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(RESEARCH ARTICLE)

Structural analysis and interpretation of stresses in the Kounsitel area (Gaoual, Republic of Guinea)

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Abstract

This study examines the structural geology of the Kounsitel gold district, located within the Bassarides region of West Africa. Its primary goal is to characterize the arrangement of geological features and to reconstruct the evolution of the stress fields that governed the deformation and mineralization processes. The methodology employed combines the interpretation of satellite imagery (Landsat 8 and 9, STRM) with detailed field observations from five specific locations: Kounsitel Centre, Concasseur, Bantala, Kérèrè, and Boumehoun. Analysis of extracted lineaments, utilizing rose diagrams, reveals three predominant structural orientations: NE–SW, NW–SE, and E–W. A detailed examination of structures such as quartz veins, massives quartz veins, schistosity, folds, and bedding indicates a polyphase tectonic evolution, characterized by alternating periods of compressive and extensive stress regimes. Quartz veins document multiple fracturing events influenced by successive rotations of the stress field. Later-forming massives quartz veins, occurring after the veins, signify a late-stage compressive phase. Schistosity, appearing in three generations (S1, S2, and S3), points to progressive deformation associated with the Pan-African orogeny. This deformation involved an initial shortening phase, followed by transpressive deformation, and concluded with a late reorganization of stresses. Collectively, these results underscore a significant structural control over gold mineralization, with the NE–SW and NW–SE orientations serving as preferred conduits for hydrothermal fluid flow. Consequently, this research enhances our understanding of orogenic gold systems and offers valuable insights for mineral exploration activities within the Kounsitel region.

Keywords: Structural Analysis; Quartz Veins; Schistosity; Gold Mineralization; Pan-African.

1. Introduction

Structural analysis represents a fundamental approach for comprehending the processes of rock deformation and reconstructing the tectonic evolution of various regions [1], [2], [3], [4]. Geological structures, including fractures, folds, cleavage, and mineral veins, record tectonic stresses and enable the identification of deformation regimes [5]. These structures, found at various scales, serve as dependable indicators of the stress fields that have impacted geological formations throughout their evolution.

The Kounsitel sub-prefecture, situated in northwestern Guinea within the Gaoual prefecture, is part of the Bassarides domain, associated with Upper Proterozoic (Neoproterozoic) formations. This domain represents a Pan-African orogenic belt formed at the margin of the West African Craton, primarily comprising volcano-sedimentary and

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sedimentary sequences deposited in marginal basins [6], [7], [8], [9]. These formations were profoundly influenced by the Pan-African orogeny (~650–550 Ma), leading to folding, pervasive cleavage development, and the formation of major shear zones [10], [11], [12].

The Kounsitel study area exhibits a notable diversity of geological structures at outcrop, including folds, cleavage, fractures, and quartz veins. These structures indicate a multi-stage evolution, characterized by a series of ductile and brittle deformations [4], [8], [13], [14]. The observed structural orientations reflect a regional tectonic control tied to Pan-African stresses, often characterized by preferred orientations consistent with the major lineaments of the Bassarides mountain range. Some of these structures have been interpreted as late-stage fracturing or reactivation events [7], [8], [9], [15].

However, it is noteworthy that the Kounsitel area remains largely underexplored regarding the quantification of stress fields and the sequencing of deformation phases. Consequently, for a more comprehensive understanding of the region's tectonic evolution, it is essential to undertake an integrated study employing an approach that combines field observations, structural measurements, and statistical analyses [4], [8], [13], [14]. This study has thus enhanced our understanding of the Bassarides' tectonic evolution within the context of the Pan-African orogeny, providing insights into the structural control of mineralization [16], [17].

The objective of this study is to characterize the geological structures of the Kounsitel region by identifying the primary structural sets and their orientations, thereby reconstructing the tectonic stress field that shaped the region.

2. Geological Context

The study area is located in northwestern Guinea, specifically within the Gaoual prefecture, which is part of the administrative region of Boké (Figure 1). It spans between 11°03'46'' and 12°19'11'' North latitude and 12°41'16'' and 14°04'13'' West longitude. This prefecture encompasses an area of approximately 11,350 km^2 with an estimated population of 137,624, resulting in a relatively low population density of around 13 inhabitants/km^2 [18]. It is bordered to the north by Koundara prefecture, to the east by Mali and Lélouma prefectures, to the south by Télimélé prefecture, and to the west by Boké prefecture and Guinea-Bissau (Figure 1).

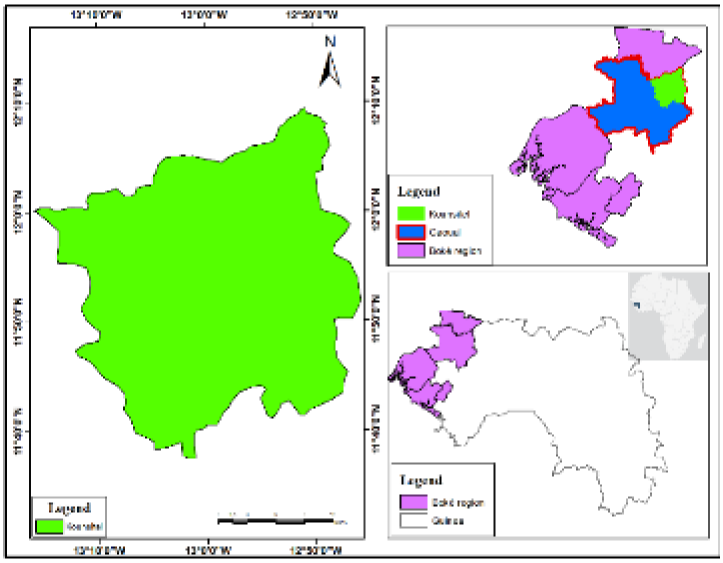


Figure 1 Map showing the geographical position of Gaoual and Kounsitel in the Republic of Guinea.

In the Kounsitel area, the geological sequence depicted on the geological map (Figure 2) aligns with the broader geological evolution of the West African Craton. It reveals a layered succession of rock units spanning from the Upper Proterozoic to the Quaternary period [7], [8].

The oldest recognized units date back to the Upper Rifean and are characterized by the siltstones of the Madina-Kouta Series [19], [20], [21], [22] (Figure 2). These formations suggest relatively calm depositional environments, likely within a platform or shallow basin setting [19], [20], [21], [22]. They are overlain by Vendian formations, which signify a transition towards more dynamic environments, characterized by both volcanic activity and sedimentary input. The

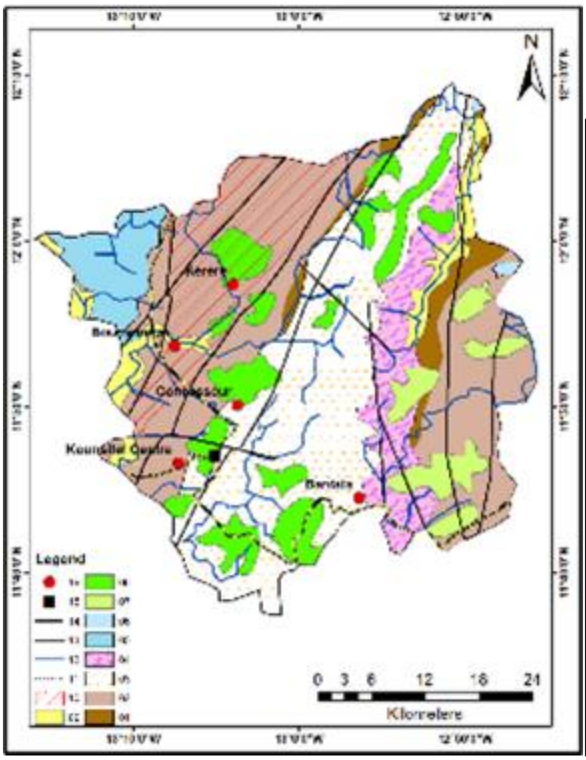
Koubia Suite is composed of basalts, indicating significant basic volcanism, while the Pananpou Suite, consisting of tuffaceous siltstones, reflects volcanoclastic activity [19], [20], [21], [22] (Figure 2). The Oundou Series, predominantly shales, corresponds to fine-grained sedimentary deposits laid down in relatively calm environments [19], [20], [21], [22].

These Precambrian units are succeeded by Paleozoic formations, which formed under transitional conditions, shifting towards sedimentary environments dominated by detrital input [19], [20], [21], [22]. The Cambrian period is represented by the shales and siltstones of the Falémé Series, as well as the polymictic and arkosic sandstones found in the upper part of the Youkounkoun Series (Figure 2). These deposits indicate more energetic sedimentary environments, likely associated with fluvial or deltaic systems [19], [20], [21], [22]. The Ordovician is distinguished by the sandstones of the Pita Suite, deposited in continental to littoral sedimentary settings, reflecting a relatively stable basin dynamic [19], [20], [21], [22], [23].

More recent Mesozoic magmatic intrusions cut across all these formations (Figure 2). They consist of diabases and dolerites, typically occurring as dikes or sills, signifying a later magmatic episode connected to the tectonic evolution of the African platform, particularly within the context of Gondwana's fragmentation [7], [8].

Finally, the Quaternary superficial formations (Figure 2) are composed of unconsolidated deposits (sands, gravels, and silts), primarily situated along watercourses such as the Tomine and Komba rivers. These deposits are a result of recent processes of weathering, erosion, and sedimentation, and can locally concentrate secondary mineralizations, notably gold, in the form of placers [19], [20], [21], [22], [23].

The entirety of this stratigraphic sequence observed in the Kounsitel area (Figure 2) reflects a complex geological evolution, characterized by alternating phases of sedimentary transgressions and regressions, likely influenced by major tectonic events that impacted the West African Craton [9, 20, 21, 22].



16- Areas measured; 15- County seat; 14- Roads; 13- Faults; 12- Rivers; 11- Supposed faults; 10- Metamorphic zone; 9- Quaternary: Sandy-clays, Sandy-loam, Gravel, Pebble; 8- Mesozoic: Dolerite, Gabbro-dolerites, Konga-Diabase; 7- Ordovician: Quartzitic and oligomictic sandstones (Pita Suite); 6- Cambrian: Argillites, aleurolites and sandstones (Faleme Series); 5- Cambrian: Polymictic and arkosic sandstones (Upper part, Youkounkoun Series); 4- Vendian: Tufaceous aleurolites, tufaceous sandstones (Pananpou Suite); 3- Vendian: Basalts, Basaltic porphyrites, andesites (Koubia Suite); 2- Vendian: Argillites, aleurolites (Oundou Series); 1- Upper Riphean: Aleurolites, Sandstones (Madina-Kouta Series)

Figure 2 Geological map of Kounsitel [19] (modified from)

3. Materials and Methods

3.1. Structural Map Development

The creation of the structural map for the Kounsitel area was based on the combined analysis of various satellite data. This included Landsat 8 and Landsat 9 imagery for observing surface structures, Sentinel-1A and ALOS-PALSAR radar data for detecting features beneath vegetation cover, and SRTM altimetry data for reconstructing the topography. After processing the images (enhancement, filtering, shading) using ArcGIS software, lineaments corresponding to faults, fractures, and shear zones were extracted with Geomatica software. These were then integrated into a lineament map that highlighted the predominant structural orientations. The coordinates of these lineaments were subsequently processed using RockWorks software to produce a rose diagram, which allowed for the visualization of preferred orientations.

3.2. Field Campaign

Fieldwork (Figure 3) was carried out in the Kounsitel area at five representative locations: Kounsitel Centre, Concasseur, Bantala, Kérèrè, and Boumehoun (Figure 2). These sites were chosen due to the quality of their outcrops, their accessibility, and the diversity of geological structures observed. This selection ensured good spatial coverage and representation of the study area.

Structural surveys were conducted using a geologist's compass (Brunton type), which enabled precise measurement of various structural parameters such as direction (azimuth), dip, structure type, and the nature of the host rock. Special attention was paid to cross-cutting relationships between structures in order to establish a relative chronology of tectonic events.

In total, nearly 200 structural measurements were collected across all sites. This data was supplemented by macroscopic observations of rocks and, where necessary, by the collection of samples for further analysis.

Figure 3 Field photograph showing two sets of veins (a) and pervasive schistosity (b).

3.3. Data Processing and Analysis

The structural data were subsequently compiled and analyzed to visualize dominant orientations and to group the structures into distinct directional families. This approach facilitated the identification of the main structural systems within the area.

Data processing was performed using Win-Tensor software, applied to 198 structural measurements. This enabled the reconstruction of stress fields and the determination of the orientations of the principal stresses (σ_1, σ_2, and σ_3).

Geographical coordinates for the various sites were recorded using a GPS device, ensuring accurate localization of the studied zones and their representation on the map (Figure 2).

4. Results

4.1. Structural Map of the Kounsitel Area from Satellite Imagery

The development of the study area's structural map (Figure 4) was based on the analysis of several types of complementary satellite imagery. Landsat 8 and 9 optical images allowed for the differentiation of various lithological units and the identification of structures visible on the surface. Sentinel-1A and ALOS-PALSAR radar data were employed to detect morphological features, including those obscured by vegetation. Furthermore, SRTM altimetry data were utilized to generate a Digital Elevation Model (DEM), which aided in highlighting lineaments.

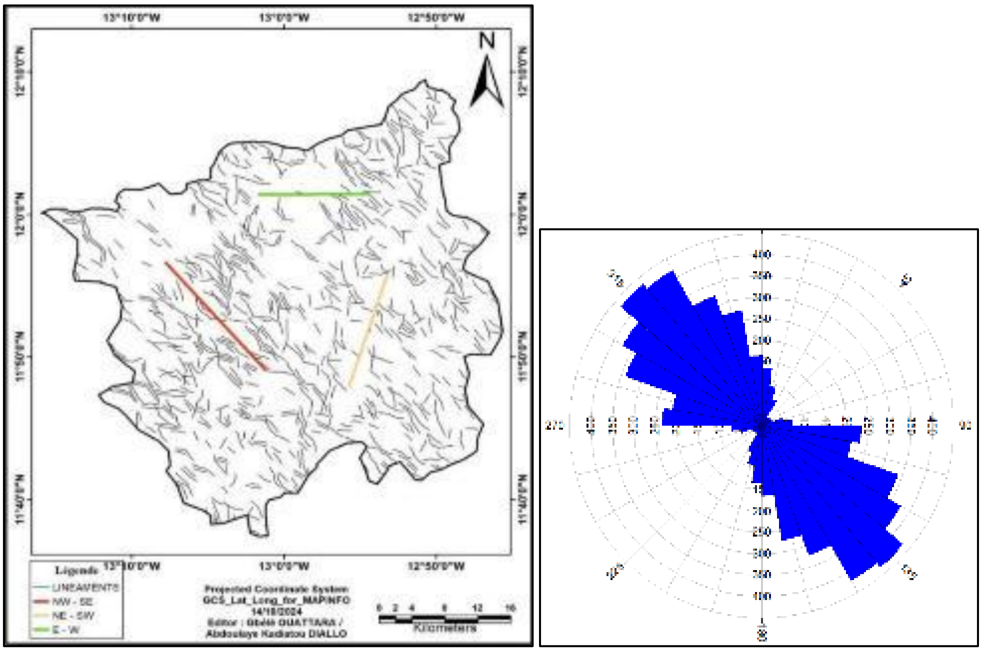


Figure 4 Lineament map of the Kounsitel area and directional rose diagram. The lines colored red, yellow, and green on the map represent the dominant NW–SE, NE–SW, and E–W directions, respectively.

The cross-interpretation of these datasets allowed for the extraction of major lineaments (Figure 4), which correspond to faults, fractures, and shear zones. This information led to the creation of a lineament map, crucial for understanding the structural organization of the area and its connection to gold mineralization (Figure 4).

The findings indicate three principal dominant structural orientations: NW–SE, E–W, and NE–SW, reflecting the influence of multiple tectonic phases (Figure 4). The rose diagram corroborates these trends and highlights preferred directions primarily between N110° and N170°, along with secondary orientations around N90°–N110° and N0°–N55°.

These orientations are also confirmed by field measurements (Figure 5), which show orientations of N120, N110, and N45. This suggests multiple phases of deformation over time during the region's tectonic evolution.

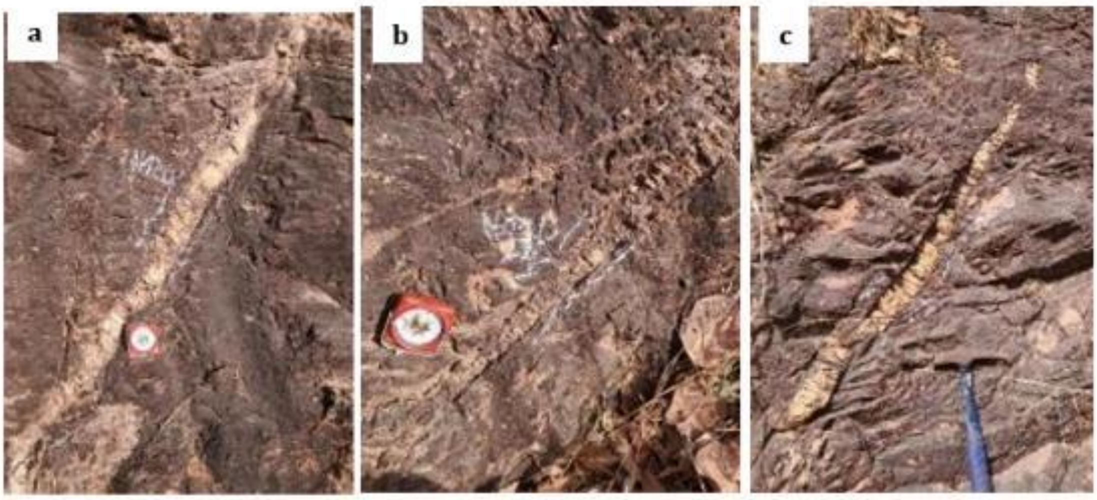


Figure 5 Quartz veins oriented (a) N120, (b) N110, and (c) N45.

Overall, these structures demonstrate a coherent and non-random arrangement of the fracture network, playing a pivotal role in controlling fluid circulation and gold mineralization within the Kounsitel area.

4.2. Structural Analysis

Within the scope of the structural analysis conducted in Kounsitel, particular attention was given to the orientation of measured structures and the characterization of tectonic stresses that affected the area. The features measured included quartz veins, mineral veins, schistosity, fractures, bedding, and folds.

These various structures serve as valuable indicators for identifying stress regimes (σ_1, σ_2, σ_3) and reconstructing the region's tectonic history. Investigations were carried out at the five aforementioned sites: Kounsitel Centre, Concasseur, Bantala, Kérèrè, and Boumehoun.

4.2.1. Kounsitel Centre

In total, 105 measurements were recorded, comprising 69 quartz veins, 3 mineral veins, 24 schistosity planes, and 8 bedding planes and fold axes.

4.2.2. Quartz Veins

Quartz veins (Figure 6) constitute the most abundant structures in this particular zone. Their analysis reveals three main families based on their orientation.

Figure 6 Quartz veins cutting across each other, observed on a roadside outcrop.

An examination of these veins reveals three distinct structural groups, indicating a complex, multi-stage evolution of the forces acting on the rock. The first group, comprising seven veins running from northwest to southeast, formed under compressive conditions (where the main squeezing force was vertical) with the compression acting from northeast to southwest. This signals a period of crustal shortening. The second group, consisting of 28 veins primarily oriented east-west, corresponds to an extensional phase (where the main pulling force was vertical) with the extension directed north-south. This indicates a period when fractures opened up, allowing fluids to move through. Finally, the third group, made up of 34 veins mostly aligned northeast-southwest, developed during a second extensional event (again with the principal pulling force being vertical), but this time with extension directed northwest-southeast.

Collectively, these observations point to a complex tectonic history, beginning with a period of compression, followed by two separate phases of extension, all accompanied by a gradual shift in the forces acting on the area.

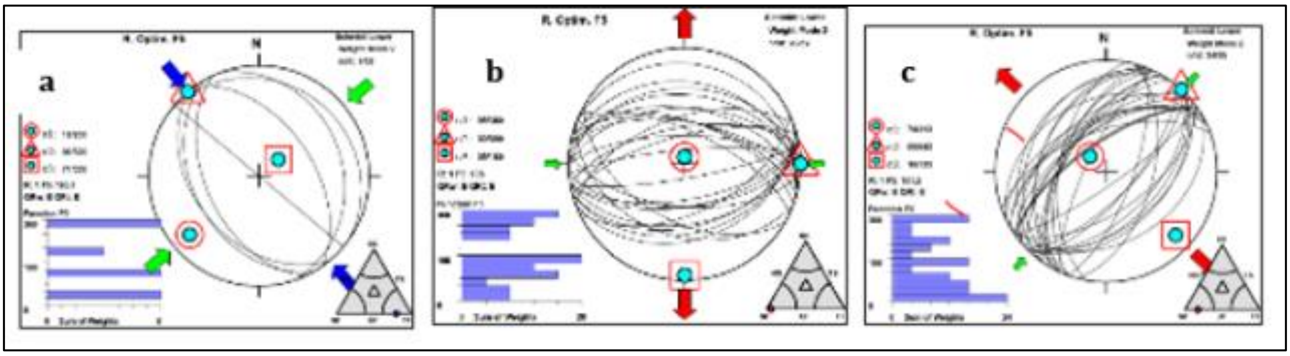


Figure 7 Stereographic diagram showing the various veins observed in the field and the reconstructed ancient stresses that created them at Kounsitel.

4.2.3. Massive quartz veins

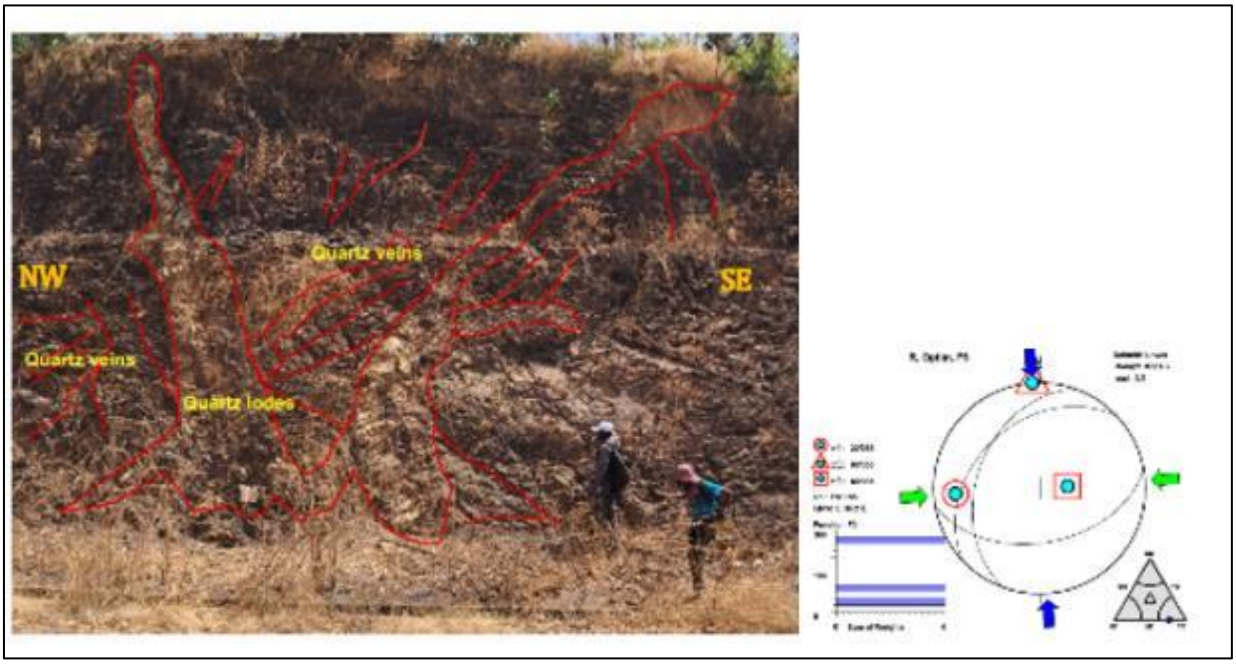


Figure 8 Interpreted photograph and stereographic diagram of the **massive quartz veins** and their associated stress regime at Kounsitel**.**

Three massive quartz veins measuring between 0.8 and 2 meters across, were identified in this area. Their analysis indicates they formed under compressive conditions (with the main squeezing force being vertical), with the massive quartz veins oriented NNE-SSW, suggesting a main compression from east-northeast to west-southwest (Figure 8). This alignment points to a shortening phase linked to a later rearrangement of the regional stress field. Furthermore, field observations show these massive quartz veins are younger than the quartz veins, as no veins cut across the massive quartz veins. This confirms they formed during a more recent tectonic event. Overall, it seems these massive quartz veins represent a final stage of deformation, occurring after the fracturing and mineralization events recorded by the quartz veins.

4.2.4. Bedding and Folds

The observed bedding layers (S0) and fold axes clearly indicate formation under a compressive regime (where the main squeezing force was vertical). The primary direction of compression that caused this folding was oriented northeast-southwest (Figures 9 and 10).

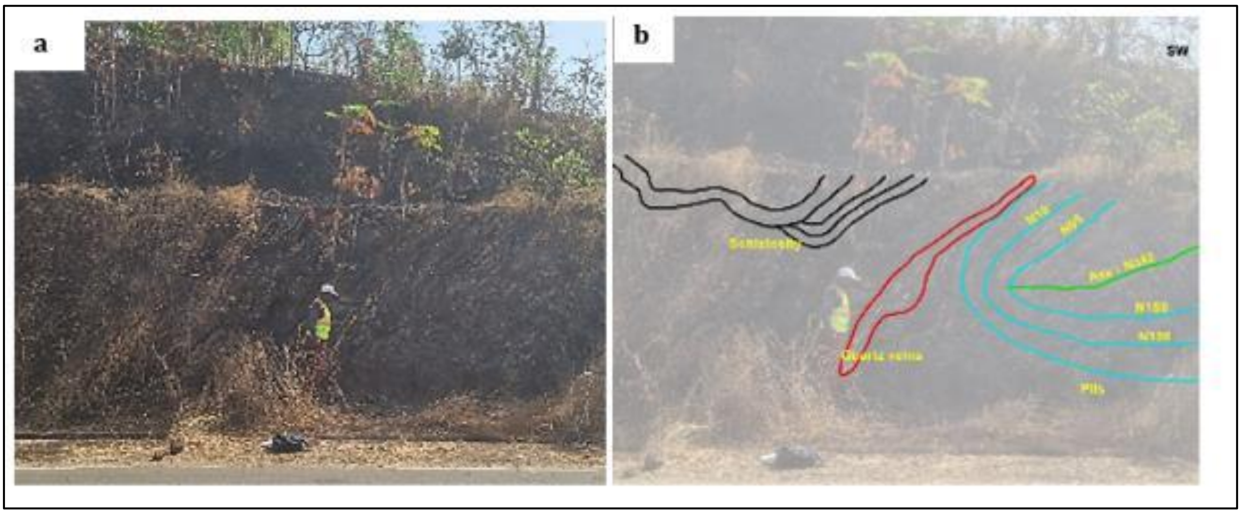


Figure 9 Photograph of an outcrop (a) and its associated interpretation (b) at Kounsitel**.**

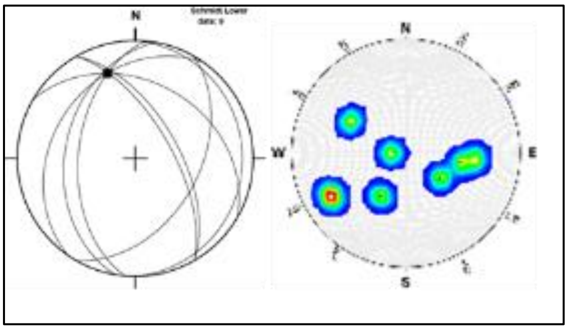


Figure 10 Stereographic diagram and pole density for Kounsitel.

4.2.5. Schistosity

The schistosity found in central Kounsitel also fits within this compressive setting, reflecting significant tectonic deformation of the surrounding rocks (Figure 11). Structural analysis reveals three distinct groups of schistosity: S1, S2, and S3.

These schistosity patterns (S1, S2, and S3) point to multi-stage deformation connected to the Panafrican Orogeny in the Bassarides region. S1 is linked to an initial phase (D1) of regional shortening under compression, with the main stress (σ1) oriented roughly east-west, responsible for the development of the early regional schistosity. S2 is associated with a more intense deformation phase (D2), characterized by the re-orientation of earlier structures and occurring under a transpressive regime, which combines compression with oblique shearing. S3 is tied to a late phase (D3) marked by a re-alignment of the stress field, likely under a late transpressive to strike-slip regime, with the main stress (σ1) rotating towards a northeast-southwest direction. Altogether, this signifies a progressive tectonic evolution, starting with initial shortening, followed by non-coaxial deformation, and a rotation of stress directions throughout the Panafrican development of the Bassarides (Figure 12).

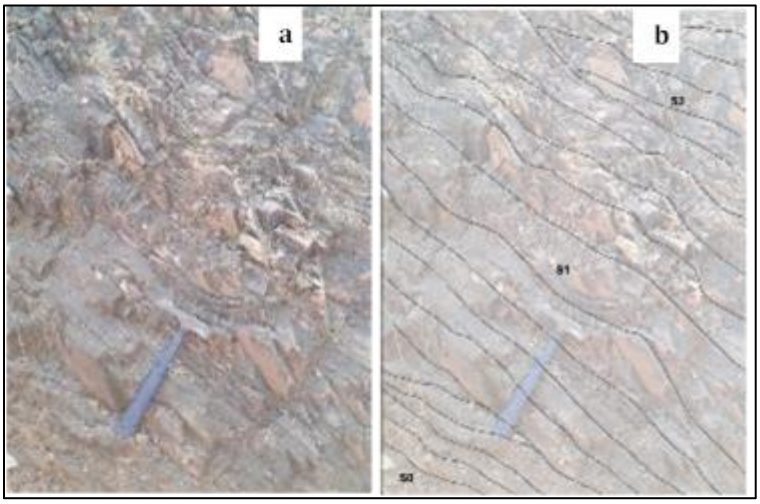


Figure 11 Photograph of an outcrop (a) and the interpretation of different schistosities (b) at Kounsitel.

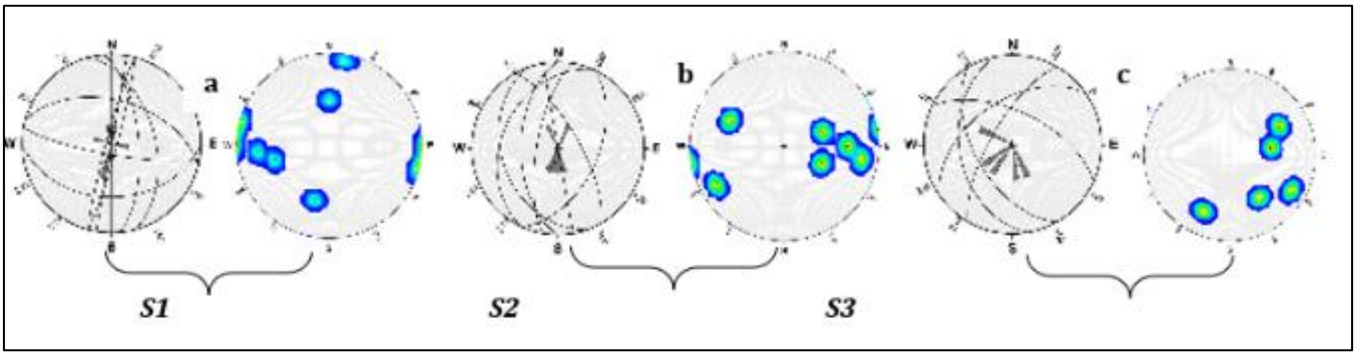


Figure 12 Stereographic diagram, associated directional rose diagram, and schistosity poles at Kounsitel.

4.2.6. Concasseur Site

At the Concasseur site, examining 39 quartz veins allowed for the identification of three main structural families, indicating several successive tectonic phases (Figure 13). The first group, made up of thirteen veins, formed under an extensional regime (with the primary pulling force being vertical) and is oriented northwest-southeast, reflecting a period of fracture opening that facilitated fluid movement (Figure 14a). The second group, comprising fifteen veins, developed under a compressive regime (where the main squeezing force was vertical) with compression directed north-northeast to south-southwest, indicating a phase of shortening and stress field rearrangement (Figure 14b). Finally, the third group, consisting of eleven veins, corresponds to another extensional episode (with vertical principal stress), but this time oriented northeast-southwest, suggesting a renewed period of extension in a different direction (Figure 14c). Overall, this reveals a multi-stage tectonic evolution marked by alternating extensional and compressive phases, alongside successive rotations of the stress field that governed the formation of these quartz veins.

Figure 13 Quartz veins observed in the field at the Concasseur site.

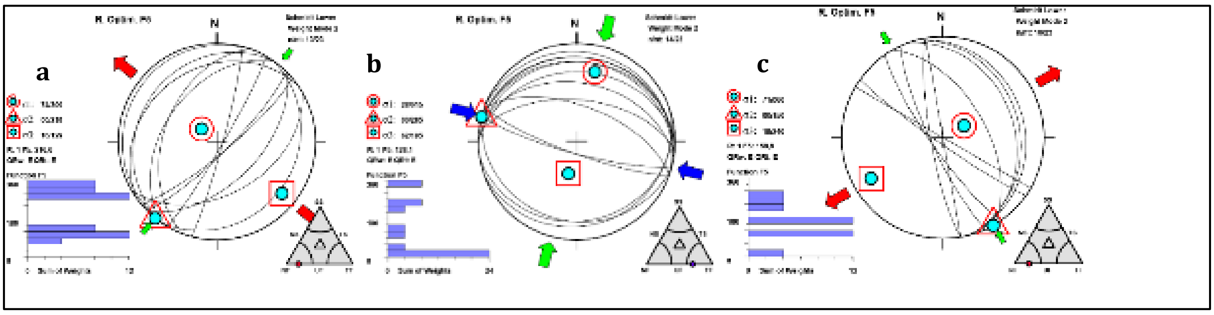


Figure 14 Stereographic diagram of the quartz veins at Concasseur.

4.2.7. Bantala

In the Bantala area, the analysis of 30 quartz veins revealed three distinct structural families, indicating a polyphase tectonic evolution (Figure 15). The first family, comprising twelve (12) veins, corresponds to another NW–SE oriented compressive episode, suggesting a fracture opening phase conducive to fluid circulation (Figure 16a). The second family, consisting of nine (09) veins, developed under a compressive regime (vertical σ3) with a NE–SW compression direction, marking a phase of shortening and stress field reorganization (Figure 16b). Finally, the third family, made up of nine (09) veins, formed under an extensive regime (vertical σ1) with a NE–SW direction, reflecting a rotation of stresses and an intensification of deformation (Figure 16c). Collectively, these observations highlight a complex tectonic history characterized by alternating compressive and extensive phases, as well as successive changes in the orientation of the stress field that controlled the emplacement of the quartz veins.

Figure 15 Quartz veinlets in the basalts and stockwerk of Bantala**.**

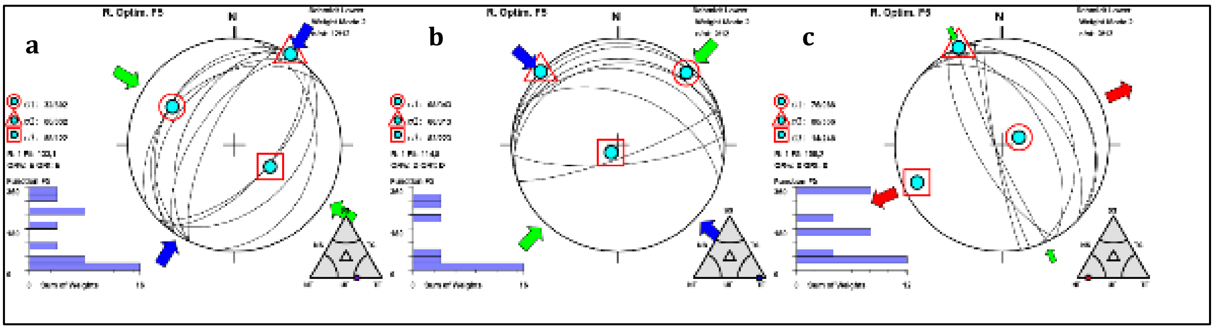


Figure 16 Stereographic diagram of the Bantala quartz veins**.**

4.2.8. Kérèrè

At Kérèrè, the analysis of 15 quartz veins identified two structural families, both associated with compressive phases (Figure 17). The first family, comprising five (05) veins, formed under a compressive regime (vertical σ_3) with a NW–SE compression direction, representing an initial shortening phase (Figure 18a). The second family, composed of ten (10) veins, also corresponds to a compressive regime, but with a NNW–SSE compression direction, indicating a reorientation of the stress field (Figure 18b). Overall, this highlights a tectonic evolution dominated by compression, characterized by at least two successive shortening episodes that controlled the formation of the quartz veins.

Figure 17 Quartz veins of Kéréré.

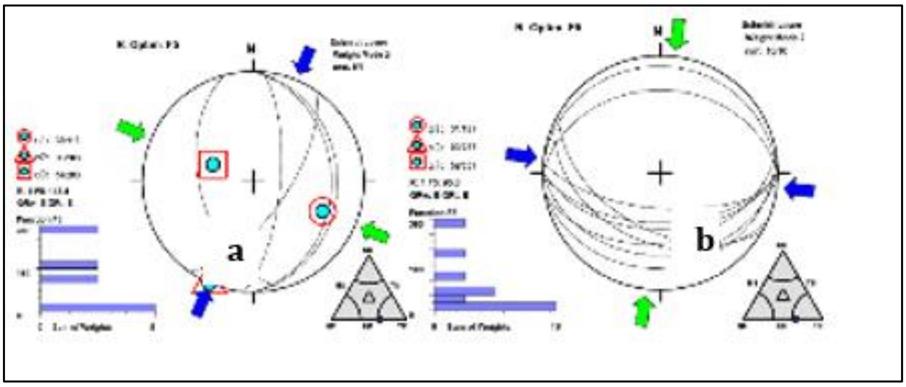


Figure 18 Stereographic diagram of the Kéréré quartz veins.

4.2.9. Boumehoun

In the Boumehoun area, structural observations primarily focused on the schistosity affecting sandstones. Its development is associated with a compressive regime (vertical σ_3) with a NW–SE compression direction, reflecting a regional shortening phase (Figures 19 and 20).

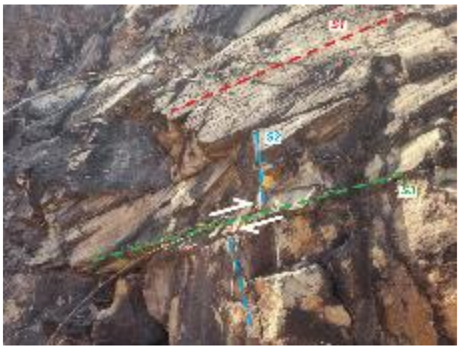


Figure 19 Schistosity in Boumehoun sandstones**.**

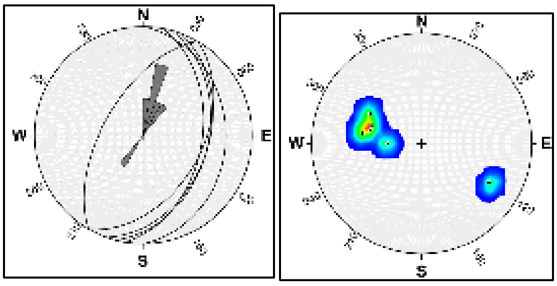


Figure 20 Rose diagram and pole density of Boumehoun schistosity.

Additionally, three (03) fractures cutting across siltstone layers were also noted (Figure 21); these developed under a compressive regime, but with a NE–SW compression direction, indicating a reorientation of the stress field during deformation (Figure 21). It should be noted that the limited amount of data necessitates a cautious interpretation due to its low robustness. The presence of stratification observed in the area complements these elements and highlights the superposition of primary sedimentary structures and tectonic structures. Together, these observations point to a structural evolution dominated by compression, marked by at least two successive shortening episodes.

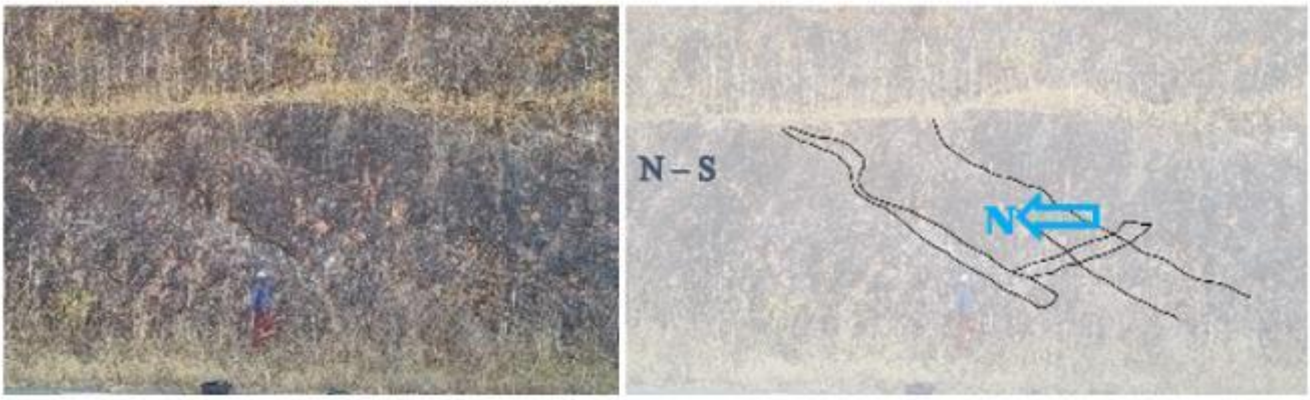


Figure 21 Fractures in Boumehoun sandstones**.**

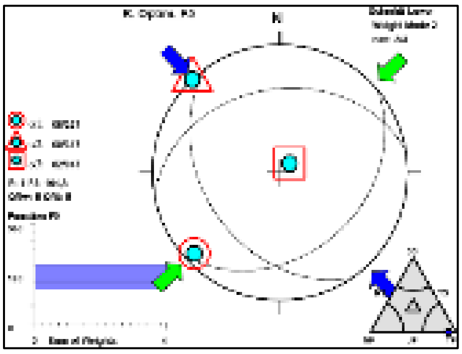


Figure 22 Stereographic diagram of the quartz veins at Boumehoun.

5. Discussion

The results obtained in the Kounsitel area fit into the broader context of the Panafrican tectonic evolution of West Africa, particularly within the Bassarides chain. The structural organization, dominated by NE–SW, NW–SE, and E–W directions, along with the alternation of compressive and extensive regimes, reflects a complex geodynamic history previously described in several regional studies [7], [8], [9], [10], [24].

The predominance of compressive regimes, evidenced by schistosities (S1, S2, S3), folds, and certain vein families, is consistent with tectonic models proposed for the Panafrican orogeny. According to Jean-Paul Liégeois [25], this orogeny is characterized by successive phases of crustal shortening linked to the collision between the West African Craton and surrounding mobile blocks. In this context, the D1 phase generally corresponds to a major regional compression responsible for the formation of the early schistosity (S1), which aligns with observations made at Kounsitel.

The D2 phase, characterized in this study by structural transposition and the development of S2 schistosity within a transpressive regime, resonates with the work of Villeneuve [8], [9], which emphasizes the importance of non-coaxial deformations in Panafrican evolution. These transpressive regimes are often associated with major shear zones, promoting both ductile deformation and hydrothermal fluid circulation.

The late D3 phase, characterized by a reorientation of the stress field and potentially strike-slip movements, is also well-documented in the literature. The studies by Wit [26] highlight that late stages of orogenies are often marked by crustal fragmentation and reactivation of pre-existing structures under transtensive or transpressive regimes. This evolution is consistent with observations from Kounsitel, particularly the rotation of stress directions and the superposition of tectonic fabrics.

Furthermore, the alternation of compressive and extensive phases observed within the quartz veins confirms that hydrothermal systems are strongly controlled by tectonic dynamics. As noted by As Goldfarb [27], [28], orogenic gold deposits are generally associated with active deformation zones, where cycles of compression and extension promote rock fracturing, fluid circulation, and gold precipitation.

In the case of Kounsitel, the NE–SW and NW–SE directions appear as major structural axes controlling the emplacement of veins and lodes. These orientations are comparable to those described in other gold districts of the West African Craton, particularly in Ghana and Mali, where Birimian shear zones play a key role in localizing mineralization [29], [30], [31], [32].

6. Conclusion

Detailed structural analysis of the Kounsitel area reveals a complex tectonic arrangement, shaped by a multi-stage evolution of the stress field. Mapping of linear features and their graphical representation highlight three primary structural orientations (NW–SE, NE–SW, and E–W). These directions correspond to systems of fractures, faults, and shear zones that significantly influenced both the regional architecture and the circulation of mineralizing fluids. Examination of various geological structures (such as quartz veins, schistosity, and folds) underscores this complexity, indicating a tectonic history characterized by alternating periods of compression and extension. Notably, the development of schistosity, observed in three generations (S1, S2, S3), serves as a key indicator of progressive deformation linked to the Pan-African orogeny. This involved an initial shortening phase (D1) forming S1, followed by a more intense, non-coaxial transpressive deformation (D2) generating S2, and a later phase (D3) potentially associated with strike-slip movements, producing S3. Findings across all investigated locations within the Kounsitel region demonstrate a consistent pattern, generally dominated by compressive regimes complemented by secondary extensional episodes. This dynamic tectonic evolution, marked by rotating stress fields, has profoundly influenced the structural architecture, which in turn plays a fundamental role in controlling gold mineralization. Specifically, fracture zones, particularly those aligned NE–SW and NW–SE, acted as preferred pathways for hydrothermal fluids and favorable sites for gold precipitation. Therefore, a thorough understanding of this tectonic progression is crucial for effective mineral exploration in the Kounsitel area.

Compliance with ethical standards

Disclosure of conflict of interest

The authors confirm that they have no conflicts of interest, whether financial or personal, that could be perceived as influencing the results or interpretation within this article.

Furthermore, this research was conducted without specific external funding from public, commercial, or non-profit organizations. The datasets underpinning this investigation, encompassing field structural measurements and interpretations derived from satellite imagery analysis, are accessible through the designated contact author upon a reasonable request. Each author played a substantial role in the conception of the study, the acquisition and examination of data, as well as in the composition and final endorsement of the manuscript. Moreover, all field investigations were performed in strict observance of the prevailing local regulations within the Republic of Guinea.

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