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Characterization of Geomagnetic Signatures and their Mineralization Potential in the Agnibilekrou Department (Eastern Cote d'Ivoire)

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Abstract

The characterization of geomagnetic signatures conducted in the Agnibilékrou department (Eastern Côte d'Ivoire) highlights several magnetic anomalies indicating strong mineralization potential. Five aeromagnetic maps (Abengourou 4c and 4d, and Agnibilékrou 1b, 2a, and 2b) were used. These maps, derived from aerial surveys carried out by Kenting Earth Sciences Ltd between 1974 and 1976, were processed using filtering techniques (Butterworth filter, tilt angle filter, and vertical integration filter) to enhance the detection of magnetic anomalies in the subsurface. The magnetic anomalies, referred to as A1 and A2, are consistently observed across the maps and follow a NE-SW orientation, indicating the presence of basic and ultrabasic rocks rich in magnetite, often associated with metal deposits such as iron, nickel, or sulfides containing copper and cobalt. Additionally, sedimentary formations derived from the breakdown of granites, containing magnetite, may contribute to hydrothermal alteration processes, facilitating the formation of gold or polymetallic deposits. The left-lateral faults F1, F2, and F3, identified through distortions in the magnetic field on the maps, could act as circulation channels for hydrothermal fluids, known for transporting and depositing metals. In particular, the right-lateral fault F, which has undergone tectonic reactivation, appears to favor the concentration of metals. The NE-SW orientation of anomalies and fractures aligns with zones prone to hydrothermal alteration, a key process in the formation of gold and sulfide deposits. Finally, some surface-level anomalies, such as A3, highlighted by the tilt angle filter, represent easily accessible targets for mining exploration. This study, therefore, reveals significant mining potential in the area, especially for iron, nickel, and gold, driven by the combination of tectonic structures, magnetized rocks, and hydrothermal processes.

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Introduction

The Agnibilékrou department, located in eastern Côte d'Ivoire, stands out for its promising geological potential, attracting increasing interest in mining exploration. The region, part of the Comoé Basin, consists of a variety of geological formations, ranging from sediments derived from dismantled granites to basic and ultrabasic rocks rich in ferromagnesian minerals. In this context, the characterization of magnetic signatures becomes essential to better understand the deep and surface geological structures likely to contain mineral resources. Aeromagnetism, as a geophysical method, detects variations in the Earth's magnetic field associated with different rock formations. It is a key tool for identifying geological structures favorable to the concentration of metallic deposits. Moreover, it helps shed light on the role of tectonic and hydrothermal processes in the formation of these deposits.

The magnetic method allows for correlating geomagnetic signatures, fractures, and mineralization indicators. This study aims to analyze the geomagnetic anomalies mapped in the Agnibilékrou department and to evaluate the mineralization potential of the geological formations associated with these anomalies. The insights gained will guide future mining exploration campaigns effectively.

Study Area Overview

The Agnibilékrou department, located 270 km east of Abidjan (Côte d'Ivoire), lies within the Indénié-Djuablin region. It is positioned between latitudes 6°46' N and 7°22' N and longitudes 3°04' W and 3°40' W. The geological history of Agnibilékrou is closely linked to that of the West African Craton, of which it forms an extension. The geological formations in this area were shaped during the Eburnean orogeny, a major geological event of the Proterozoic era, which played a key role in the region's structural development.

Several previous studies, including those by Géomines (1982) and Delor *et al.,* (1995), have examined the geology of the area, focusing on petrography and tectonics. These studies reveal that the region exhibits polyphased tectonics, marked by several successive deformation phases. These tectonic processes have resulted in the emergence of numerous fractures, varying in size from a few meters to several kilometers, reflecting intense structural activity. The region's geological formations have also undergone regional metamorphism, altering some rocks and modifying their internal structure.

In terms of petrography, the region is dominated by two main types of formations: granitoids and volcano-sedimentary formations. Granitoids account for about 9% of the formations, while volcano-sedimentary formations, mainly composed of schists, represent nearly 80% of the geological structures. These schists are oriented along a NE-SW axis, reflecting the preferential direction of the tectonic forces that shaped the region (Figure 1).

These geological characteristics make the Agnibilékrou region a complex terrain, where the diversity of rocks and tectonic structures reflects a rich and dynamic geological history.

Materials and Methods

Cartographic Data Basis

The aeromagnetic maps used in this study were provided by the Geology Directorate of Côte d'Ivoire. These maps are derived from aerial surveys conducted by Kenting Earth Sciences Ltd between 1974 and 1976.

The data were recorded along flight lines, with a theoretical spacing of 500 m and a flight altitude of 150 m ± 15 m, after being corrected for altitude, latitude, and diurnal variations. The flight lines were transcribed onto photomosaics, and the coordinates of the turning points were determined and compiled digitally on magnetic tape.

Magnetic field intensities were obtained either from analog magnetometer profiles, digitized onto tape, or directly from digital profiles recorded during the flight. The magnetic field values were interpolated at the nodes of a square grid with a side length of 2.5 mm, based on a simulated polynomial variation of the magnetic field in the direction perpendicular to the flight lines. This grid served as the basis for mechanographic plotting of isogams. As a result, several maps, divided into square-degree sections, were produced. For the Agnibilékrou department, five (5) aeromagnetic maps were used: Abengourou 4c and 4d and Agnibilékrou 1b, 2a, and 2b.

Processing of Geomagnetic Maps

The processing of geomagnetic maps involves applying filters to the corrected aeromagnetic maps to enhance geomagnetic anomalies, thereby facilitating the extraction of fracture networks. For this purpose, the aeromagnetic maps provided by the Geology Directorate were vectorized.

The coordinates of the points forming the magnetic field contour lines (isovalues) were extracted and recorded in an Excel file, creating a new database containing information on latitude, longitude, and magnetic field intensity.

These data were then processed using the Magmap module of the Geosoft software, enabling the application of specific filters and the generation of the final aeromagnetic maps (Figure 2).

Butterworth Filter

This filter allows for the retention of short magnetic wavelengths, which correspond to surface anomalies, while also permitting the passage of longer magnetic wavelengths, which reflect anomalies from deeper sources. It is generally used to smooth magnetic waves with easy control over the filter's degree. Its mathematical expression is given by (Equation 1):

$$L(k) = \frac{1}{\left[1 + (1 + \left(\frac{k}{k_0}\right)^n\right]}$$ --- (Équation 1)

With n representing the degree of differentiation (by default, its value is 8), k_0 being the number of cycles per reference ground unit, and k the number of cycles per ground unit, with a value of 4.

The Butterworth filter was used to generate the total magnetic field map.

Tilt Angle Filter

The tilt angle operator (Miller and Singh, 1994; Verduzco *et al.,* 2004) is defined as the arctangent of the ratio between the vertical derivative of the total field anomaly and the magnitude of its horizontal gradient. The tilt angle or inclination derivative and its total horizontal derivative are useful for mapping shallow subsurface structures. This filter is particularly valuable because it provides a similar representation of both low- and high-amplitude anomalies (Bouiflane, 2008).

Additionally, Salem *et al.,* (2008) demonstrated that the tilt angle filter, when applied to pole-reduced data, enables the estimation of source depths. Therefore, the tilt map offers a combined analysis of 2D structure boundaries and their depths (Simon, 2011).

The tilt angle operator H_θ applied to the anomaly F is expressed as (Equation 2):

$$H_\theta(F) = \tan^{-1} \frac{\frac{\partial F}{\partial z}}{\sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2}}$$ --- (Équation 2)

Vertical Integration Filter

Vertical integration, the inverse of differentiation, acts as a low-pass filter, similar to upward continuation. This process smooths the signal, emphasizing the effects of large deep structures over small surface objects. It can be particularly useful for studying large anomalies, especially those generated by the basement (Simon, 2011).

The mathematical expression of this operator Hiv is given by (Equation 3):

$$Hiv = \left(iLu + iLv - N\sqrt{u^2 + v^2}\right)^\gamma$$ --- (Équation 3)

Hiv represents the vertical integration; L and N are the directional cosines of the magnetic field; u and v are the angular frequencies associated with the x and y directions in the spectral domain; and γ is the negative real number for integration of order γ.

Results and Discussion

Total Magnetic Field Map

The total magnetic field map reveals the magnetic signatures of both deep and shallow structures. With an intensity ranging between 31,503 nT and 31,572 nT, the map identifies three main zones: magnetic, weakly magnetic, and moderately magnetic (Figure 3).

The magnetic domain, represented in blue, is characterized by two nearly parallel anomalies, labeled A1 and A2, located in the northwest and southeast of the study area, respectively. These anomalies, which are elongated and oriented NE-SW, may indicate the presence of basic and ultrabasic rocks.

Furthermore, a gradual transition from magnetic to non-magnetic zones is observed, reflected by a progressive decrease in magnetic field intensity from the southwest to the northeast. This decrease may be explained by the gradual leaching of magnetite from the higher altitudes to the lower areas within the study region.

The weakly magnetic domain, identified by shades ranging from orange to magenta, is primarily located in the northern and eastern regions of the study area. It reflects the presence of granitoids and their weathering products, particularly siltstones and arenites, as indicated by the geological map.

These weakly magnetic zones are separated by a moderately magnetic domain represented in green. This magnetic halo may correspond to metamorphic aureoles formed around granodiorite intrusions, near which green biotites have been observed. It could also result from the gradual leaching of ferromagnesian minerals or magnetite from higher-altitude areas.

The map also highlights several distortions in the magnetic field caused by fractures. These fractures, generally oriented NW-SE, are identified as faults F1, F2, and F3. Fault F1, located in the southern part of the study area, is less pronounced and only affects anomaly A2.

In contrast, F2 crosses the entire area from southeast to northwest, influencing both the magnetic and moderately magnetic domains. F3, located in the east, impacts both the moderately magnetic and weakly magnetic domains.

These left-lateral strike-slip faults (F1, F2, and F3) are thought to be synchronous with the regional schistosity S2, characterized by left-lateral shearing movement.

Tilt Angle Map

The tilt angle analysis highlights an alternating pattern of magnetic formations (blue to green) and weakly magnetic formations (orange to magenta), all oriented NE-SW (Figure 4). The A1 and A2 anomalies, previously detected on the total magnetic field map, are more pronounced here. They extend towards the northeast, with regular contours and several distortions, indicating the presence of fractures.

A third anomaly, A3, stands out in the center of the study area due to its width and shallow nature, which explains its absence on the total magnetic field map. Like anomalies A1 and A2, A3 is elongated and follows a NE-SW orientation. It is intersected by a right-lateral strike-slip fault, labeled F, oriented NW-SE, which coincides with the course of the Ifou River. The movement of fault F differs from that of fault F3, indicating opposite directions of displacement.

Vertical Integration Map

Similar to the tilt angle map, the vertical integration map (Figure 5) reveals an alternating pattern of magnetic formations (blue to green) and weakly magnetic formations (orange to magenta), oriented NE-SW. These formations appear more extensive at depth, corresponding to the rooting of the A1 and A2 anomalies observed in Figure 4.

However, the A3 anomaly, identified through the tilt angle, disappears with depth, allowing for a greater extension of the A2 anomaly. Additionally, most of the fractures revealed by the tilt angle are no longer visible on the vertical integration map (Figure 5), except for fault F1, which was also identified on the total magnetic field map.

Interpretation

The analysis of the magnetic signatures highlights several indicators favorable for potential mineralization within the study area. The A1 and A2 magnetic anomalies, oriented NE-SW, reflect the presence of basic and ultrabasic rocks rich in magnetite.

This type of rock is often associated with deposits of metallic minerals such as iron, nickel, and even sulfides containing copper or cobalt, making these anomalies promising targets for mining exploration.

In addition, the alternation of siltstones and arenites, resulting from the breakdown of granites, may contain concentrations of accessory minerals such as magnetite, which has already been identified in previous studies. The presence of magnetite can serve as a key indicator of metallic deposits and hydrothermal alteration processes, which are often linked to the formation of gold or polymetallic deposits.

The F1, F2, and F3 faults, identified through magnetic field distortions, are tectonic structures that could act as conduits for hydrothermal fluids. These fluids are known to transport and deposit metals along fractures, forming mineralized veins. Specifically, fault F, oriented NW-SE, is associated with late-stage deformation, suggesting tectonic reactivation favorable to the infiltration and concentration of metals.

Moreover, the NE-SW orientation of magnetic anomalies and fractures aligns with areas conducive to hydrothermal alteration, a key process in the formation of gold and sulfide deposits. The overlap of these structures with the course of the Ifou River suggests potential interaction between water and minerals, further increasing the potential for gold mineralization.

Additionally, the surface-level location of certain anomalies, such as A3, indicates accessible targets for mining exploration.

In conclusion, the results suggest that the study area exhibits multiple characteristics favorable for mining exploration, particularly for metals such as iron, nickel, and gold, due to the combination of fractures, magnetized rocks, and hydrothermal processes.

The results of this study, which highlight magnetic anomalies favorable for potential mineralization, align with findings reported by several authors. The A1 and A2 anomalies, indicating the presence of basic and ultrabasic rocks rich in magnetite, corroborate the studies of Hrouda (1982) and Reeves (2005), which demonstrated that these formations are often associated with iron, nickel, or copper deposits. These findings are consistent with the observations of Koduah *et al.,* (2013) in West Africa, where NE-SW-oriented magnetic structures were identified as favorable for mining exploration.

However, according to Siméon *et al.,* (1995), the Comoé Basin primarily consists of rhythmic alternations of siltstones and arenites, which originate from the breakdown of granitic rocks (Alric *et al.,* 1987). The observed magnetization may be related to the presence of magnetite as an accessory mineral in meta-arenites and meta-siltstones. The identification of magnetite in these formations, already noted by Siméon *et al.,* (1995), suggests continuity in the geological observations of the region.

These accessory minerals often play a crucial role as vectors for hydrothermal alterations, as emphasized by Pirajno (2009), further enhancing the mineralization potential of the area. Additionally, the fractures identified specifically F1, F2, and F3 act as conduits for hydrothermal fluids, consistent with the findings of Sillitoe (1992), who demonstrated that these fluids can form mineralized veins along faults. The left-lateral strike-slip faults (F1, F2, and F3) are thought to be synchronous with the regional schistosity S2, characterized by left-lateral shearing (Guibert and Vidal, 1984).

Figure.1 Geological map of the Agnibilékrou department (Delor *et al.*, 1995)

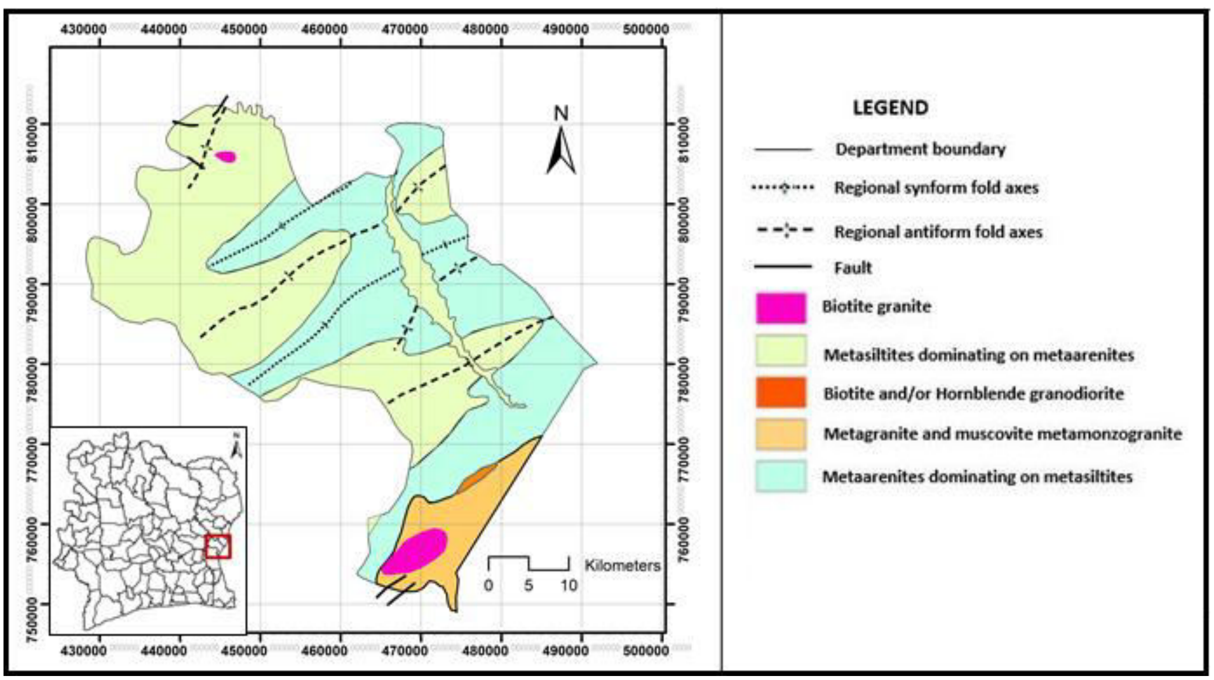


Figure.2 General flowchart for the processing of aeromagnetic data

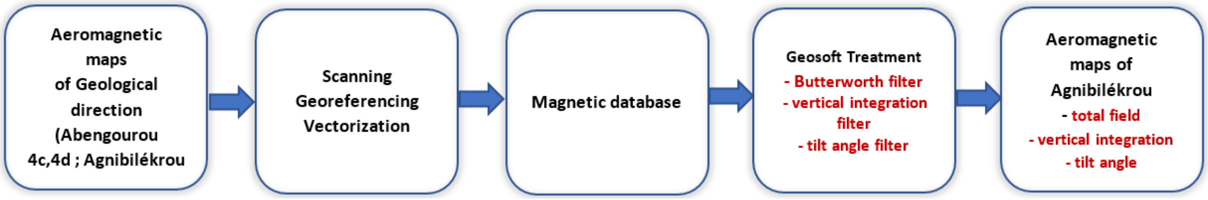


Figure.3 Total Magnetic Field Map

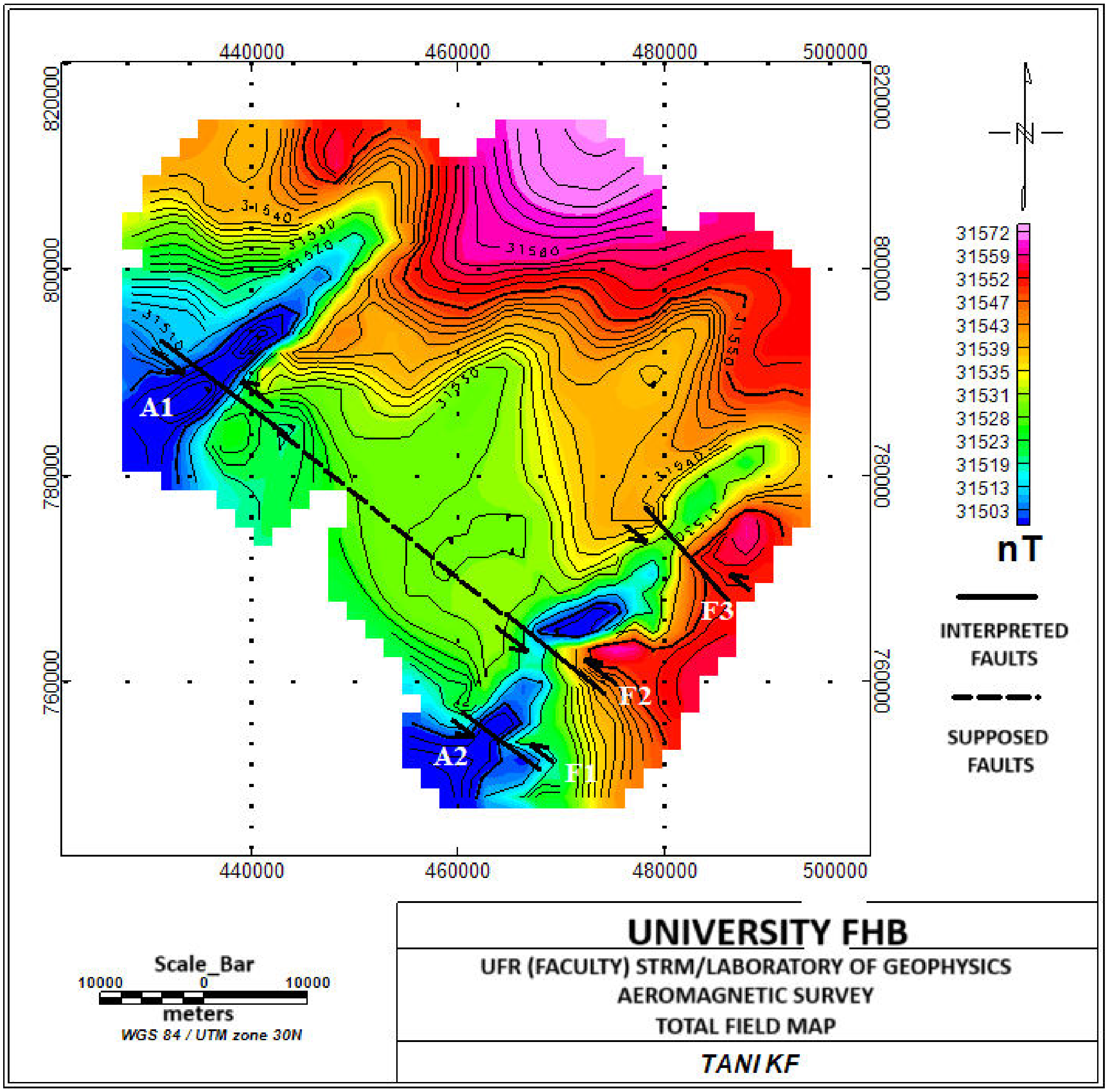


Figure.4 Derivative tilt angle map

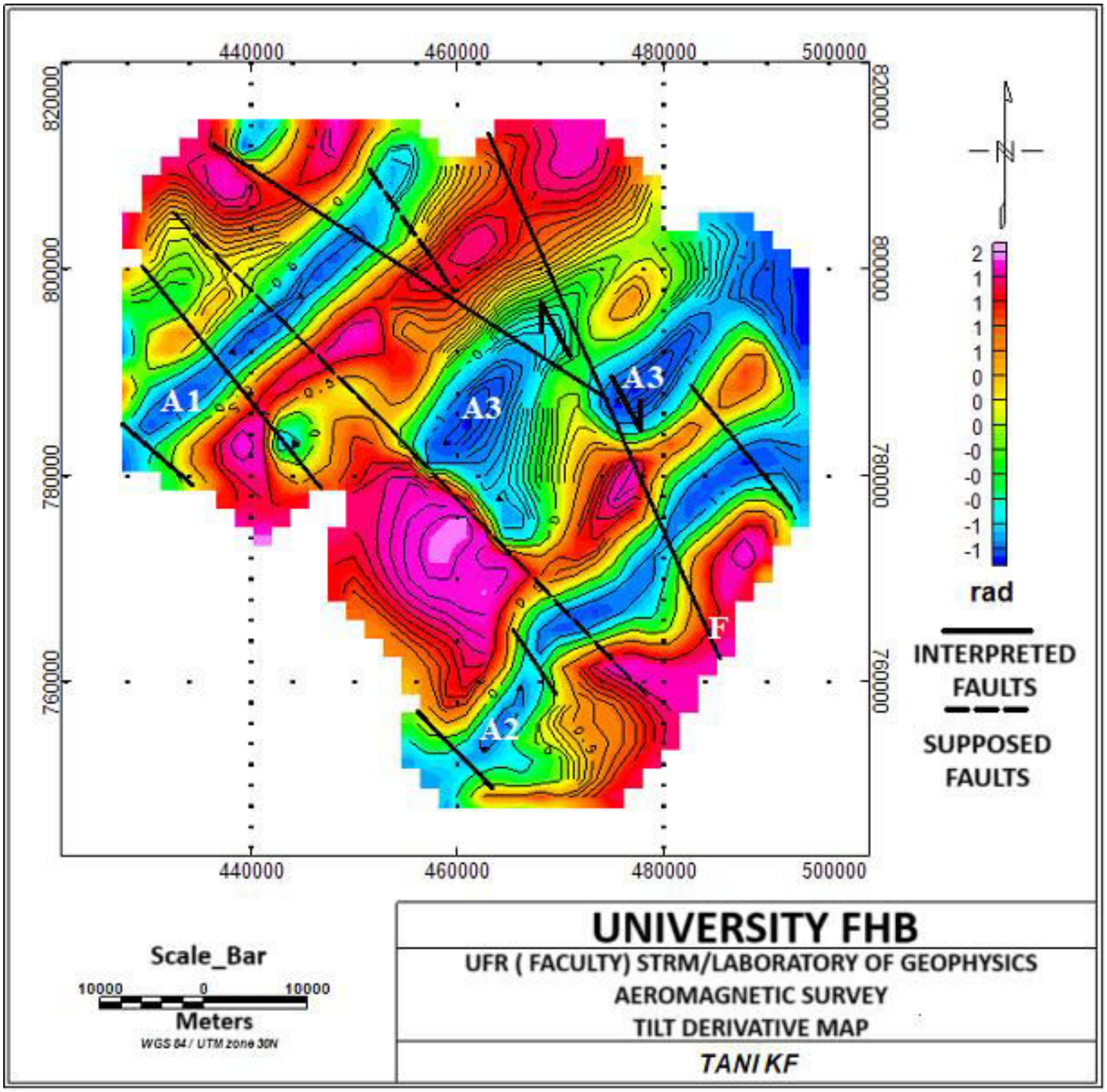
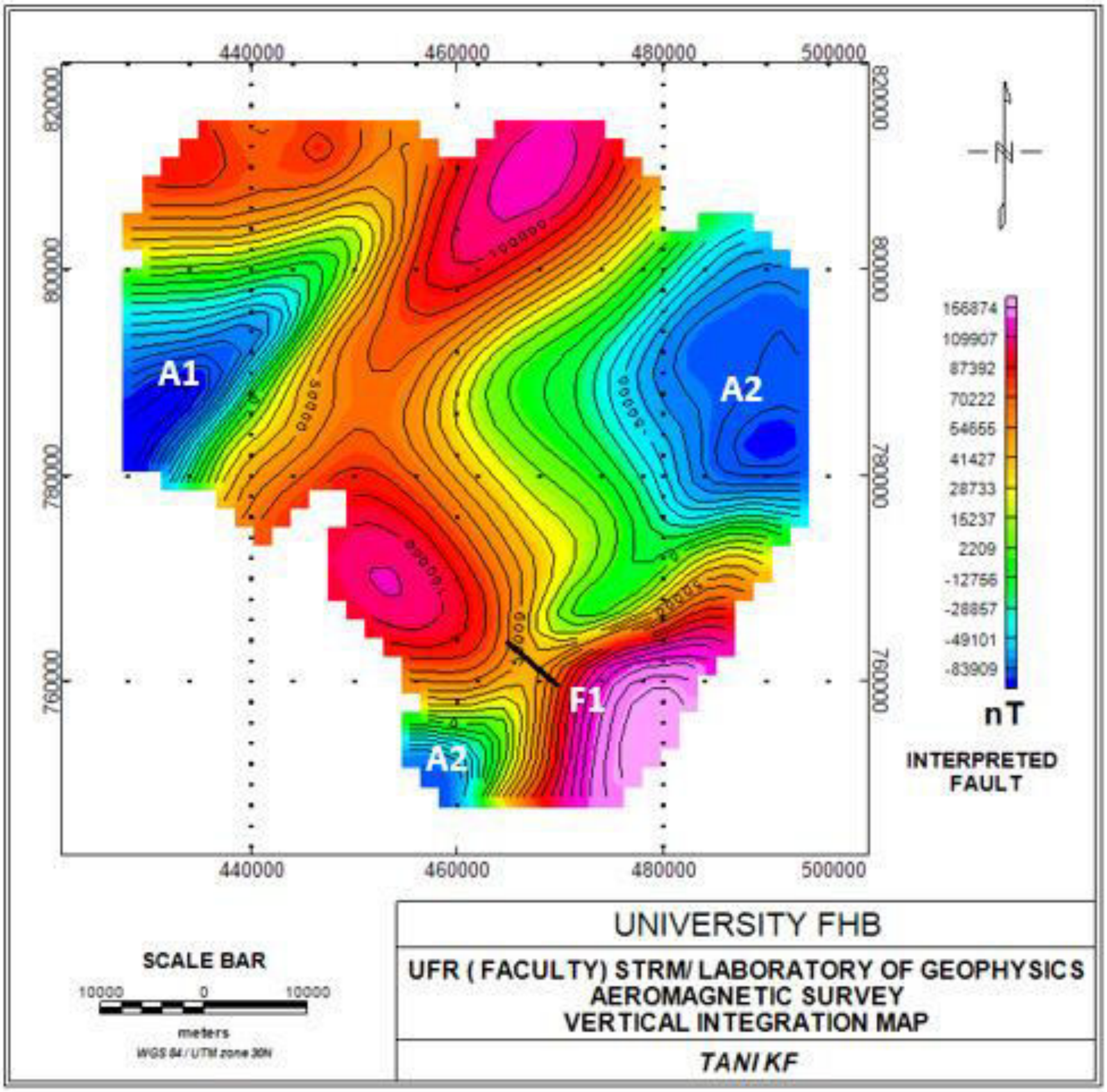


Figure.5 Vertical Integration Map



The right-lateral movement of fault F contrasts with the left-lateral faults (F1, F2, and F3), indicating opposite directions of displacement. Fault F likely results from late regional deformation, associated with N120° crenulation schistosity (Siméon *et al.,* 1992; Vidal *et al.,* 1995). This fault may correspond to a reactivation of fault F3, affecting more recent and shallow geological formations dating back to approximately 1.7 billion years (Siméon *et al.,* 1992). The tectonic reactivation observed along fault F, oriented NW-SE, aligns with trends described by Blenkinsop (2000), who identified late-stage fault reactivations as conducive to the concentration of precious metals.

Moreover, most of the fractures revealed by the tilt angle map are no longer visible on the vertical integration map, except for fault F1, which was identified on the total magnetic field map. This suggests that these fractures are not deep but are instead located within weathered layers and/or the fractured horizon, consistent with the stratiform conceptual model of basement aquifers (Wyns *et al.,* 1999).

The NE-SW orientation of the anomalies and fractures aligns with the findings of Goldfarb *et al.,* (2001), who demonstrated that such orientations are frequently associated with gold deposits in West Africa.

Additionally, the overlap of these structures with the Ifou River suggests fluid-mineral interaction, which is favorable for mineralization, as noted by Taylor *et al.,* (1999).

Finally, anomaly A3, despite being shallow, represents an accessible target for rapid exploration. These observations align with the work of Groves *et al.,* (2010), who emphasized the importance of exploring near-surface targets for efficient and timely mining operations. Therefore, the combination of anomalies, tectonic structures, and hydrothermal processes suggests promising mineralization potential, particularly for metals such as iron, nickel, copper, and gold.

Conclusion

The analysis of magnetic signatures in the study area reveals significant mineralization potential, particularly with the A1 and A2 anomalies, which are associated with basic and ultrabasic rocks rich in magnetite. These types of geological formations are often correlated with metallic deposits, such as iron, nickel, and potentially sulfides containing copper and cobalt.

Additionally, hydrothermal alteration processes, often linked to the formation of gold deposits, appear to be facilitated by the presence of tectonic fractures, such as faults F1, F2, and F3, which may act as conduits for mineralizing fluids. These findings present promising opportunities for mining exploration, especially in areas where magnetic anomalies coincide with active faults and hydrothermal processes.

Moreover, the presence of surface-level anomalies, such as A3, offers an opportunity for fast and cost-effective exploration. Future research should focus on complementary geological and geophysical surveys, including geochemical and seismic surveys, to better characterize these structures and confirm their mineralization potential.

A 3D modeling of tectonic structures could also enhance the understanding of subsurface dynamics and optimize exploration strategies for more efficient mining operations.

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