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MAPPING OF DEEP GEOLOGICAL FORMATIONS WITHIN THE AKAKRO LOCALITY, TOUMODI REGION, CENTRAL CÔTE D'IVOIRE - WEST AFRICA

Konan Roger ASSIE [1*], Kouamelan Serge KOUAMELAN [2], N'Guessan Eric YAO [1] et Eric Thompson BRANTSON [3]

[1] *Université Jean Lorougnon Guédé, UFR-Environnement, Department des Sciences de la terre, Laboratoire de Géologie Appliquée, BP 150 Daloa, Côte d'Ivoire*
[2] *Université Felix Houphouët-Boigny, UFR des Sciences de la Terre et des Ressources Minières, Laboratoire de Géologie, Ressources Minérales et Energétiques, 22 BP 582 Abidjan 22, Côte d'Ivoire*
[3] *University of Mines and Technology, School of Petroleum Studies, Department Petroleum and Natural Gas Engineering, Tarkwa*

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* Correspondance, e-mail : *krogerassie@gmail.com*

ABSTRACT

This study aims to improve our knowledge of the subsurface geology, and to create a comprehensive geological framework to highlight potential opportunities in the region. It involved analyzing the electrical and magnetic parameters of the subsurface formations, comparing dipole-dipole electrical resistivity and Schlumberger borehole data with magnetic data, and then determining the level of alteration by means of conductive and resistant anomalies. The results reveal that the area is characterized by resistant anomalies and a high magnetic field of felsic formations, extending over a total area of 85.56 ha and covered by a thick layer of alteration averaging 15 m in depth. These formations span the entirety of the eastern portion of the study area, and isolated areas situated to the west and southwest. A major network of fractures running NE-SW and NNE-SSW was highlighted through the analysis of the conductive anomalies. Overall, this study has enabled us to use a geophysical approach to distinguish the spatial distribution of the sound lithological series in the area, the degree of alteration of the series and the related fracture and fault systems, which could serve as a valuable guide for any mineral resource and aggregate exploration activity in the region.

Keywords : *electrical resistivity, Magnetic anomalies, felsic rock, Toumodi region.*

RÉSUMÉ

Cartographie des formations géologiques profondes dans la localité d'Akakro, région de Toumodi, Centre de la Côte d'Ivoire - Afrique de l'ouest

La présente étude vise à améliorer notre connaissance de la géologie du sous-sol, et à créer un cadre géologique complet afin de mettre en évidence les opportunités potentielles dans la région. Elle a consisté à analyser les paramètres électriques et magnétiques des formations du sous-sol, par la comparaison des données de résistivité électrique dipôle-dipôle et des sondages schlumberger aux données magnétiques ensuite déterminer le niveau d'altération au moyen des anomalies conductrices et résistantes. Les résultats révèlent que la zone est caractérisée par des anomalies résistantes et un champ magnétique élevé de formations felsiques, s'étendant sur une superficie totale de 85,56 ha et recouvertes d'une épaisse couche d'altération qui atteint en moyenne 15 m. Ces formations couvrent la totalité de la partie orientale de la zone d'étude, ainsi que des zones isolées situées à l'ouest et au sud-ouest. L'analyse des anomalies conductrices révèle un important réseau de fractures orientées NE-SW et NNE-SSW. Dans l'ensemble, cette étude nous a permis de distinguer par une approche géophysique, la distribution spatiale des séries lithologiques saines de la zone, le degré d'altération des roches et les systèmes de fractures et décrochements qui leur sont relatifs ce qui pourrait servir de guide pour toute activité d'exploration de ressources minérales et de recherche de granulats dans la région.

Mots-clés : *résistivité électrique, anomalies magnétiques, roche felsique, région de Toumodi.*

I - INTRODUCTION

The advancement of Côte d'Ivoire necessitates the use of more aggregates to construct significant economic infrastructures. The national production of crushed granite has been estimated to have reached 1.46 million tonnes over the past decade, and demand for granite is still growing. This has led to increased interest in finding sites that have high potential for granitic minerals in the region. The largest proportion of birimian formations in Côte d'Ivoire, around 35 %, are found within volcanosedimentary trenches consisting mainly of granitoids, thereby offering significant potential for aggregates [1]. The Toumodi region area has attracted a great interest in the search for both materials and mineral resources, with a growing number of local research projects of petrographic, geochemical, and even geomorphological nature [2 - 4]. Several of these studies focused on a few rare outcrops that are difficult to access due to thick vegetation cover and intense weathering that can reach depths of 30 to 50 m. These studies, mostly dealt with the southern sector of the region, have highlighted the presence of intense volcanic activity that has given rise to mafic volcanic to felsic volcanic complexes [5, 6]. They also revealed zones of contact metamorphism around volcanic rock intrusions. Petrographic and geochemical analyses have identified andesitic to basaltic rocks, metamorphic rocks derived from the upwelling of andesitic to basaltic lavas [6]. A recent geological study defined three (03) lithostratigraphic groups in the Toumodi region, namely the Kan river group, the Toumodi volcanites and the S-type intrusive granitoids [7]. His results shown that the lithology of the Kan Group is marked by granitoids, orthogneisses and amphibolites. He also emphasized that the Toumodi volcanic groups are nothing more than volcanosediments associated with pillow-lava. Later, a geological map of the Dimbokro sheet following a synthesis of geological information identified the Kan granitoids and the Toumodi granodiorite as intrusions [8]. A field survey within the locality of Anikro, revealed that the polygenic conglomeratic formations originate from granitoid pebbles and volcanoclastites with a predominance of felsic and mafic volcanites [9]. The results of the published works on the petrography and structural evolution of the Anikro syncline in the Toumodi region showed that the Anikro conglomeratic formations are hosted in Rhyolite and Dacite units forming a complex. They also indicated that this complex is affected by several NNW - SSE-striking fractures [10].

The geochemistry of these volcanics in the Akakro-Anikro area using a petrogenetic and tectonic approach [11]. In their view, this sector is a mixture of predominantly felsic volcanics that have long been subjected to intense alteration processes. All these studies were based on superficial observations of certain major outcrops, generally covered by cuirass in places. But what about the deeper formations? Does of the septentrional part of the Fettékro sillon contain large quantities of felsic rock? And what is the exact distribution of the felsic and mafic formations that make up the volcanics in this part of the sillon so often discussed by these authors? To provide an answer, we undertook a geophysical study of a magnetic and electrical nature in the area. Geophysical approaches are a robust and efficient tool for surveying geological information in deepest weathering area where direct field observations are impossible [12, 13]. They enable to understand the distribution, properties, and characteristics of deep felsic rocks in the region [14, 15]. This information can be valuable for various purposes, such as geological mapping, resource exploration [16], and environmental assessments [17]. The main objective of this study is to enhance our knowledge of the subsurface geology and unlock potential opportunities in the area. This research can contribute to creating a comprehensive geological framework for the region, and ensuring the sustainable utilization of the geological resources.

II - METHODOLOGY

II-1. Study site

II-1-1. Location

Our study region lies between longitudes 4° and 5° W, and latitudes 6° and 7° N. It is bordered to the north and south by the District of Yamoussoukro and the Agneby-Tiassa region respectively. This region, which covers our study area, also shares borders with the N'Zi region to the east and the Gôh region to the west. Our study site, Akakro, is accessible by road and is located 15 km from Toumodi, 30 km from Yamoussoukro and 200 km from Abidjan.

II-1-2. Regional and local geology context

The geological context of Côte d'Ivoire is part of the history of the West African craton, which outcrops in three unevenly distributed sectors ***(Figure 1a)***. Côte d'Ivoire belongs singularly to the Man ridge and is essentially characterized by two major distinct geological units: on the one hand, a narrow coastal basin occupying 2.5 % of the territory and made up of sedimentary formations of secondary-quaternary age, and on the other, a Precambrian basement subdivided into two domains of different formations separated by the north-south trending Sassandra fault [18]. These two main domains are the Archean and the Paleoproterozoic domain ***(Figure 1b)***. The Archean domain, also known as the Kénéma-Man domain, lies to the west of the Sassandra fault. The geological formations of this domain were structured during two megacycles: the Leonian, dated between 3500 and 2900 Ma, and the Liberian, dated between 2900 and 2500 Ma [19]. The degree of metamorphism affecting the formations is meso to catazonal [20]. The Paleoproterozoic domain, also known as the Baoulé-Mossi domain, lies to the east of the Sassandra fault. It is made up of Paleoproterozoic formations structured during the Eburnaean megacycle and dated at 2500 - 1600 Ma [2].

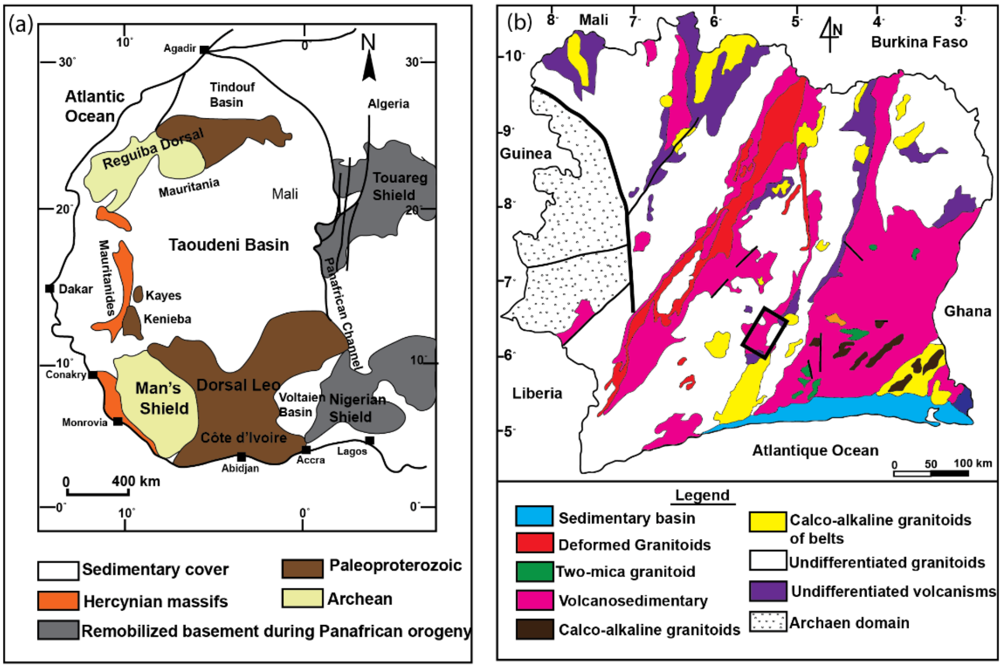

Figure 1 : *Geological context maps of the study. (a) West African craton map the main subdivisions of geological domains and the location of Côte d'Ivoire, b) geological map of Côte d'Ivoire, the rectangle denotes the study region*

The Toumodi region is represented by the geology of the Toumodi-Fettékro sillon. This central part of the sillon reveals granitic zones, metamorphic units associated with volcanic intrusions, and certain sedimentary deposits in the Bandama N'Zi and Kan valleys. The granitic zone is a vast region of plutonites of Lower Proterozoic age including two-mica granitoids and homogeneous granitoids, within which are granodiorite intrusions such as the Toumodi granodiorite. Associated with the intrusions, the metamorphic units include metasediments, N'Zi schists, and slightly metamorphosed granitic rocks. These NNE-trending volcanic intrusions are birimian age and include basalts, andesites, amphibolites, rhyolites, dacites, and a few isolated basites and ultrabasites. The sedimentary rocks of this region include schist conglomerates, some river deposits, and some lateritic cuirasses covering this part of the sillon. Our study site near Akakro straddles the divided formations between metamorphic units and volcanic intrusions ***(Figure 2)***.

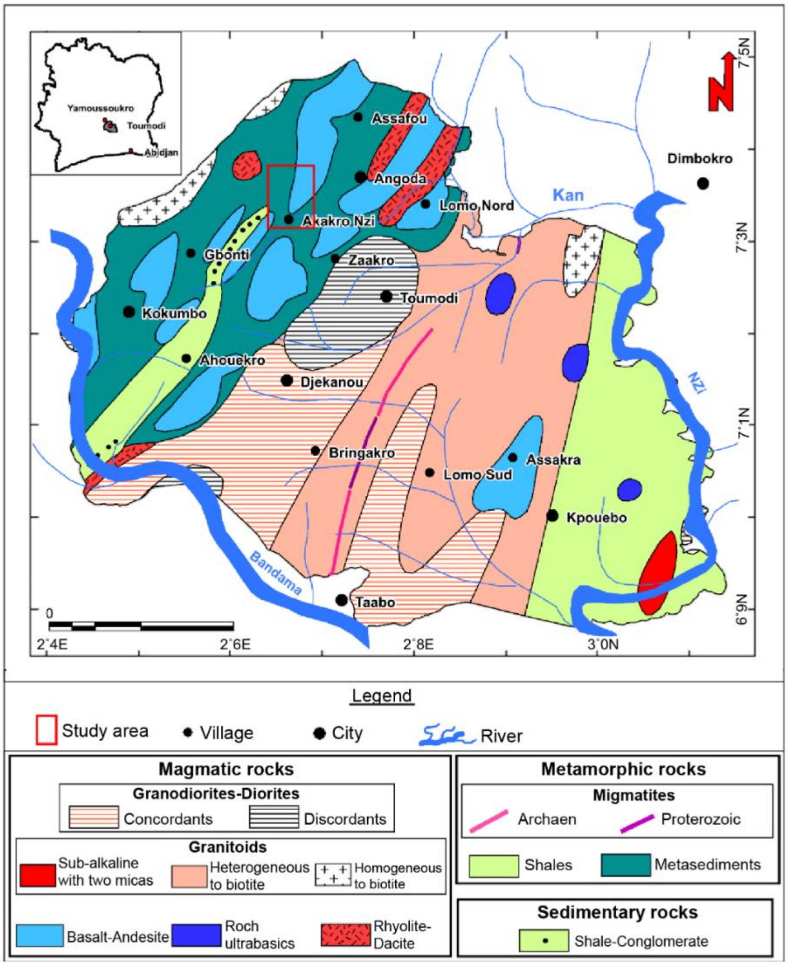

Figure 2 : *Geological map of the Toumodi region*

II-2. Working method

The methodological approach involves firstly a geological survey, followed by a ground magnetic survey and electrical prospecting, and lastly a data processing phase.

II-2-1. Field investigations

This phase consists of a field survey, followed by a direct macroscopic description and sampling of the occasional encountered outcrops. Samples were taken from the outcrops encountered along the transversal lines. The data collected were then used to produce an outcrop map of the study area, using MapInfo software. To ease the measurement process, a baseline was defined following the direction of the birimian formations (NE-SW). The transverse lines were then laid out perpendicular to this baseline (NW-SE), followed by the marking of measurement points. These transverse lines are spaced by 100 m intervals, with a measurement step of 25 m, thus justifying the precision or resolution required. The staking or graduation of our various lines consists in placing wooden stakes at the various measuring points, on which are indicated the line number and the measuring pitch or station (e.g. L200P100 corresponds to stake 100 of line 200) so that they can be easily located during geophysical campaigns. Finally, the last step consists of the GPS surveys.

II-2-2. Magnetic campaign

The ground magnetic survey is the first stage of our geophysical campaign. The principle is to measure the magnetic field using at least two (2) Geometrics G-858SX magnetometers. The first magnetometer is placed in an area free of any metal elements, recording magnetic field values at a fixed point at very short time intervals of milliseconds order, under the supervision of an operator. A second operator uses the second magnetometer to carry out measurements along the transverse paths of the various stations, while ensuring the quality of the recorded values of the sound signal emitted by the device and of the good reception solar radiation to the optical pump sensor.

II-2-3. Electrical survey

The electrical survey focused on two configurations. The first was a dipole-dipole configuration for geoelectrical cross-sections, and the second was a Schlumberger configuration for electrical soundings. The dipole-dipole configuration enables us to obtain the electrical mapping of our study area. The parameters are 25 m for the injection electrodes and the potential electrodes, respectively. We first insert the device parameters into the Elrec-Pro resistivity meter ***(Figure 3a)***, install the injection electrodes in the soil, then connect them to the transmitter ***(Figure 3b)***. Also, we place the seven (7) receiving electrodes at the various measuring stations on the concerned layout, and connect the receiving electrodes to the resistivity meter. After that, we send electrical current into the underground through the injection electrodes using the transmitter-generator system. We check, then the electrical measurements to ensure and define the data being recorded, the measurements of the various pairs of receiving electrodes corresponding to the stakes in our survey area are recorded in the internal memory of the Elrec- Pro resistivity meter ***(Figure 3c)***.

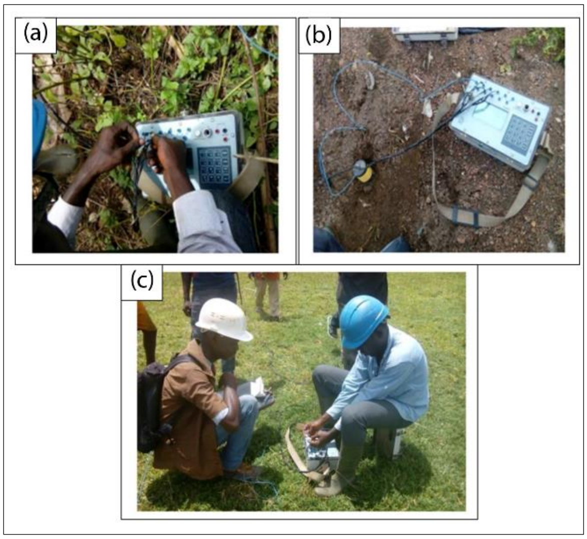

Figure 3 : *Implementation of the electrical of dipole-dipole method. (a) Connection of potential electrodes, (b) resistivimeter configuration, (c) measurement recording*

The Schlumberger type probe aim to establish a cross-section of the vertical distribution of apparent soil resistivities by varying the size of the device. Once the resistive anomaly has been located by the electrical profiling, the standard vertical electrical sounding follows the dipole-dipole method to locate the depth of the explored structures ***(Figure 4)***. In our case, the point of the resistive anomaly or sounding point is the center of the device (Pt O).

Figure 4 : *Implementation of the Schlumberger configuration. (a) device installation, (b) data recording*

II-2-4. Data processing

The raw data from the magnetic and electrical surveys process was carried out exclusively on the computer, using several software packages such us Res2DInv, Prosys II and Geosoft. For the magnetic prospecting, the processing discussed in this study concerns diurnal correction to eliminate daily variations in the magnetic field. This is followed by filters applied with the aim of eliminating the distortion of anomalies caused by inclination. These processes consist of obtaining corrected data to produce total magnetic field (TMF) and magnetic gradient (VG) maps. As regards the electrical prospecting, processing was carried out using Prosys II, Res2DInv and Geosoft software to eliminate negative apparent resistivity values and produce pseudo-section maps and vertical sounding profiles.

III - RESULTS

III-1. Magnetic field map

The results of the magnetic survey presented here are in the form of maps, and concern the TMF map and the VG map. They enable us to identify the major geological units or formations in our study area, as well as their level of alteration.

III-1-1. Total Magnetic Field (TMF)

After reducing the measured magnetic field to the diurnal variations and regional values of the pre-calculated International Geomagnetic Reference Field (IGRF) model, we realize that there are considerable differences between measured and calculated theoretical intensities. Our study site presents three (3) large magnetic clusters of different values, influenced by an inclination of -14° versus a declination of -4° ***(Figure 5a)***. The first set, blue color, is characteristic of low magnetic field values ranging from 30 to 93nT. This set is clearly located at the western and south-western extremities of our study zone. It represents the set of negative anomalies. The second set is represented by warm or vivid colors ranging from yellow to purple. violet through to red. It includes only all high magnetic field values (120 to 150nT). This group covers the entire eastern part of our study area, as well as a few isolated areas to the west and southwest. It constitutes the set of positive magnetic anomalies. Finally, the third group, green to greenish-yellow, comprises average values ranging from 103 to 118nT. Crossing the entire length of the study zone, this set serves as a transition between the low and high values of the reduced TMF. In the north, it contains traces of the second color set, compared with a few traces of the first color set in the centre and south.

III-1-2. Vertical gradient (VG)

The VG showing the sources of anomalies associated with the different domains are identified on the TMF map ***(Figure 5b)***. Two (2) large zones can be identified. The first zone is represented by blue color representing very negative values of the magnetic gradient. They range from -0.2nT/m to -2nT/m. These contours are perfectly observable to the west and southwest, followed by a few isolated ones to the northeast. They show to the existence of structures or formations and confirm the negative anomalies identified on the total field map. The second zone, meanwhile, shows points of high concentration. These positive vertical gradients are shown in purple to green. This zone contains all positive values between, 0nT/m and 1.3 nT/m. Scattered throughout the study area, these identified sources of magnetic anomalies, making it possible to specify the superficial nature of these dominant formations or structures.

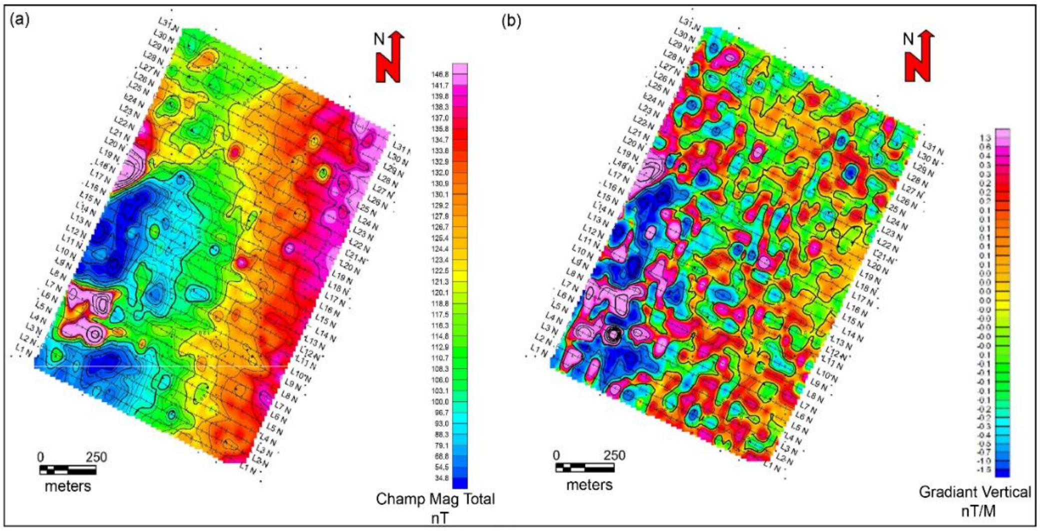

Figure 5 : *Magnetic survey maps. (a) Total magnetic field map, (b) vertical gradient map*

III-1-3. Interpretation of magnetic field data

Positive and negative magnetic anomalies identified on the reduced TMF map show a change in magnetization. They are generally due to a change in magnetite or paramagnetic mineral content. In our case, the transition from magnetic to geological information is not very delicate, since a few major outcrops have been identified in the study area ***(Figure 6)***. Our study area is close to the magnetic equator, with a shallow magnetic inclination. This means that a normally magnetized body is likely to produce a negative magnetic anomaly instead of a positive one. Therefore, we can assimilate negative magnetic anomalies to magnetized bodies (mafic) versus positive magnetic anomalies for paramagnetic bodies (felsic). The TMF map, enables us to identify the contours of the major geological structures that characterize our study area. Thus, we have identified three (3) major domains of different magnetic nature ***(Figure 6a)***. The first domain concerns positive magnetic anomalies, and represents zones of high felsic potential. These felsic zones are superficial in nature, hosting a positive vertical gradient. They cover a total area of 85.56 ha, unevenly distributed over three sites such as Z_{f-1}, Z_{f-2} and Z_{f-3} ***(Table 1)***. The second domain comprises negative magnetic anomalies associated with a negative magnetic gradient. This denotes that these deep-seated structures are mafic to ultramafic in nature with two potential sites covering together a total area of 34.16 ha. The third area is a transition zone between positive and negative anomalies. Geological interpretation shows that this zone is either overlain by a thick layer of weathering, or by a series of metamorphic formations or volcano-sediments. However, it hosts superficial felsic formations to the north and deep mafic to ultramafic bodies to the south. This might be explained by the sources of positive and negative anomalies associated with the positive and negative gradient. This intermediate domain covers a surface area of 40.3 ha. Our study area has significant potential for felsic formations, i.e. 53.47 % of the total surface area ***(Table 1)***. However, these geological structures are overlain by weathered series and it would be interesting to know the thickness and, if necessary, the depth of contact between sound rocks and weathered rocks through the results of electrical resistivity campaign ***(Figures 6b, c)***.

Table 1 : *Area of felsic, mafic and intermediate domains*

Magnetic domain	**Mafic-Ultramafic domain**		**Felsic domain**			**Intermediary domain (Z_i)**
	Z_{m-1}	**Z_{m-2}**	**Z_{f-1}**	**Z_{f-2}**	**Z_{f-3}**	
Surface area (ha)	22.18	11.98	71.2	9.42	4.94	40.3
Total	34.16 ha either 21.35 %		85.56 ha either 53.47 %			40.3 ha with 25.18 %

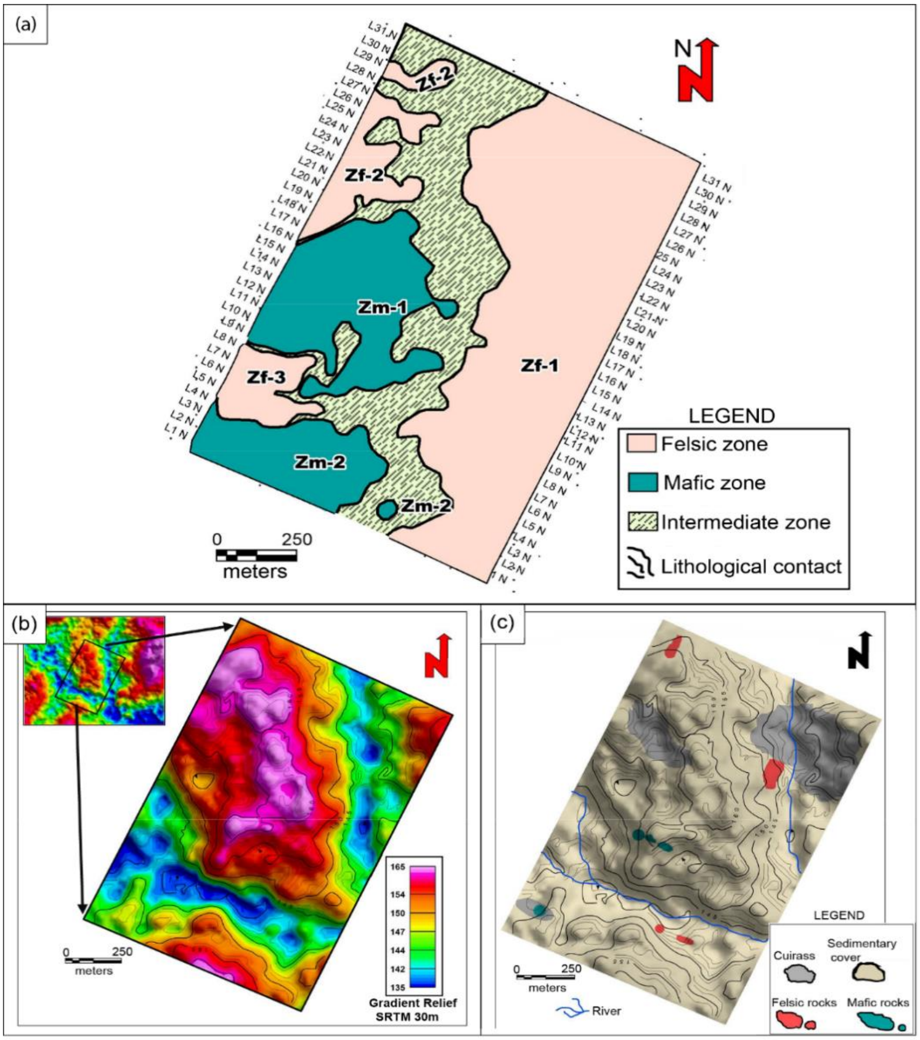

Figure 6 : *Lithological interpretation map of magnetic anomalies. (a) Felsic potential map, (b) study site relief, (c) Outcrop map*

III-2. Electrical resistivity analysis

The results of the electrical survey are presented in the form of level maps, and electrical resistivity profiles. They also highlight the major geological units, as well as the degree of weathering within the studied area.

III-2-1. Electrical resistivity maps

Two electrical resistivity maps were analyzed, namely at level 1 and 2. These maps provide information on the electrical resistivity of the formations in our study area at different pseudo-depths of investigation (Ze) according to the following ***Formula*** :

$$Ze = 0.19a(n + 2) \quad (1)$$

where n : represents the corresponding level, a : constancy.

III-2-1-1. Level 1 electrical resistivity

The level 1 map reflects the apparent resistivities of the formations in our study area at a depth of around 15 m ***(Figure 7a)***. We distinguish two (2) different domains. A first resistive domain over the entire area, represented by warm colors (greenish-yellow to purple) ***(Figure 7b)***. It includes high resistivity values ranging from 140 to 800 ohm.m. Together, these values constitute resistive anomalies, with lens-shaped, trending NE-SW, NNE-SSW. These high values, which reflect the resistive anomalies, could denote the presence of sound formations or, alternatively, the presence of a cuirassed level. The second area has low resistivity values ranging from 18 to 137 ohm.m, with coloration ranging from blue to green ***(Figure 7c)***. These series of resistivity form the conductive anomalies, and are also extended in the form of lenses striking NS to NNE-SSW. In sum, the low values, which are rarely found in the study area, could correspond to fracture zones, mineralization zones, or altered rocks under the influence of the watercourses draining our study area.

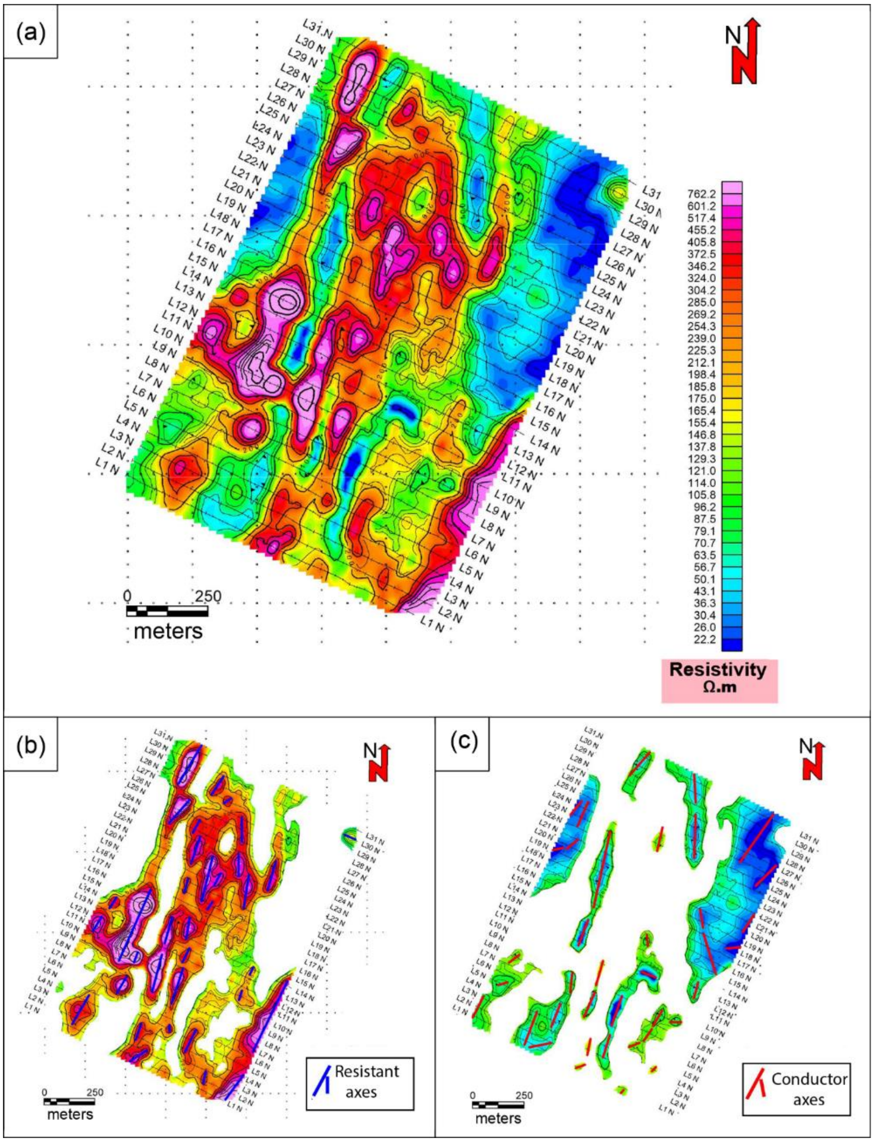

Figure 7 : *Level 1 resistivity analysis map. (a) Level 1 resistivity map, (b) resistive anomalies, blue lines show the resistant axes; (c) Conductive anomalies, red lines denote the conductor axes*

III-2-1-2. Level 2 electrical resistivity

The resistivity map of level 2 obtained at a depth of 25 m is shown in Figure 8a. At this position, we also distinguish two (2) main categories of resistivity. The first category, greenish-yellow to purple, concerns high resistivities ***(Figure 8b)***. They range from 101 to 1000 ohm.m and define resistive anomalies. They are elongated, lens-shaped, and oriented N-S to NNE-SSW.

These zones thus represent sound rock, fractured in places. The second category is characterized by a blue-to-green color contrast ***(Figure 8c)***. It includes low resistivity values ranging from 2 to 50 ohm.m. This range characterizes negative anomalies while highlighting conductive zones. These conductive anomalies are also elongated in the shape of lenses and follow N-S to NNE-SSW directions. These conductive zones could correspond to zones of alteration or fracture, or of course to the presence of water. To sum up, both level maps show virtually identical resistivity contrasts. However, the resistive anomalies observed at 15 m depth are replaced by conductive zones at 25 m depth. These abrupt changes testify to a significant thickness of alteration, which requires an analysis of the vertical electrical soundings.

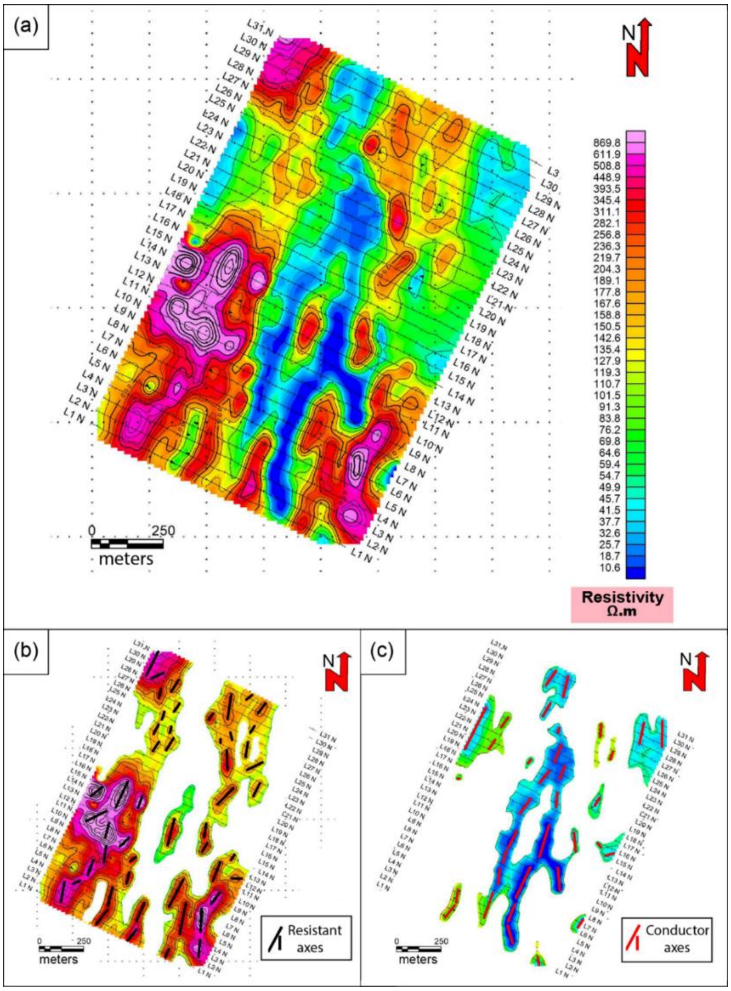

Figure 8 : *Level 2 resistivity analysis map. (a) Level 2 resistivity map, (b) conductive anomalies, (c) Resistive anomalies*

III-2-2. Vertical electrical soundings analysis

To determine weathering thicknesses, confirmed conductive and resistive anomalies, and identify the bedrock roof, eight (8) Schlumberger-type electrical soundings were carried out, including four (4) in the resistive domain and four (4) in the conductive domain.

III-2-2-1. Resistant zones S_{E3} and S_{E7} profiles

In the resistive domain, the results show two main categories of electrical sounding profiles, namely type A for profiles S_{E3} and S_{E7}, and type H for profiles S_{E17} and S_{E19}, (S_E: Electrical sounding). The electrical sounding S_{E3} reveals four (4) major layers of increasing electrical resistivity. The first marks the 15m-thick alteration zone, characterized by a resistivity of 40 ohm.m. The last three (3) layers reveal the presence of sound formations. They indicate that the roof of the sound rock is located at 15m depth. However, between 40 - 60m depth, however, the sound rock shelters a network of fractures, resulting in lower resistivity values ***(Figure 9a)***. The S_{E7} shows increasing resistivities divided into three (3) layers. The first two layers of increasing resistivity (25 - 60) ohm.m characterize a 5m-thick alteration zone. The third layer shows an estimated resistivity of 200 ohm.m. It characterizes the sound formations and indicates that their roof is more than 5m deep ***(Figure 9b)***.

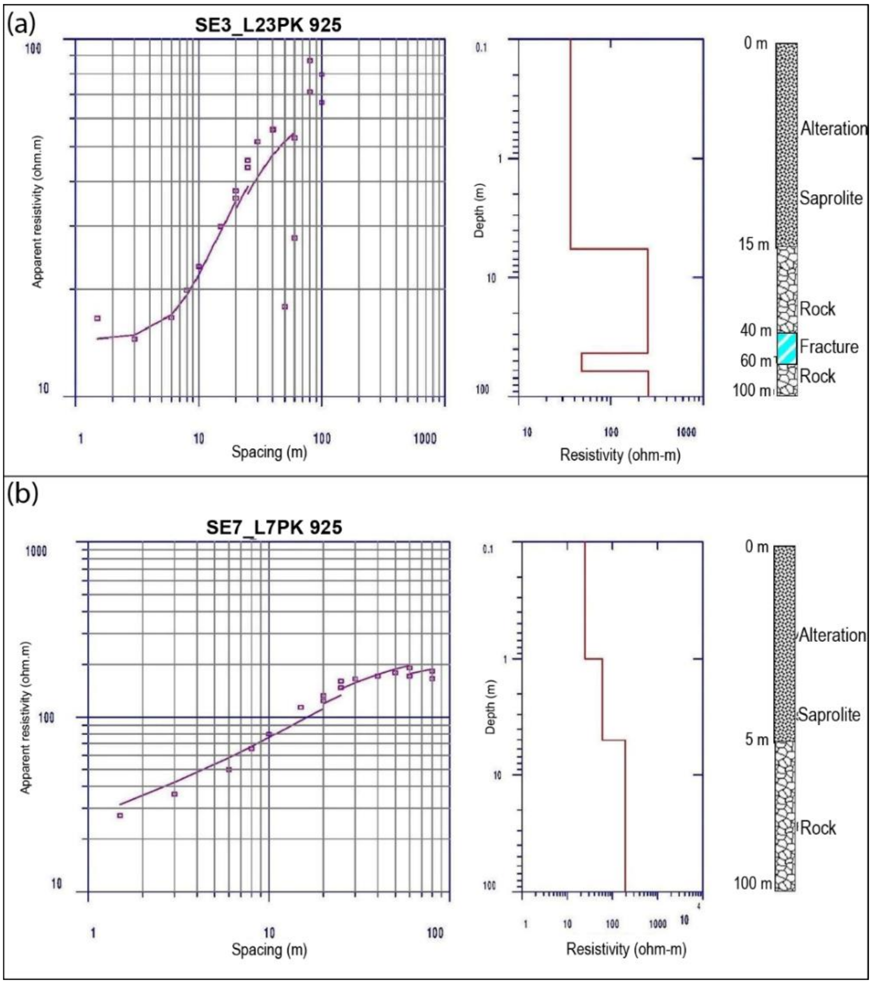

Figure 9 : *A-type electrical soundings (a) Profile S_{E3}, (b) Profile S_{E7}*

III-2-2-2. Resistant areas S_{E17} and S_{E19} profiles

For profiles S_{E17} and S_{E19}, type-H carried out in the resistant part of our study area, we observe three (03) large electrically different layers ***(Figure 10)***. On profile S_{E17}, the first two (2) layers have virtually identical resistivities, with a value of 130 ohm.m. They characterize a 12m-thick alteration zone. But the third layer covers resistivities above 250 ohm.m. It reveals that the sound formations lie over 12m depth ***(Figure 10a)***. As for profile S_{E19}, the first two resistivity layers mark a 20m-thick zone of alteration ***(Figure 10b)***. This layer contains a large network of fractures, resulting in a sharp drop in resistivity from 2,000 to 450 ohm.m. On the other hand, the third layer has resistivity values more than 2000 ohm.m. This indicates that the roof of the unweathered formations lies at a depth of 20m.

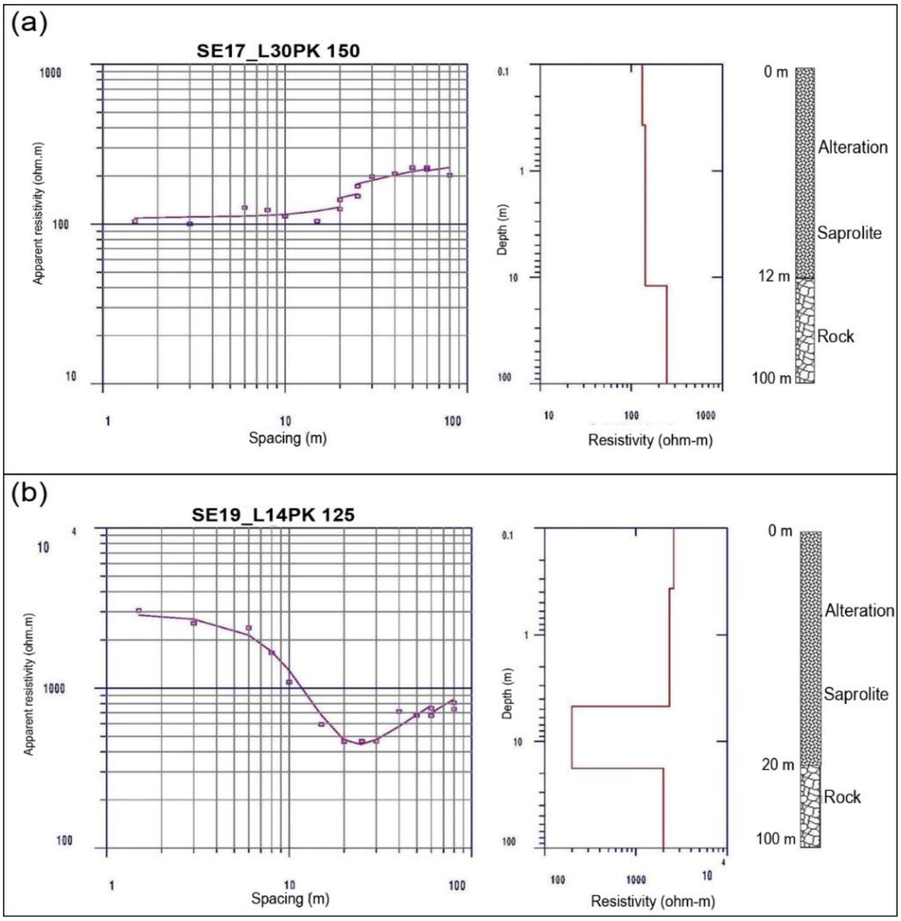

Figure 10 : *H-type electrical soundings, (a) Profile S_{E17}, (b) Profile S_{E19}*

III-2-2-3. Conductive areas S_{E1}, S_{E5}, and S_{E16} profiles

In the conductive domain, the results of the electrical soundings are H-type for profiles S_{E1}, S_{E5}, and S_{E16}, and K-type for profile S_{E9} ***(Figure 11)***. Sounding S_{E1} shows three (3) large electrical zones. The first two (2) indicate a significant alteration thickness (0 – 20 m) and result in a drop in resistivity values ranging from 400 to 20 ohm.m. However, the third layer is characterized by a very high resistivity value (2000 ohm.m). This zone, located at a depth of over 20 m reveals the presence of sound formations ***(Figure 11a)***. The S_{E5} survey also reveals three (3) major layers. First, there is a thick 25m zone of alteration ***(Table 2)*** characterized by the first two layers of decreasing resistivity (180 - 60) ohm.m. Then, the third layer of high resistivity (4000 ohm.m), reveals that the roof of the unweathered formations lies over 25 m depth ***(Figure 11b)***. On profile S_{E16}, the first three (3) electrical layers with respective resistivities (200 - 80 - 100) ohm.m represent an intense 15m thick alteration zone (***Table 2***). The second layer is characterized by a high resistivity value (1100 ohm.m). This indicates that the roof of the rock lies at a depth of over 15 m ***(Figure 11c)***.

Table 2 : *Summary of soundings in the conductive domain*

Electrical soundings	**S_{E1}**	**S_{E5}**	**S_{E9}**	**S_{E16}**	**Synthesis**
Resistivity (ohm.m)	60	70	40	70	[40 – 70]
Depths	[5 – 20]	[4 – 25]	[15 – 50]	[2 – 10]	[2 – 50]
Thicknesses (m)	15	21	35	8	20

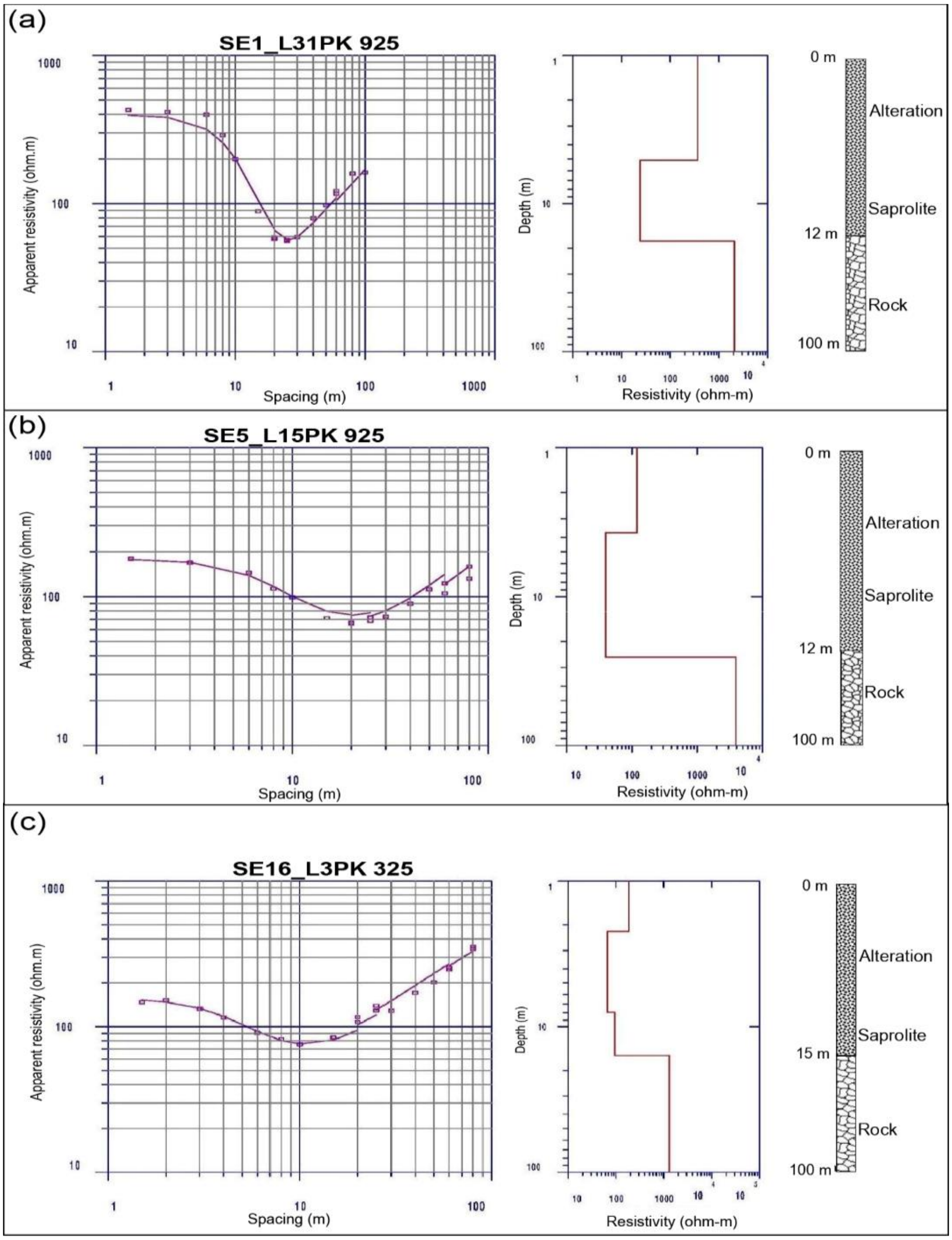

Figure 11 : *H-type electrical soundings, (a) Profile S_{E1}, (b) Profile S_{E5}, (c) Profile S_{E16}*

III-2-2-4. Conductive areas S_{E9} profiles

Profile S_{E9} shows four electrical layers. The first three (3) reflect a very large alteration thickness of around 50 m. This weathered layer comprises an extensive fracture network (15-50) m ***(Table 2)***. In contrast, the fourth underlying layer is a sound rock. This resistive layer, at around 250 ohm.m, indicates that the roof of the sound formations lies at a depth of over 50 m ***(Figure 12)***. A synthesis of the results of electrical sounding in the resistive and conductive domains reveals an altered layer of variable thickness. These thicknesses range between 5 and 50 m.

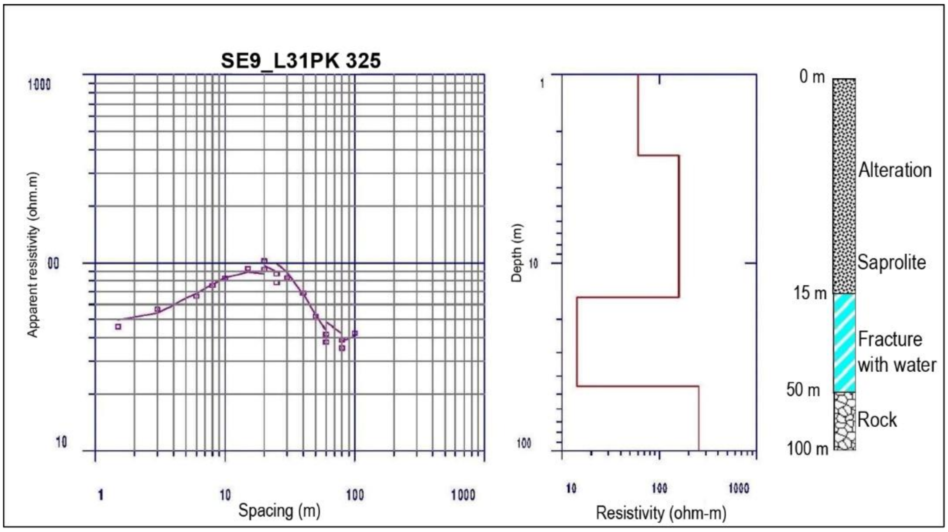

Figure 12 : *K-type electrical sounding, Profile S_{E9}*

III-2-3. Interpretation of electrical resistivity data

In general, sound rocks tend to oppose the passage of electric current and are characterized by resistive anomalies. Conductive anomalies are the electrical signatures of altered rocks and fractures. In our case, the set of resistive anomalies identified highlights the superficial and rooted sound formations. Electrical sounding carried out in these zones indicate that all the sound rock bodies are located at shallower depths, and are affected by fractures and detachments trending NE-SW to NNE-SSW ***(Figure 13a)***. The conductive anomalies highlight the altered formations, which host an extensive network of fractures-oriented N-S to NNE-SSW. These could well constitute potential aquifers. Electrical soundings indicate that the sound formations are very deep, 25 m to 50 m in places. But these zones are very compromising for exploitation, as a huge layer of weathered rock will have to be stripped. Furthermore, our results confirm the resistive and conductive anomalies identified on Level 1 and 2 maps. This stipulates that the estimation of sound rock areas will be more complete using the level 2 map. Therefore, estimating the areas of sound and weathered bedrock, boils down to delineating resistive and conductive anomalies. It involves mapping the sound formations shown on the level 2 map. The sound formations cover around 87.12 ha of our study area, representing a percentage of 54.45 %. Weathering extends over an area of 72.88 ha, or 45.55 % of a total area of 160 ha ***(Table 3)***. Comparison of the magnetic and electrical analyses enables us to identify sound rocks in the felsic and mafic domains ***(Figure 13b)***. All the electrical soundings (S_{E1}, S_{E5}, S_{E9}, S_{E16}) implemented in the conductive zone, showed low resistivities at a certain depth ***(Table 4)***.

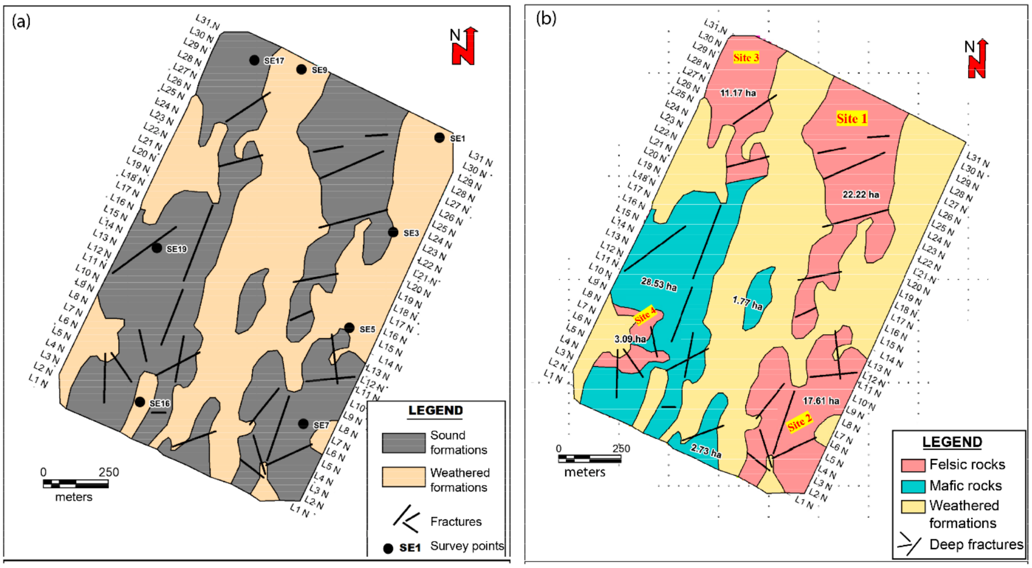

Figure 13 : *Spatial distribution of rocks along the study area. a) sound and weathered formations; b) felsic and mafic formations of the study area*

Table 3 : *Potential in sound rock*

Designation	**Resistive domain**				**Conductive domain**			
Electrical soundings (S_E)	S_{E3}	S_{E7}	S_{E17}	S_{E19}	S_{E1}	S_{E5}	S_{E16}	S_{E9}
Base roof	15	5	12	20	20	25	15	50
Mean depth (m)	13				28			
Surface areas (ha)	87.12 ha (54.45 %)				72.88 ha (45.55 %)			

Table 4 : *Surveys summary within the conductive domain*

Electrical soundings	**S_{E1}**	**S_{E5}**	**S_{E9}**	**S_{E16}**	**Synthesis**
Resistivity (ohm.m)	60	70	40	70	[40 – 70]
Depths	[5 – 20]	[4 – 25]	[15 – 50]	[2 – 10]	[2 – 50]
Thicknesses (m)	15	21	35	8	20

IV - DISCUSSION

IV-1. Lithological features

Felsic formations are the most dominant over our entire study area, with a total surface area of 54.09 ha. Our study area has a very high potential for felsic rocks spread over four sites. The surface areas are 22.22 ha at site 1 ; 17.61 ha at site 2; 11.17 ha at site 3 and 3.09 ha at site 4. But the conductive anomalies in sound felsic zones indicate that these felsic formations are affected by a series of NE-SW to NNE-SSW-trending fractures or detachments that could correspond to narrow shear zones [21]. For the calculation of felsic formation volumes and tonnages, only drill holes located in felsic zones were considered. For a thickness of 50 m of felsic layer, the rock volumes of the various sites are obtained from the product of each of the surface areas (in m^2) by the thickness considered (50 m). The less dominant mafic formations occupy a total surface area of around 33.03 ha. They are affected by several fractures trending NNE-SSW to NW-SE, consistent with that observed within Zahakro [22]. Overall, the distribution of deep fractures and stalls in our study area leads us to conclude that the felsic formations are intrusive in nature in agreement with that previously found [23]. Our results are then compared with previous geological work in the region to highlight the lithological, metallogenic, and structural contexts, often associated with basement aquifers [24]. The deep formations in our study area are composed of felsic and mafic rocks with a dominance of felsic levels like that of most of the sillons in the Baoulé-Mossi area [25, 26]. The geological units of the Anikro zone near the Akakro sector consist of granitoid pebbles, quartz, very few volcanoclastites (mafic), and above all, an abundance of felsic volcanics [8]. This also confirms the dominant character of the felsic formations identified in our study area. However, these felsic formations identified could be an extension of those at Anikro, thus justifying their volcanic nature [27]. The geochemical and petrogenetic approach to the Akakro-Anikro area shows the presence of volcanites including basalts, andesites, dacites, rhyolites, and rhyodacites [27, 28]. For him, the sector is dominated by acidic facies (ensialic origin), with quartz, pegmatite, and aplite veining in places. This ensialic origin is shown by the predominance of acidic facies over basic facies. We can therefore assume that the felsic domains determined in our study area are a combination of rhyolites, dacites interspersed with quartz veins, pegmatites, and aplites. These observations are consistent with the hypotheses put forward by certain authors [29, 30]. In volcanic zones, felsic rocks, more precisely rhyolites and dacites, always derived from highly viscous, silica-rich lavas, are found in extrusive volcanic apparatuses such as domes [31, 32]. We can also assume that the resistant anomalies identified in the felsic domain would therefore be geophysical signatures of an electrical nature specific to the tops of domes or cupolas [33, 34]. Therefore, our study area seems to be home to ancient felsic domes with formation conditions similar to those described by certain authors around the world [35, 36].

IV-2. Deformation and structural features

In general, temperature (geothermal gradient) plays a key role in fracture setting. Acidic bodies are warmer than basic bodies. This difference of temperature difference means that the setting of felsic bodies creates several openings through the basic (mafic) formations. We can therefore assume that the emplacement of the felsic rocks in our study area would be the origin of all these fractures and dislocations along the birimian directions [22, 27]. These fractures can be considered as intrusions [28]. Consequently, their emplacement would be syngenetic with the felsic rocks, then posterior to the formation of the mafic host rock. The positive and negative effects of magnetic anomalies measured by satellite in the Yunnan region (China) revealed the presence of deep fractures along the Red-River [37]. Compared with our study, we can therefore stipulate that the sources of positive and negative anomalies obtained on the gradient map would be magnetic signatures specific to deep fractures and detachments in the Akakro sector in agreement with previous observations in the region [22].

IV-3. Deep weathering

In general, mafic, and ultramafic rocks have a high magnetic intensity due to the presence of magnetite [38]. Once metamorphosed, they have low magnetic intensity. Felsic rocks, on the other hand, have very low magnetic intensities. Once altered (oxidized), their magnetic intensity increases [39]. These oxides can be viable in the depths of the lower crust, or even the upper mantle, when temperatures are cooler than the Curie temperature of magnetite, considering the effects of pressure. [38]. These interpretative hypotheses confirm the negative and positive magnetic anomalies identified in our study area. The mafic formations would therefore have been metamorphosed during the emplacement of the felsic volcanic intrusions. Subsequently, this felsic (volcanic) and mafic (metavolcanic) complex would have undergone a series of surface and deep alteration [22]. We maintain that the positive magnetic anomalies detected are therefore due to oxidation of felsic volcanic rocks. Analysis of drilling results on the Toumodi-Fettékro sillon revealed the nature and depth of altered levels in the mafic and felsic domains [40]. The results showed that in the mafic domain, the weathered levels were in fact ferruginous crust that reached an average depth of 15 m, but in the granitic (felsic) domain, the weathered levels are of a bauxitic nature, reaching a maximum depth of 10 m. Correlated with our electrical results, electrical sounding S_{E19} indicates that in the mafic domain, the weathered layer reaches a depth of 20 m. This superficial layer could be ferruginous crust. This observation is in line with that observed within the Southern Sierra, Eastern California [12]. In addition, within the felsic domain, electrical soundings S_{E17} (12 m) and S_{E7} (5 m) reveal a weathered layer with an average thickness of 9 m. This layer would therefore be bauxitic in nature. This implies that the resistive and conductive anomalies detected on the Level 1 resistivity map, would certainly be the electrical signatures of altered layers of a ferruginous and bauxitic nature. Vertical electrical soundings data allowed to characterize certain aquifers in northwest Tunisia [41]. These aquifers in the Bou-Salem plain are linked to generally low electrical resistivities. The low resistivities at a certain depth observe within the conductive zone suggest the presence of an aquifer at around 20m depth [40]. Consequently, the conductive anomalies identified in the Akakro area would therefore be due to a water-bearing aquifer with an average thickness of 20 m.

V - CONCLUSION

This work is a contribution to the knowledge of geological formations in Akakro locality within the Toumodi region. The magnetic and electrical resistivity methods used have enabled us to provide a better picture of the surface and deep formations through maps of the TMF, VG, electrical resistivity (levels 1 and 2), as well as electrical sounding profiles. Our study revealed that Akakro area is marked by volcanic intrusion of felsic rocks. Characterized by resistive anomalies and high magnetic field, these rocks deal of space with a large part covered with 85.56 ha of our study area. These felsic hard rocks overlay about 54.09 ha, and are surmounted by a thick weathered layer of 15 m on average extending on 31.47 ha. Resistive anomalies observed at 15 m depth are replaced by conductive zones at 25 m depth. Within the felsic rocks' domain, the analysis of conductive anomalies also revealed an important NE-SW and NNE-SSW-striking fractures network. The relationship between fractures network and investigated rocks shows that they would have occurred after the formation of felsic volcanic rocks. The results clearly show that the Akakro area contains a set of predominantly felsic volcanic formations, mafic metavulcanites, and a thick layer of weathered formations averaging 20 m in thickness.

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