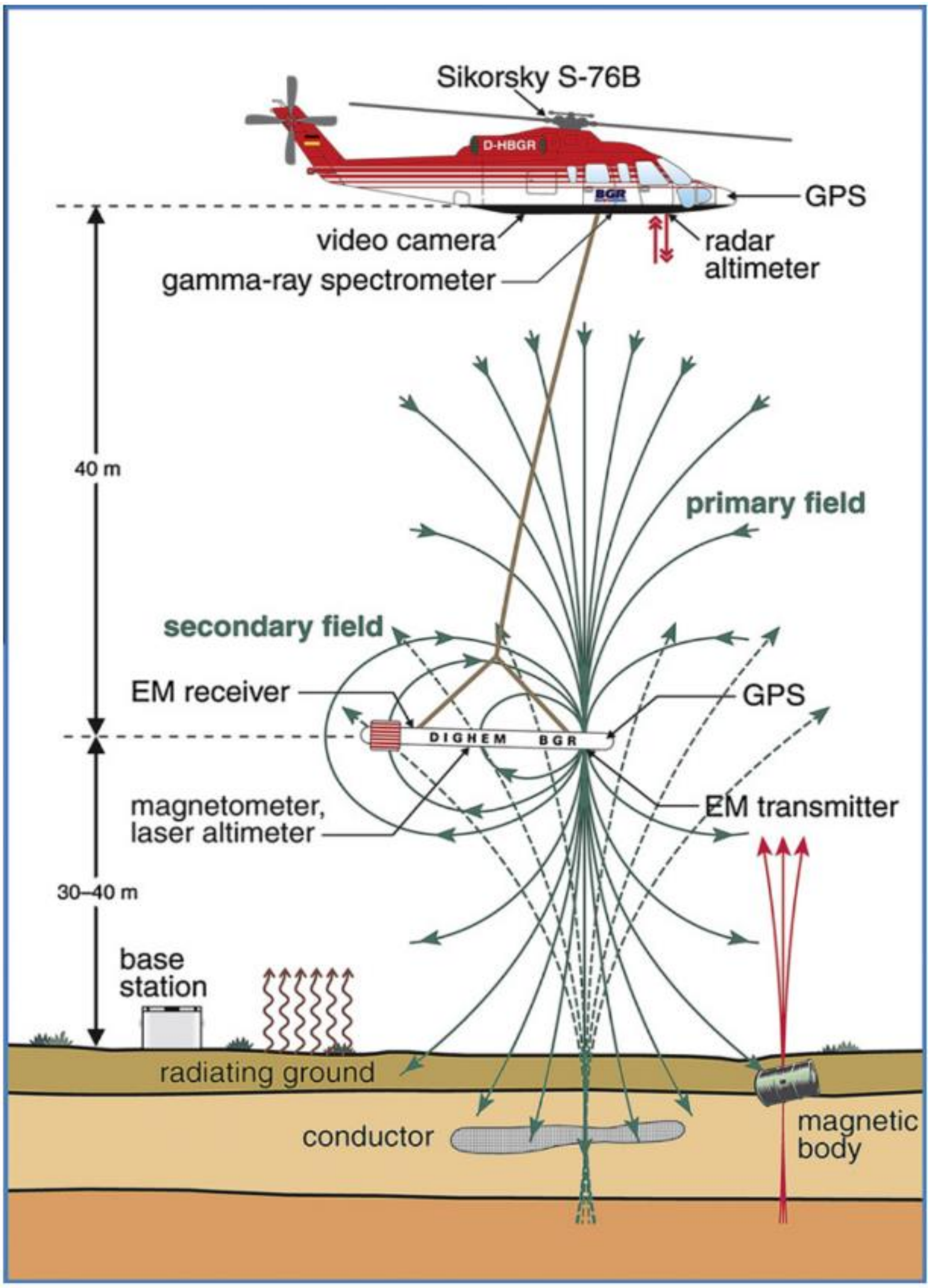

Figure 3 : Sketch of BGR's frequency domain helicopter-borne electromagnetic system. [7]

The values of apparent resistivity, in ohm-m, were calculated from the data of the phase and quadrature electromagnetic components of the coplanar coils and using a pseudo-layer half-space model (Figure 4).
Resistivity values were interpreted on a 125-meter-square mesh grid.

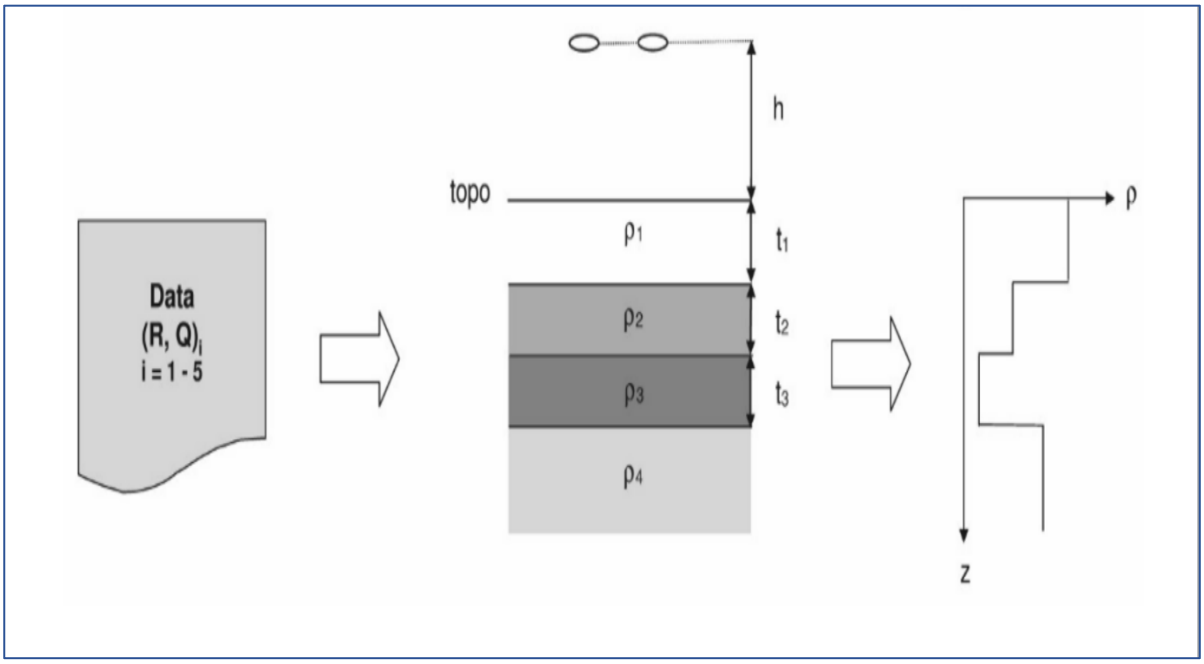

Figure 4 : Half layer model[39].

In such high-frequency regions, anomalous skin effects become significant. Which is considered a complex of size effect and skin effect. The size effect is a phenomenon in which the resistivity of a conductor depends on its size when the conductor size becomes comparable to the mean free path of the electrons[40], [41] (Figure 5). The skin effect is a phenomenon that causes current flow to concentrate on the surface of the conductor when the frequency becomes high. As frequency becomes higher, skin depth becomes smaller. When skin depth becomes as small as the mean free path of the electron, the effective resistivity depends on the skin depth due to the size effect. This complex effect is called the anomalous skin effect (ASE)[42], [43] . It is said that the size effect becomes significant when the conductor size becomes smaller than fivefold of the mean free path of the electron. At room temperature, the mean free path of an electron in copper is about 40 nm. Skin depth reaches 200 nm at about 140 GHz. Therefore, it is predicted that ASE may become significant around 140 GHz. However, it is not clear how serious ASE is because quantitative evaluation is difficult. In an anomalous region, the effective resistivity depends on skin depth, and skin depth is affected by the effective resistivity. Thus, it is difficult to evaluate ASE using existing field solvers. [44][45]. Effective skin depth due to a grounded wire source depends on frequency, offset, conductivity, and field components (Figure 4).

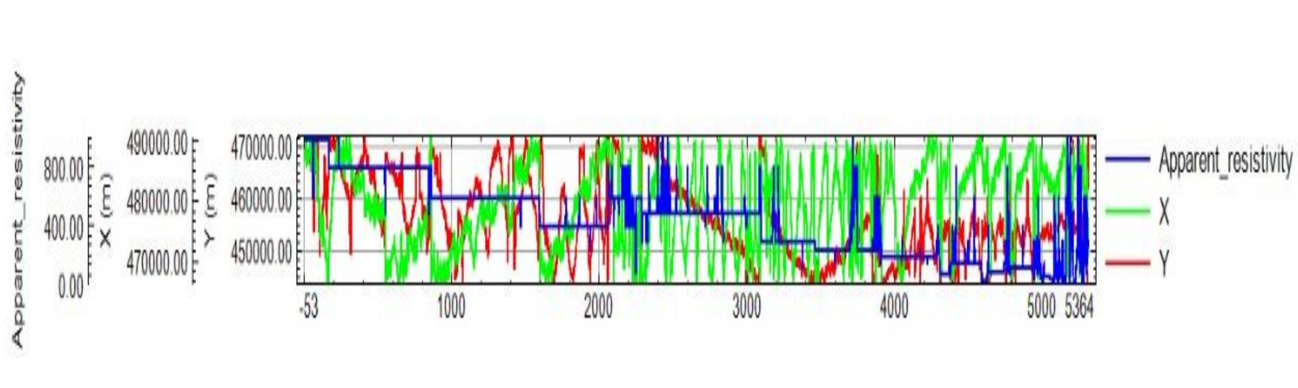

Figure 5 : Apparent resistivity profile depth

4. Results and discussion:

We have organized the results into two main visual representations· Firstly, we present a coloured map showing the apparent resistivity identified from the coplanar electromagnetic data (EM). This map reveals differentiation in apparent resistivity across the area and includes an interpretation of these modifications, particularly in terms of conductor bodies and resistive axes (Figure 6). Secondly, we provide a profile map displaying the in-phase and quadrature components of complementary coaxial frequency pairs. These components are represented as coloured profiles that run along the flight path (Figure 7). The map pinpoints the locations of significant electromagnetic anomalies.

In our study area, the distribution of apparent resistivity shows two distinct sections separated by a line with varying directions ranging from East-West to Northeast-Southwest· A region of rather high resistivity values, spanning from 500 ohms·m· to over 900 ohms·m·, is seen to the north ·This sector displays resistive axes that trend north-easterly to easterly· However, a zone with low resistivity values between 100 and 500 ohm.m· to the south indicates that resistive axes that tend north-easterly are more prevalent· (Figure 6).

We identify minor patches, similar to those of the southern zone, with low resistivity values within the northern high-resistivity sector· They are distributed throughout three districts and correlate to conductor bodies that exhibit trending directions that are similar to those of the resistive axis(Figure 8): The north area (Z7 and Z8 on the map) corresponds to the Oussilkane and Aqqa Granites· The central zone (Z1, Z2, Z3, Z4, Z6, and Z9 on the map) is related to the lava flows of Jbel Al'Assa and Yadawdane, along with a part of the Ikniouen Granite. A SW sector (Z5 on the map) corresponds to the lava flows in Tigoulzatine and Amtattouch reliefs and their surrounding region. The northern area is marked by four small conductor bodies with a big one, all oriented NE-SW, while the central area is characterized by five conductor bodies with an E-W trend· Lastly, the SW is characterized by six roughly N-S-striking conductor bodies (Figure 9).

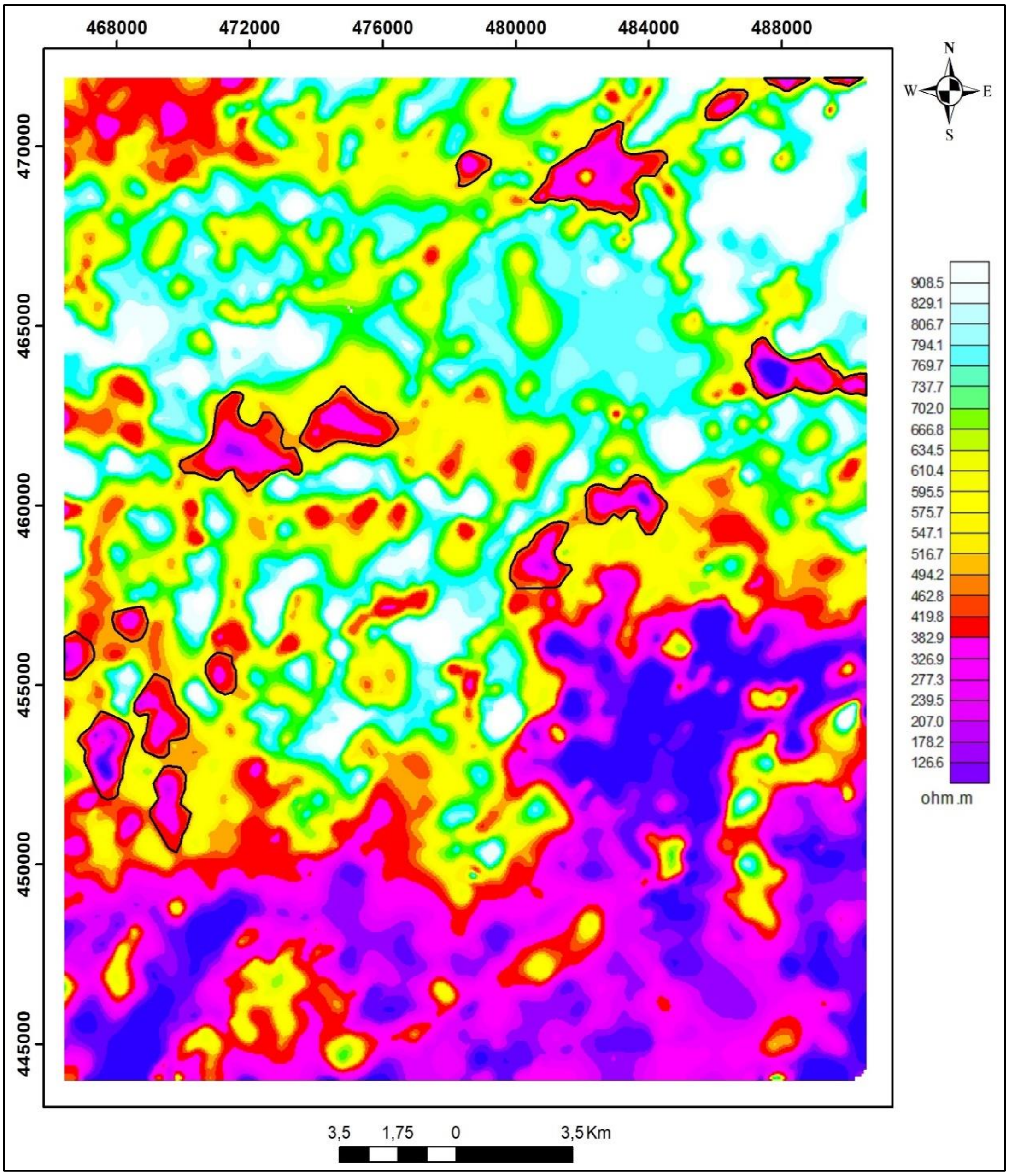

Figure 6 : Apparent resistivity map of the study area.

There are all EM anomaly grades present in the study area (Figure 7). The less common anomalies are those of order 2. On the other hand, order 6 and 7 anomalies are the most prevalent. This suggests that the research area is typical in having both good and weak conductor zones·

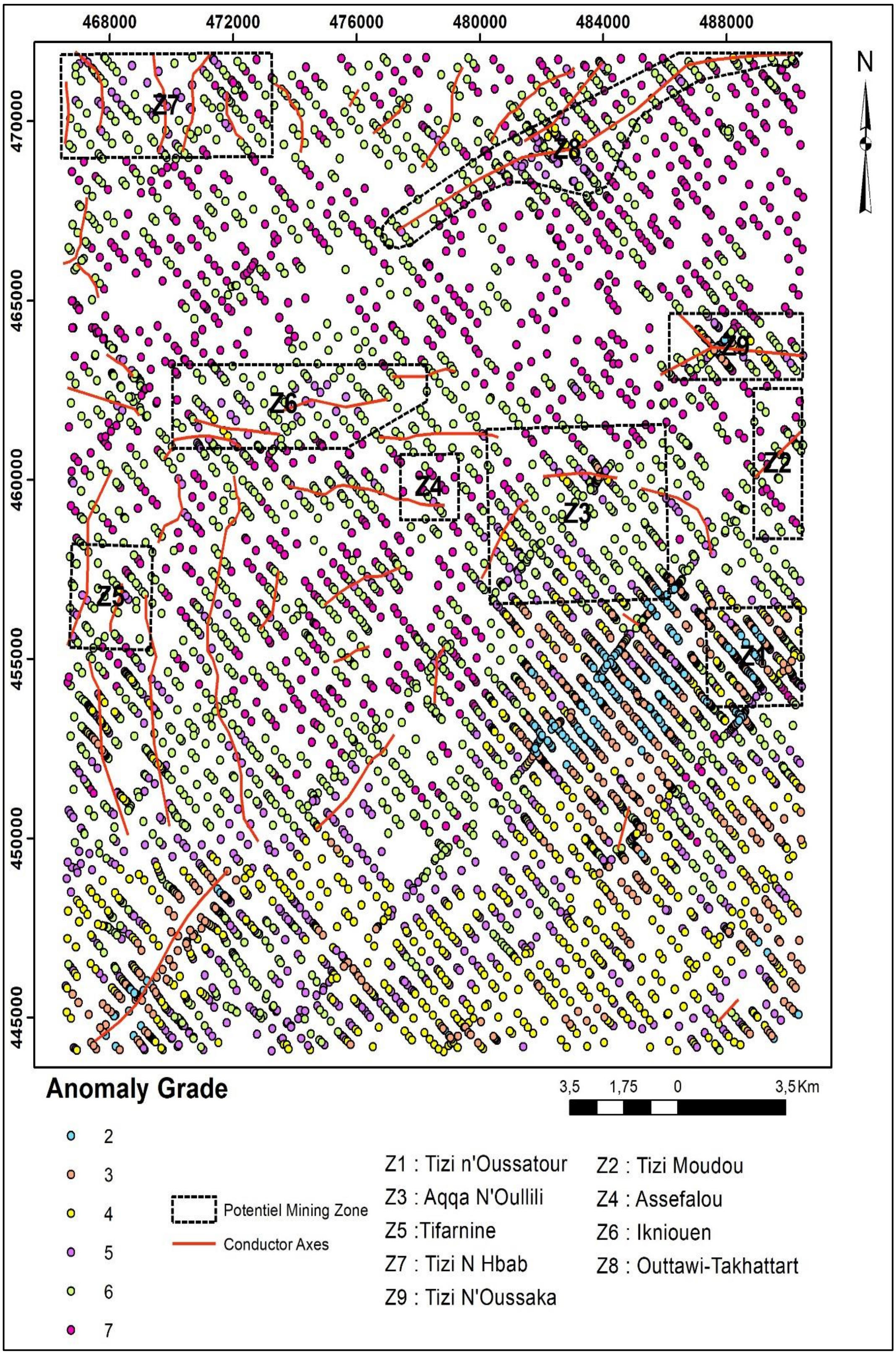

Figure 7 : Electromagnetic anomalies map of the study area picked from the in-phase and quadrature coaxial profiles.

The analysis of the EM anomalies map allows us to draw various conductor axes that strike in the same N-S, NE-SW, and E-W directions as the resistive axes (figure 7).

The N-S trending:

It appears in the western part of the study area (Z7 and Z5), with a significant number of EM anomalies with high conductance values that can reach 100S (grade 5 to grade 7).

The NE-SW trending:

Shows in the southwest to the northeast of the study area (Z8) and in the east (Z2); it is characterized by an EM response more in-phase than quadrature, which reflects the presence of good conductors, with conductance values that exceed 100 S (grades 6 and 7).

The E-W trending:

involved in the central section (Z3, Z6, and Z9). This area is characterized by a significant number of EM anomalies with conductance values varying from 1 S (grade 2) to more than 50 S (grades 5 and 6).

Figure 7 shows that most of these anomalies are due to an EM response more in-phase than quadrature, which reflects the presence of good conductors with conductance values. Except for a few profiles where the quadrature response is greater.

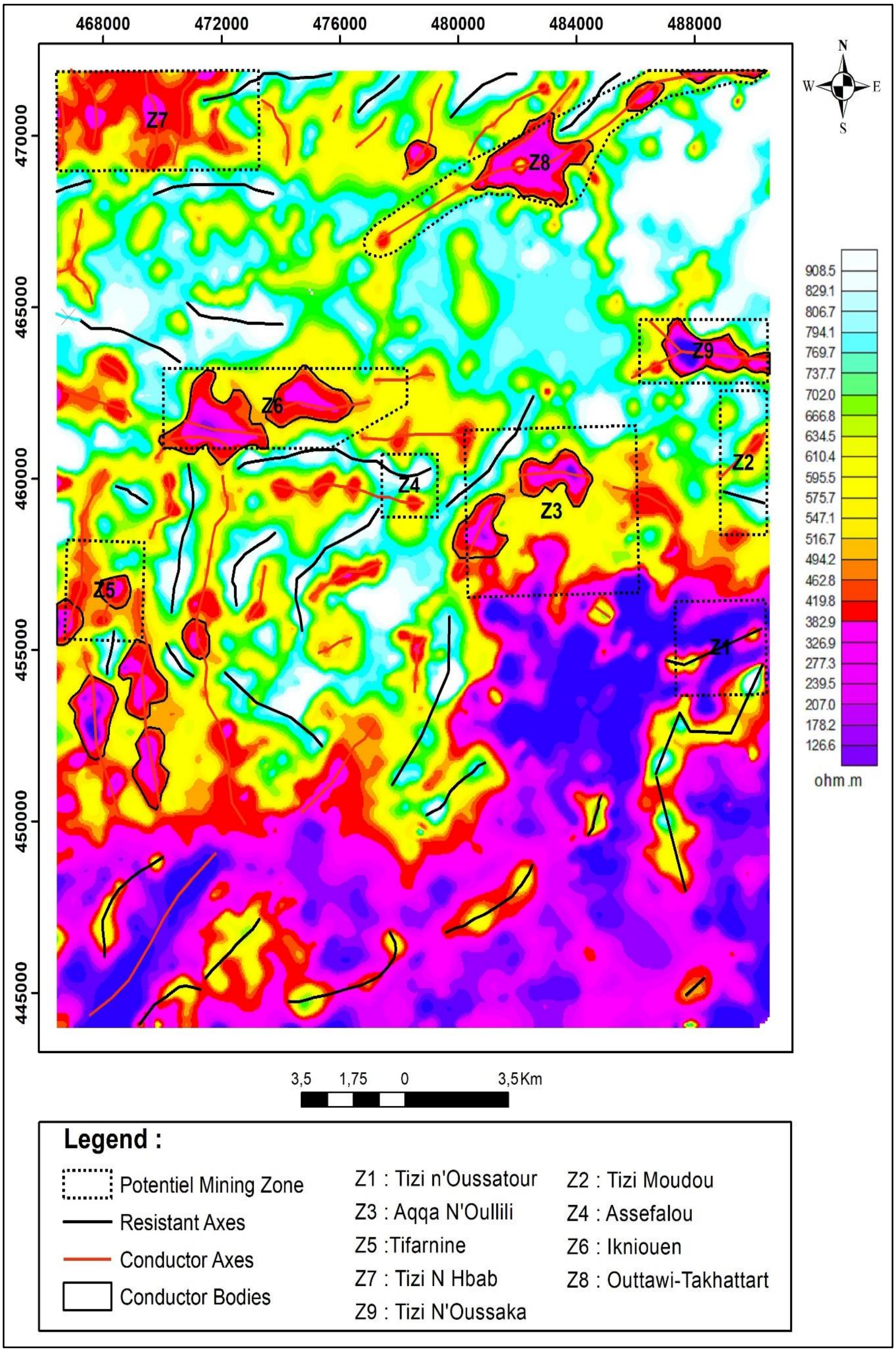

Figure 8 : Interpreted the Apparent resistivity map of the study area.

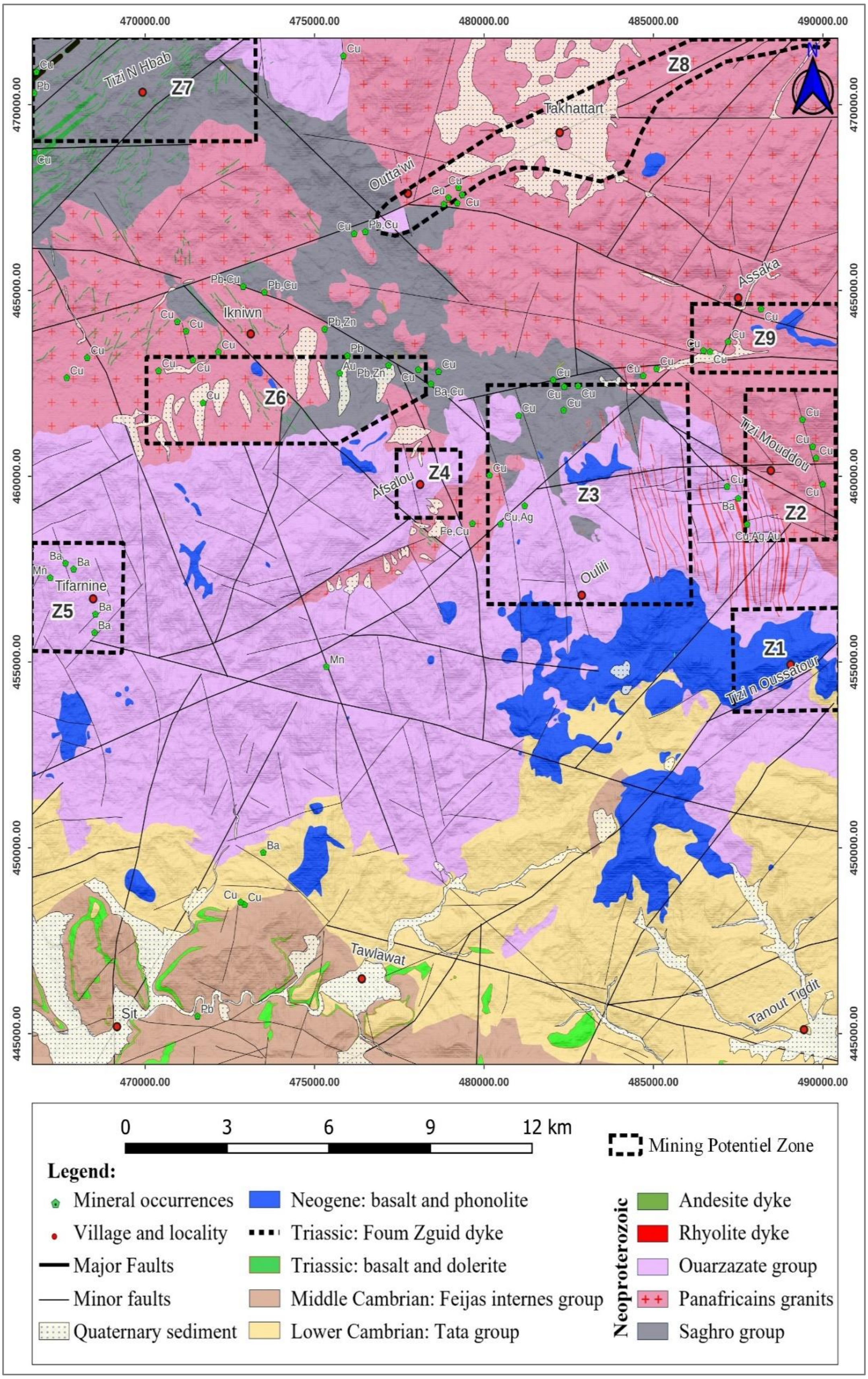

Figure 9 : The mining potential zone superimposed on the geological map of the Southeast of Saghro inlier (After Iknioüen 1/50 000 geological map).

By interpreting the above-mentioned geophysical results within the context of regional geological settings and correlating them with the electromagnetic responses, we can ultimately identify the geological parameters influencing mineralization in the Iknioüen district and identify potentially mineralized zones. The final mineral potential map (Figure 9) displays nine anticipated and noteworthy potentially mineralized zones: Z1 to Z9
The geological description of the mining zones:

Tizi n'Ousatour (Z1):

This zone is situated in the east of the study area, and it is characterized by a high resistivity anomaly associated with tuffs, rhyolites, and andesite of the Ouarzazate group (Ediacaran). The potential for minerals in the Tizi N'Ousatour sector is indeed controlled by an NNW-SSE trending fault system. The mineralization is observed in veins with a mineral paragenesis of bornites and chalcopyrite, suggesting that this area is a significant target for exploring both precious and base mineralization types, genetically related to the Ediacaran volcanic rocks of the Ouarzazate group.

Tizi Moudou (Z2):

This area is located to the north of the potential mining zone of the Tizi N'Ousatour region· Volcano-clastic rocks of the upper Ediacaran outcrop in this area, formed by rhyolite and ignimbrites, are affected by a WSW-ENE trending fault system. Tizi N. Moudou exhibits high mining potential, with mineralization occurring in veins and stockwerk, featuring a paragenesis of chalcosine, bornites, malachite, azurite, copper, and silver.

Aqqa N'Oullili (Z3):

The Akka N'oullili region provides a notable example of mineralized NW-SE directional trends with a considerable extent of mining threads, demonstrating significance that cannot be overlooked· In this area, a black patina quartz breach enclosed in the Bougafer monzogranites can be traced. This feature is associated with prominent grinding sectors, exhibiting a similar discontinuity characteristic as observed in E-W faults. The region serves as a dense reservoir of thin siliceous veins, showcasing a remarkable development of chlorite on the surfaces. Additionally, there are occurrences of accidents with quartz-filled vertical trains· The cutting area is covered by important chaplet-cupriferous indices.

The Aqqa N'Oullili potential zone emerges as a crucial target for exploration, particularly for the Ag-Hg Imiter mineralization type. This mineralization is known to outcrop in the Cryogenian Saghro massif and is genetically linked to the late Neoproterozoic volcanic rocks of the Ouarzazate group.

Assefalou (Z4):

The Assefalou mining potential zone is located approximately ten kilometers west of the Akka N'oullili area. It is spatially associated with the Rhyolite volcanic rocks of the Ouarzazate group and the Bougafer granite intrusion. This sector demonstrates significant mining potential, with mineralization predominantly comprising chalcopyrite, azurite, malachite, silver, and copper.

Tifarnine (Z5):

Situated in the western part of the study area· Associated with volcanic rocks of the Ouarzazate group. Tifarnine is composed of porphyric andesite, alkaline rhyolites, tufs, and conglomerates. These formations have been impacted by NE-SW faults, resulting in barite and manganeseiferous mineralization· These fault systems seem to relate to earlier volcanic activities.

Iknioueen (Z6):

Significant mining zones showcase diverse mineralization, including copper, gold, zinc, and lead. It is situated in the Iknioueen district; as the name implies, this area is comprised of ancient lands from the lower Cryogenian age, invaded by highly potassium-rich granitoïdes of Iknioueen and charnockite or granite of Oussilkane.

Tizi n Hbab (Z7):

Tizi N. Hbab is situated in the northern mining zone of the study area· It features clay grounds approximately ten meters thick, intercalated with a set of rhyolite or andesite dykes· From a mining potential perspective, the presence of copper and lead has been noted.

Outtawi-Takhattart (Z8):

This potential mining zone is located in the northeastern part of the studied area· Outtawi-Takhattart assumes an elongated form. It is affected by major structural faults oriented NE-SW. Based on our field observations, the mineralization in this area typically comprises copper and lead associated with ferric oxides. It is identified in the Oussilkane granite.

Tizi N'Oussaka (Z9):

Situated in the eastern part of the study area, Tizi N'Oussaka is formed by rhyolitic and Andesite terrains along rivers. E-W dropouts likely represent the primary manifestations of the Assaka shear zone, associated with an N-S fault. The mineralized infill is notably cupriferous, making it potentially significant from a mining perspective.

Mineralization:

The Iknioueen prospecting region reveals promising indications of polymetallic mineralization targets, with a specific focus on Au, Ag, and Cu· These targets are primarily associated with the interface between the Iknioueen prospecting region, which reveals promising indications of polymetallic mineralization targets with a specific focus on Au-Ag-Cu. These targets are primarily associated with the interface between the Neoproterozoic basement and its Palaeozoic cover. The mineralization is closely linked to ore occurrences within Ediacaran volcanic rocks and the Cryogenian sedimentary rocks of the Saghro Group. Abundant mineralized indices are observed in the Akka N'oullili and Tizi Moudou localities. The most frequently observed minerals, in order of occurrence, include chalcosine and malachite, chalcopyrite and bornites, azurite, and grey copper.

Regarding the connection between mineralized indices and tectonics, copper indices align with the E-W and NE-SW trend faults with vein systems. They are also associated with the N-S to NNE-SSW rhyolitic dykes· Additionally, the potential mining target in the Iknioueen area is notably linked to a zone of structural complexity, with a focus on the N-S shear zones of the Akka N'oullili area.

Lithologically, it is observed that quartz has a crucial function in hosting copper sulphide mineralization. The investigation conducted in the shear zone of Akka N'oullili indicates that significant lenses are consistently associated with a robust quartz matrix. Tizi Moudou substituted the mineralizing compound with a string of quartz that was highly oxidized. Conversely, mineralization from EW faults is frequently found in a baryte gang. Among the various rocks in the stratigraphic series, the study of the deposits reveals that certain varieties serve as better hosts for mineralization than others[46].

Consequently, the delineated targets exhibit significant resemblance to the mineralization outcrops found in the Cryogenian sedimentary rocks of the Saghro group and the volcanic rocks of the Ouarzazate group in the Moroccan Anti-Atlas belt [10] [11] [14] [43] [44] [17] [15]. These areas of high prospectivity present favorable conditions for continued prospecting and exploration aimed at discovering ore mineralization deposits within the study area.

5. Conclusion:

The Iknioun prospecting area is considered very favourable for polymetallic mineralization, with emphasis on gold (Au), silver (Ag), and copper (Cu). Mineralization occurs at the boundary between Neoproterozoic basement and Palaeozoic cover, which is closely related to Ediacaran volcanic rocks and Cryogenian sedimentary strata. Akka N'oullili and Tizi Moudou are the basic key locations where some minerals are identified as chalcosine, malachite, and chalcopyrite. Mineralization follows E-W, NE-SW, and N-S trending fault systems related to rhyolite dykes and shear zones. The geophysical survey of the deposit before drilling testing identified nine zones that are mineralized (Z1 to Z9), indicated by large EM anomalies, which will suggest conductive mineralization. The N-S, NE-SW, and E-W trending anomalies each consist of different conductance levels, with the higher peaks corresponding to stronger target indications for mineral potential.

Disclosure and conflict of interest

"The authors declare that they have no conflicts of interest."

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