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Tectonic Evolution of Paleoproterozoic Formations in the North-East of Côte d'Ivoire (Bondoukou-Tanda, West African Craton)

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Abstract

The objective of this work is to contribute to the crustal evolution during the Paleoproterozoic in the Northeast of Côte d'Ivoire through the structural study of the Bondoukou-tanda locality. To do this, we proceeded by a macroscopic observation of the outcrops for the identification of the structures (schistosity, fold, shear, and lineation). The structures indicated the direction of the main constraints and the relative correlations between the lithologies. The structural measurements, in particular the direction and the dip obtained, were all processed by the GEOrient software to draw up the stereographic projections for a static interpretation of the measurements. Given the rarity of rock outcrops in the study area, the teleanalytical data were of considerable support in the structural analysis. The various treatments carried out on the ENVI 5.2 software made it possible to identify a total of 471 lineaments. They cover the entire area and are of variable lengths (1.24 to 9.73 km). The different directions highlighted from this methodology are a main direction: NNW-SSE to NW-SE; a secondary direction: NNE-SSW to NE-SW; a tertiary direction: ENE-WSW to E-W. Associated with the lithology map, the teleanalytical map shows that the lineaments are unevenly distributed throughout the study area. The lineaments appear more compact in the volcano-sedimentary and sandstone-conglomeratic units than in the granitoid intrusives. However, the Bondoukou granodiorite appears to be the least fractured lithology.

Keywords

Structural, Birimian, Bondoukou-Tanda, Tarkwaian, WAC

1. Introduction

The North-Eastern region of Côte d'Ivoire, particularly Tarkwaian formations, has aroused the curiosity of many authors including [1] [2]. This region, which straddles the regions of Agnibilékrou, Tanda and Bondoukou, contains different lithological sequences which have experienced several episodes of deformation. The lithostratigraphy and geodynamic evolution of these Paleoproterozoic terrains proposed by the various authors continue to fuel discussions. The first authors including Bouige, Archambault and Bonnault individualized in the region strongly dipping Birimian series and Tarkwaian deposits, discordant in the Birimian. The work of [3] revealed this angular unconformity existing between various Tarkwaian terms and the Birimian volcano-sedimentary complexes. Later, inspiration from the "Ghanaian" model of [4], most authors including [5] reveal the existence of two Birimian volcano-sedimentary sets (B1 vs B2, BS vs BV) and three major tectonic episodes in the region. However, if this bimodal interpretation of the Birimian is unanimous among English and French geologists, there remains less regarding the stratigraphic order. The English geologists [6] subdivide the Birimian into the Lower Birimian (B1) made up of sedimentary rocks with intercalations of volcano-sediments and the Upper Birimian (B2) made up of volcanic rocks. The French geologists [7] [8] for their part propose a stratigraphic order reversing the stratigraphic succession of the English geologists; they subdivide the Birimian into the Lower Birimian (B1) with volcanic or volcano-sedimentary dominance and the Upper Birimian (B2) with sedimentary dominance. Located in the Paleoproterozoic domain, the geological formations of the Bondoukou region were structured during the Eburnean orogeny. The geological formations in the Bondoukou region and the complexity of the structural phenomenon make their study difficult. From a lithological point of view, the study area is covered by a complex set of geological formations. This work is a contribution to the lithostructural study to know the history of tectonic events which affected the geological formations in this region.

2. Geological Context

The West Africa crust is made up of a Precambrian basement commonly called the West African Craton with an area of approximately 4,500,000 km^2 (**Figure 1**). The Leo-Man Rise is composed by an Archean cratonic nucleus in the southwest, the so-called Kéména-Man domain (KMD), surrounded by some Paleoproterozoic belts in the north and east forming the Baoulé-Mossi domain [9]. The Kénéma-Man Domain covering Liberia, part of Côte d'Ivoire, Guinea and Sierra Leone, where the rocks are of Archaean age. They are banded gray gneisses of tonalitic composition with intercalations of pink granulite orthopyroxene, and charnockites [10]. Calco-alkaline granite plutons, after metamorphism of granulite facies, intruded the grey gneiss. Two orogenic phases are recognized in this domain: the Leonian cycle (3.3 - 3.2 Ga) and the Liberian cycle (2.8 - 2.7 Ga). Baoulé-Mossi Domain, covers part of Côte d'Ivoire and its neighboring countries as well as Niger and Togo.

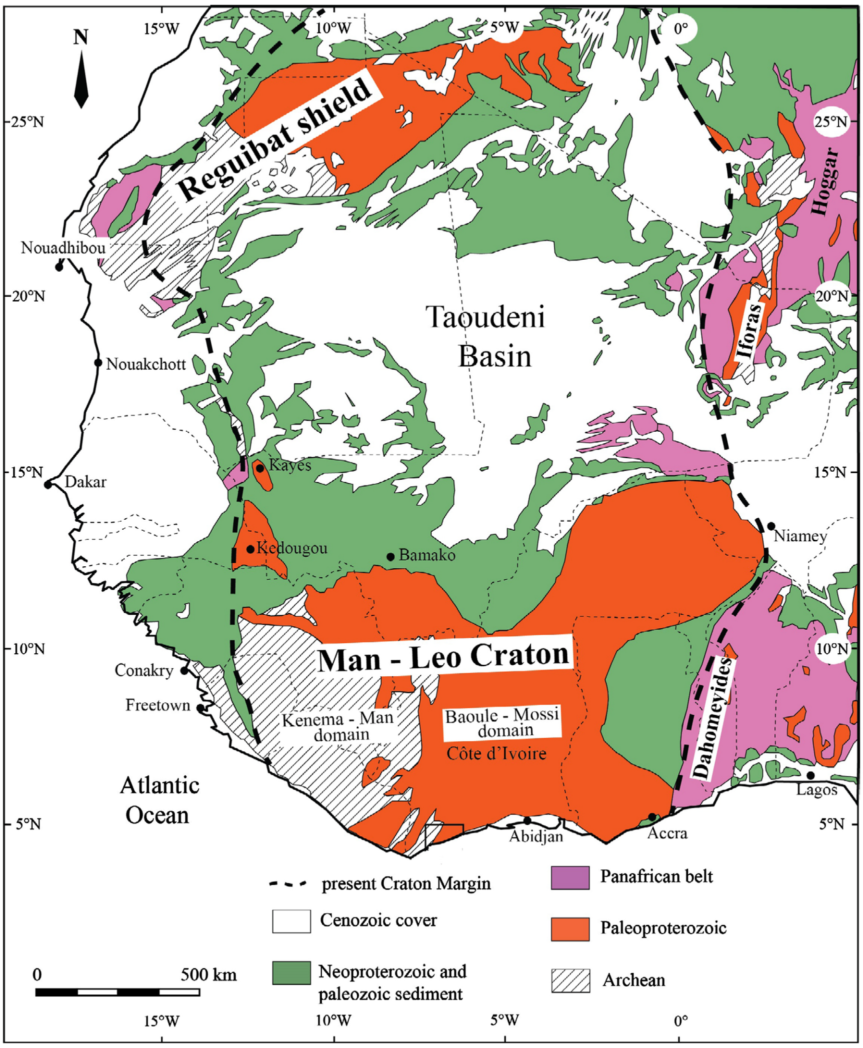

Figure 1. Simplified tectonic map of West African Craton [36].

The Baoule-Mossi Paleoproterozoic domain of the West African Craton (WAC) was accreted to the Archean nucleus of The WAC During the Eburnean orogeny [11]-[15] (**Figure 1**). The Baoule-Mossi domain is composed of Birimian greenstone belts made of metavolcanic, metavolcanosedimentary, and metasedimentary rocks, emplaced between 2220 and 2160 Ma [16] [17], And Bandamian Volcanic rocks aged between 2120 And 2080 Ma [13] [18] [19]. The greenstone belts alternate with gneiss, migmatite, and granitoids that are referred to as granitoid gneiss complexes. Greenstone belts were affected by greenschist grade metamorphism during the Eburnean orogeny, rising to amphibolite grade in granitoid gneiss complexes. The greenschist-amphibolite facies transition has been interpreted to represent metamorphic.

In the western subprovince, the Baoulé-Mossi Paleoproterozoic domain is tectonically juxtaposed with the Archean KMD, and separated from it by the

Sassandra fault [20] [21]. Important Paleoproterozoic reworking of the margins of the Archean KMD is described southwestern Côte d'Ivoire [10] [22] and southeastern Guinea [23]. Two models have been suggested to explain the reworking process. The first model postulates enormous crustal thickening due to large-scale thrusting of Paleoproterozoic formations onto the Archean craton, in agreement with a collisional-type orogen [5] [24]-[28]. The second model proposes crustal thickening accommodated by a combination of transpressive shear zones and lateral crustal spreading [16] [18] [22] [29]-[34], *i.e.* structures typically developed in accretionary-type orogens [35].

3. Methodology

The approach to the structural study was done in combination with macroscopic petrography on the outcrops. Following the identification of the structures (schistosity, fold, shear, and lineation), the appropriate structural measurements were collected using the clinometer compass. The structures indicated to us the direction of the main constraints and the relative correlations between the lithologies. The structural measurements, notably the direction and dip, obtained were all processed by the GEOrient software to draw up stereographic projections for a static interpretation of the measurements (**Figure 2**). Also, the measurements were associated with geological sections in order to make structural syntheses but also litho-structural syntheses using the software ArcGIS, GEOrient, Adobe Illustrator and MapInfo associated with Discover. The microscopic approach to the structures is carried out during observation sessions with a polarizing microscope. Given the rarity of rock outcrops in the study area, the teleanalytical data provided considerable support in the structural analysis.

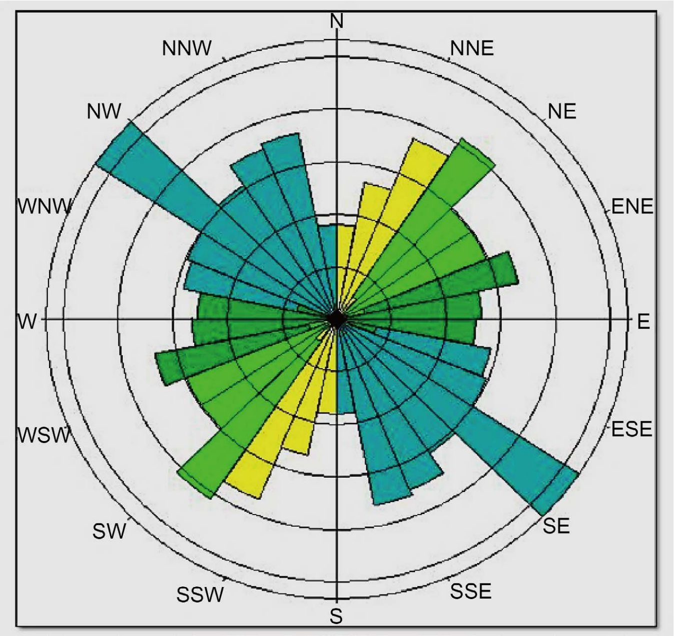

Figure 2. Directional rosette showing lineament orientations.

The remote sensing work was carried out on synthetic aperture RADAR (SAR) images (**Figure 3** and **Figure 4**). The images come from the Canadian RADARSAT-1 satellite. They were acquired on August 21, 1999 in descending orbit in Scansar mode with a resolution of 50 m in the C band and in HH polarization. The various treatments were carried out on ENVI 5.2 software. The images acquired underwent two essential stages to be used properly. These are: pre-treatment and the treatment itself. Preprocessing takes into account radiometric and atmospheric correction of the image. As for the processing, it was carried out in three stages: speckle reduction, linear spreading and application of directional filters. Several adaptive filters have been tested for speckle reduction. These are

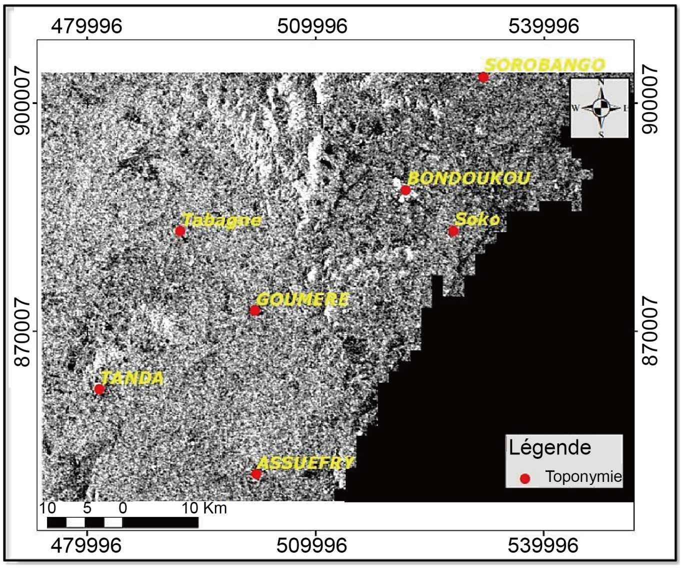

Figure 3. Radarsat-1 image enhanced with the 3 × 3 Gamma filter.

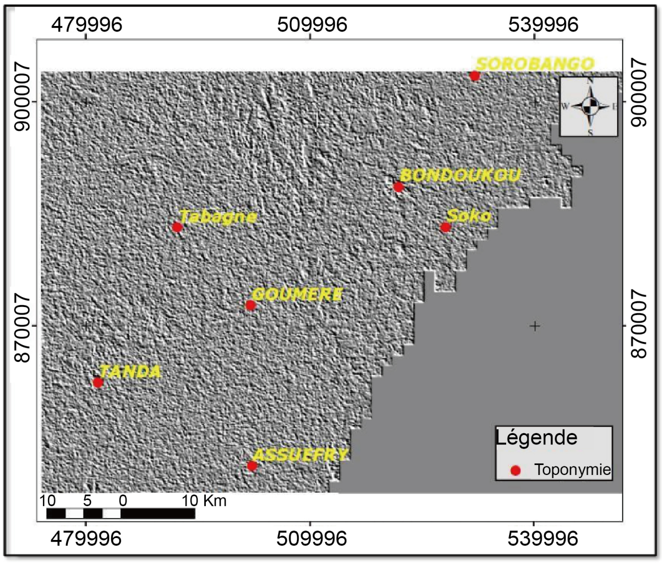

Figure 4. Radarsat-1 image enhanced by the NE-SO Sobel filter.

Gamma, Frost, Lee, Kuan, etc. filters. The Gamma filter of size 3 × 3 was selected for speckle reduction. A linear spread of 2% was applied to the enhanced image from the Gamma filter in order to improve contrast. On the image obtained from previous processing, several directional filters were applied including the Sobels filters (NE-SW, N-S, E-W and NO-SE), the Prewitt filter and the Yesou filter. From the different enhanced images, several lineaments were identified. A lineament validation phase was carried out in order to discriminate natural lineaments from anthropogenic lineaments. This phase was carried out on the Global Mapper 21.1 software. This step was carried out by superimposing the lineaments obtained on the topographic map of the study area.

4. Results

4.1. Structural Context in Outcrop

The various outcrops encountered revealed the existence, on the one hand, of well-preserved stratifications in certain lithological facies and on the other hand, of structural elements such as regional folds, schistosities and foliations, microfolds and crenulations, faults and shears as well as joints and veins.

4.2. Regional Stratifications and Folds

Stratification (So) is preserved in the metasediments represented by sandstones, conglomerates and sericitoschists (**Figure 5(a)**, **Figure 5(b)**). In the sandstone-conglomeratic metasediments of Bondoukou, Tanda and Zanzan, the rhythmic alternation of sandstone-conglomerates and their orientations suggest the existence of large regional folds whose generally E-W axes sometimes evolve in ENE-WSW and WNW-ESE directions. These sediments lie unconformably on all other lithological facies in the region, including sericitoschists. In sericitoschists, stratification is difficult to perceive due to the fine grain size of the constituent elements of the original rock. We note an alternation of purely phyllite beds and quartzo-phyllite beds that are sometimes very compact, rigid and difficult to break with a hammer. However, in the sericitoschists, the deformation has strongly obliterated the stratification.

4.3. Flow Schistosities and Lineations

In metavolcanics and volcano-sediments, the dominant deformation structures are flow schistosities and fracture schistosities. However, in plutonic massifs, schistosity is expressed by the preferential orientation of minerals in the planes. In the sandstone-conglomeratic metasediments, there is no sign of penetrative deformation. Disjointed schistosity (S0/S1) is dominant with very low to medium dips of around 10 to 40˚ and E-W directions. In metavolcanics as well as in sericitoschists metasediments, the schistosity is well marked and more or less penetrative. This schistosity is marked by the crystallization of sericite or muscovite and chlorite. It has generally steep dips (>60˚) and orientations N-S to NNESSW (**Figure 5(b)**, **Figure 5(c)**). In the village of Chiago on the Tanda-Bondoukou

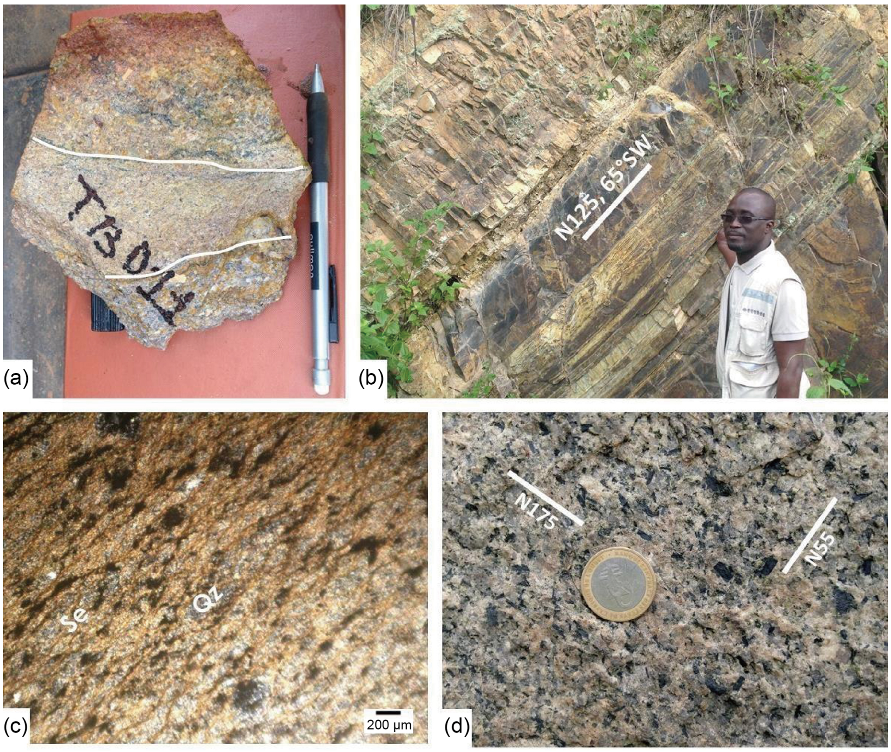

Figure 5. Stratifications and schistosities. (a) Stratification with alternation of sandstone and micro-conglomerate; (b) Stratification subparallel to the schistosity in the Chiago sericitoschists indicating a dolerite sill; (c) Schistosity marked by sericite and quartz minerals in the sericitoschists; (d) Isotropic appearance of Bondoukou granodiorite with variable mineral orientations.

axis, we were able to observe a beautiful outcrop in the road trench made during the reprofiling work. The schistosity (S1) in the sericitoschists is oriented N125, 65˚SW. Several other measurements indicate WNW-ESE and N-S schistosity directions. The schistosity planes (S1) are formed of chlorite-muscovite or sericite minerals testifying to a low degree regional metamorphism, of the greenschist facies. However, near the plutonic massifs, we note a crystallization of biotite and amphibole minerals in the metasediments and annealing textures. The biotite and/or amphibole crystals form a mineral stretching lineation (L1) with a strong dip of 50˚ to 70˚. Initially flattened, the schistosity becomes rotational at the periphery of the granitoid plutons and gradually matches their internal schistosity. It is subject to the establishment effects of intrusives and often changes in directions NNW-SSE to NW-SE. In plutonites, on the other hand, the schistosities correspond to a magmatic fluidity marked in certain places by the preferential orientation of the minerals (**Figure 5(c)**). These plutonites present magmatic banding in contact with volcano-sedimentary rocks. They are marked at the heart by a more or less horizontal mineral lineation which gradually gives way to flattening then to transcurrent shearing on the edges. The Bondoukou granodiorite shows an isotropic texture in its central part and a submagmatic foliation towards its ends. This foliation has variable directions with strong (>70˚) and centrifugal dips around the central part. The biotite-amphibole crystals form with the plagioclase crystals a strongly dipping mineral stretching lineation (Lm) carried by the foliation. Two major directions of more or less perpendicular mineral lineation have been described: N175 and N85 (**Figure 5(d)**). In granites where the mineral lineation is difficult to identify, the elongated shapes of the mafic enclaves make it possible to determine the stretching directions of the minerals. These stretching lineations defined by the enclaves can be interpreted in terms of magmatic stretching.

4.4. Microfolds and Crenulations

During the fieldtrip, there did not exist crenulation schistosities (S2) in the strict sense of the term in the volcano-sediments. These structures are also almost absent in plutonites. However, poorly penetrative crenulations and microfolds folding stratification (So) and schistosity (S1) have been described in volcano-sedimentary formations.

On the road to the village of Zanzan precisely in Kaniassé, we observe microfolds with an orientation axis (N125, 25˚SE) associated with sandstone-conglomeratic metasediments (**Figure 6(a)**). Training folds corresponding to point crenulations of parallel hinges have been described in sericitoschists. In Chiago, these local folds indicate the existence of a major fold corresponding to an anticline whose axis is subhorizontal. Crenulation microfolds of oriented axial planes (N40, 80 - 90˚) have been described in certain metavolcanics. At the apex of certain granitoid domes, recumbent microfolds develop showing a direction of centrifugal spilling. This crenulation of the axial planes corresponds to the schistosity planes (S2) where the recrystallizations are chlorite and muscovite or sericite. This S2 crenulation schistosity locally carries a subhorizontal mineral stretching lineation (L2).

4.5. Faults and Joints

The brittle deformation affected all the lithological facies of the study area. It is abundant in metavolcanics and volcano-sediments and less abundant in plutonic massifs. Several structural elements have been highlighted for this purpose:

- sinistral shears oriented N30 90˚ (**Figure 6(b)**), conjugate joints with respective orientations N165 90˚ and N30 90˚, as well as families of joints with orientations N65 70˚NW; N80 35˚S; N45 78˚SE; N165 67˚E and N15 63˚W in sandstone-conglomeratic sediments;
- strike-slip faults oriented N65 45˚SE as well as transcurrent faults which cut and offset the So/S1 schistosity in the sericitoschists (**Figure 6(c)**);
- in the plutonites and intrusive massifs, dextral or sinistral shears of orientation (N50, N150 and N175) highlighted by the shapes of the mafic enclaves (**Figure 6(d)**), normal faults (N180 75˚W), dextral or sinistral strike-slips N110 90˚ shifting submagmatic foliation (**Figure 6(e)**), N110 90˚ orientation tension slots, as well as joints orientations (N50 20˚SE; N125 70˚SW; N95 75˚N; N150

60˚SW and N120 80˚NE;

- dextral microshears affecting dolerites and sericitoschists (**Figure 7**).

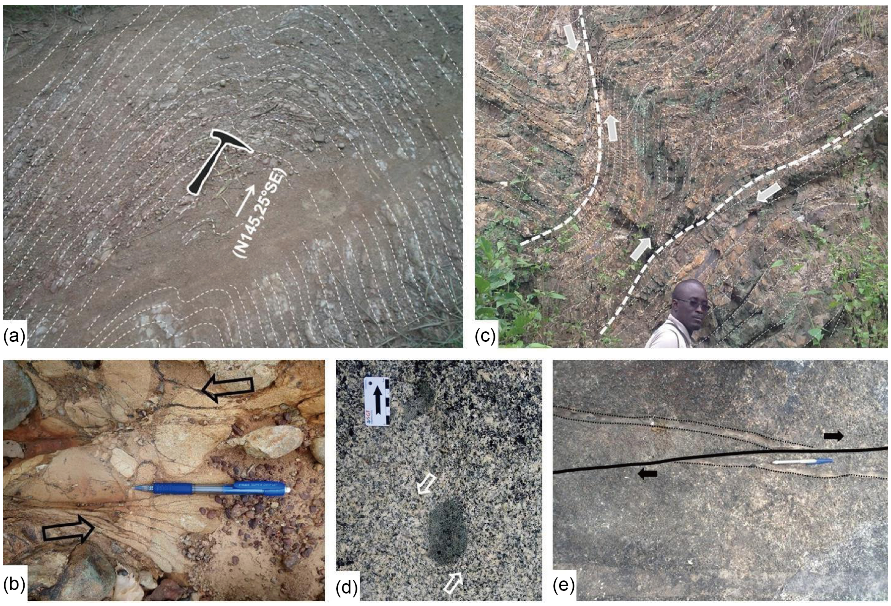

Figure 6. Deformation structures. (a) Microlplis with axis plunging 25˚ to the southeast in Arkoses; (b) Senestre shear (n30 90˚) affecting metaconglomerates; (c) Faults shifting sericitoschists; (d) Senestre shear marked by the mafic enclaves; (e) Dextre strike-slip crossing the Bondoukou granodiorite.

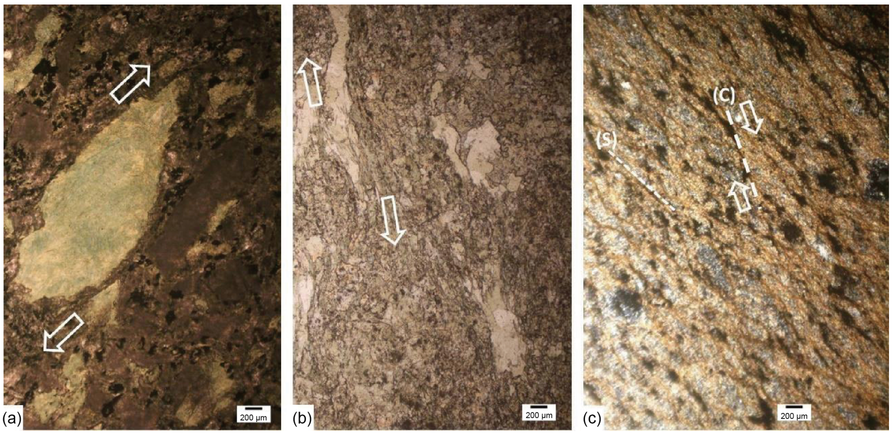

Figure 7. Deformation microstructures. (a) Dextre shear affecting the diorites in enclave; (b) Dextre shear in sericitoschists; (c) Factories indicating a dextre shear in sericitoschists.

4.6. Veins

All lithologies in the region are affected by several generations of fractures in which rocks or minerals sometimes crystallize to form veins or veins. We distinguish:

- late microgabbro veins oriented N125, 70˚SW cutting the sandstone-conglomeratic metasediments (**Figure 8(a)**);
- veins of N180, 90˚ microgranite, metarhyolite (**Figure 8(b)**), N115 90˚ pegmatite

and aplite (N115 90˚) associated with plutonites;

- quartz veins of variable orientations crossing all types of lithological facies: quartz veins (N65 70˚SE) offset the veins (N130 90˚) in a sinistral movement, quartzo-feldspathic veins (N110 90˚) in the village sector of Djani Yao (Figure 9(a)), boudinated quartz veins (N85, 90˚) in the metagabbros (Figure 9(b)), quartz veins cutting the Bondoukou granodiorite and the mafic enclaves it contains, oriented quartz veins N105 90˚ (Figure 9) and N80 40˚S and veinlets observed by microscopy (Figure 9(d)).

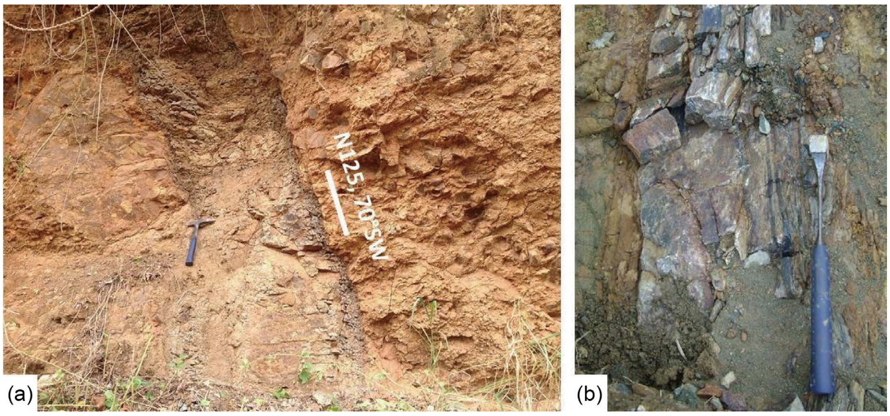

Figure 8. Different veins. (a) Late microgabbro vein (N125 70˚SW) intersecting the meta-conglomerates; (b) metarhyolite vein crossing metagabbros.

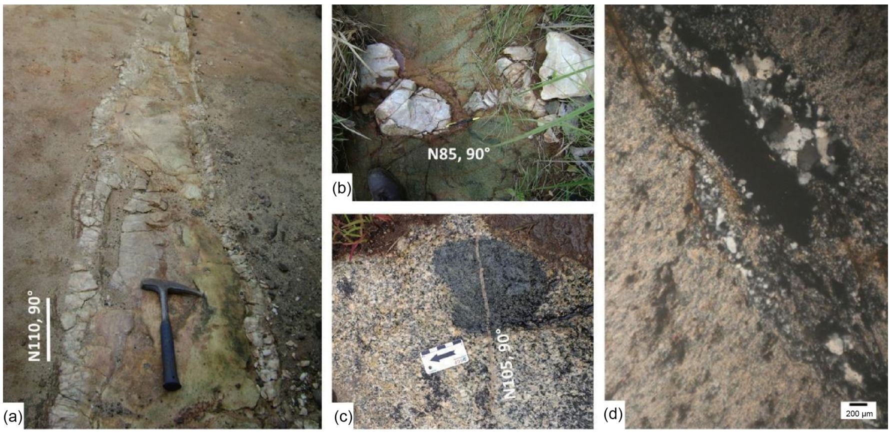

Figure 9. Different types of veins and Venules. (a) Extension vein with quartzo-feldspathic composition (N110 90); (b) Boudinée vein; (c) Quartz vein cutting the granodiorite and its mafic enclave; (d) Quartz microveinule observed by microscopy (polarized light).

5. Discussion

The Bondoukou region contains a sandstone-conglomeratic sequence which rests in unconformity on the ensemble formed of volcano-sediments and plutonic massifs of the region, a thrust of low dips (<40˚). In the sandstone-conglomeratic sequence, S0 stratification and the presence of a stretching lineation marked by phyllite minerals suggest the existence of large regional folds. The presence of these plicative structures of large amplitudes with axes oriented N100-110 and the crenulation schistosity in direction N125˚E make it possible to highlight the existence of a late regional tightening or shortening oriented N-S or NNE-SSW which is posterior to the sandstone-conglomeratic deposition. In metavolcanosediments, S0 stratification is underlined by an original granoclassification or by an alternation of levels rich in ferromagnesians [37] [38]. This S0 stratification is transposed along an early regional schistosity S1 oriented NE-SW. The S1 schistosity is subparallel to the S0 stratification thus forming an S0/S1 schistosity which does not appear homogeneous on a regional scale. It is sometimes penetrative and more intense (marked by the minerals of biotite and muscovite) near granitic intrusions. This schistosity devoid of lineation disappears as well as the associated metamorphism at a distance from the granitoids with complete preservation of the synsedimentary structures. However, at the periphery of the intrusions, a steeply dipping muscovite lineation can become individualized. The schistosity which shelters this lineation molds the granite massifs. A biotite paragenesis, subsequent to the S1 schistosity, can appear at the periphery of certain intrusions. The S1 schistosity clearly fades away where the granitoids are significantly less abundant. The S0 stratification is then predominant, showing well-preserved sedimentary textures. The S1 schistosity is therefore linked to early intrusions, near which pre-S2 minerals are located (chlorite, biotite and muscovite), or even synchronous with S1 (biotite). Near the granite apices, we note the presence of microfolds. In granitoids, several types of structure have been observed: magmatic banding without deformation, plane of flattening, mineral elongation, mineral stretching and C/S type shear. Flattening or slightly shearing foliations (normal to strike-slip movements) are often superimposed on the magmatic banding of granodiorites and tonalites. The early kinematics expressed by these structures most often correspond to normal movements of the periphery of the intruders in relation to their heart. Lineation is the kinematic indicator of finite stretching at the time of pluton emplacement. The lineations highlighted around the granitoid intrusions are subvertical. These steeply plunging lineations are most often interpreted as magma supply zones. The fluid structure of these plutons is marked by the NW-SE and NE-SW orientation of the enclaves. The melanocratic enclaves of quartz microdiorite correspond to witnesses of magmatic mixing, certainly between a felsic component of crustal origin and a mafic component of mantle origin. The tectonics of the Bondoukou region seem complex and characterized by several phases of deformation [39]. This region owes its structure to four deformation phases D1, D2, D3 and D4 (Siagne *et al.*, 2021, 2022) [40] [41]:

- peri-plutonic deformations or deformation phase (D1): The steeply dipping foliation and lineation assembly and the microfolds express a normal gravity-type movement of the surrounding formations in relation to the intrusions. This first phase of deformation reflects a synchronous gravitational movement and/or metamorphic crystallization of the intrusions [42] [43]. The NNE-SSW elongation of the intrusive massifs supposes the appearance of initial distensive then slightly compressive phases following an E-W to WNW-ESE direction.

The S1 foliation is typical of the installation of granitoids in an extensive to slightly compressive context; it does not come from tangential shortening deformation and is therefore not the trace of collisional tectonics as has been proposed for the Ivory Coast D1 of [5] [15] [44]-[48].

- major folds and N-S strike-slip corridors: a second deformation (D2) is responsable for the current structuring of the Birimian series oriented NNE to ENE and with fairly steep dips. It is attributed a very penetrative S2 schistosity, axial plane of isoclinal folds, folding S0/S1. Chlorite and muscovite locally define on S2 a horizontal stretching mineral lineation, typical of epizonal metamorphism, as for the deformation phase D1. On a regional scale, this second phase of deformation is accompanied by sinistral N-S shear zone illustrated by the deflection of foliation or schistosity trajectories [16] [49] [50].
- the dextral strike-slip shear: a third phase of deformation (D3) is marked by dextral shifts oriented N60 (ENE) which offset the S2 schistosity. An S3 schistosity is associated with them and locally carries a stretching lineation (L3) oriented E-W. These phase 3 structures are consistent with a regional direction of EW shortening. They are compatible with the D3 episode of [5], for which the final stages are dated at 2073 Ma. D3 is expressed more particularly in Burkina Faso by an S3 foliation [44], and in Ghana by N60˚ dextral strike-slip [51]. Late deformations or deformation phase (D4): A final tightening phase of regional magnitude has been well studied by [52] and [33]. It is marked by a crenulation schistosity with an N120 orientation, an axial plane of open and straight folds. It obliterates all previous penetrative microstructures. Rotational deformations in the volcano-sedimentary series indicate centrifugal movement, generally in normal faulting around the plutons. The “extensive” character of these deformations superimposed early on the volcanic structures, as well as the thermal aureoles associated with them, fit perfectly into a “diapiric” continuum between 2195 and 2165 Ma [39]. These lithostructural arguments militate in favor of an early Eburnean regime dominated by diapirism and the gravitational movements, that is to say essentially vertical, induced by the latter. In this they are opposed to the collisional type process envisaged in West Africa [44]. The contrast between the stretching of the enclaves and the isotropic aspect of the surrounding magmatic paragenesis suggests the synchronous nature of the deformation and magmatic recrystallizations. Only a few veins of aplite and peribatholitic quartz (*i.e.* circumscribed to the edges of the pluton), sometimes intersect these enclaves. This late diapiric vein system therefore postdates the deformations of the plutons. From a metamorphic point of view, the S1 schistosity is characterized in the most basic volcanic rocks by a dominant chlorite + epidote + calcite ±quartz paragenesis, defining a greenschist facies metamorphism. The amphibole (hornblende) crystals which define a lineation (L1) near the plutons, however, reflect higher thermal conditions. This observation is confirmed in the rare pelitic facies mapped in contact with the massif bordering the Bondoukou granodiorite in the northwest

by syn to post-folial staurolite assemblages involving minimum temperatures of around 550˚C.

Based on teleanalytic and field data, the final geological map of the Tanda-Bondoukou region, north-east of Côte d'Ivoire (**Figure 10**) was established. This map was also produced using extracts from maps produced by previous authors [39]. Stereographic projections (**Figure 11**) allowed the processing and interpretation of all structural data such as the So stratification and S1 schistosity described in the volcano-sediments, the foliation associated with the intrusives, the faults and the various quartz veins.

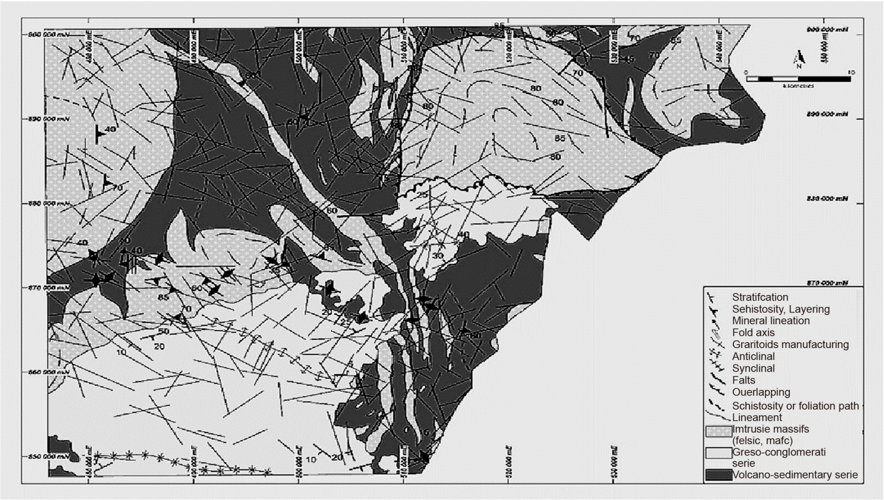

Figure 10. Final geological map of the Tanda-Bondoukou zone (Modified extract from the maps of [38].

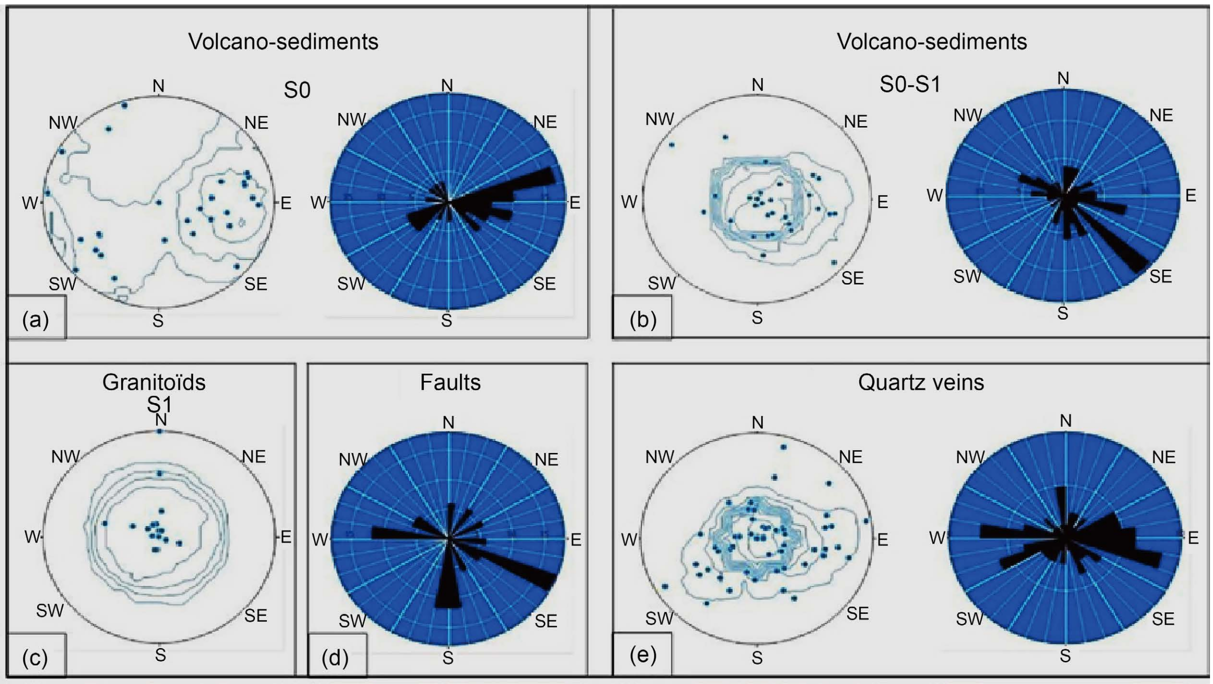

Figure 11. Stereographic projections of the different deformation structures.

6. Conclusions

Field observations coupled with the decryption of Landsat 8 satellite images made it possible to highlight two types of deformation in the Tanda-Bondoukou sector: ductile deformation and brittle or fragile deformation. Ductile deformation is marked by stratification So, schistosity planes S1 and S2, mineral lineations L1 and L2 and stretching and folds. The stratification (So) is preserved in metasediments. It undergoes folding, and generally, E-W axes sometimes evolve in ENE-OSO and WNW-ESE directions. The various treatments carried out on the radar images made it possible to identify a total of 471 lineaments with a main direction: NNW-SSE to NW-SE. Associated with the lithology map, the teleanalytic map shows that the lineaments appear compact in the volcanosedimentary and sandstone-conglomeratic units than in the granitoid intrusives. Associated with these regional lineaments are dextral or sinistral shears, faults, veins and veins of variable directions.

Analysis of satellite images confirms that the N10 and N45 directions of the intercepted quartz veins, for example, coincide with those of the major lineaments revealed by remote sensing. These quartz veins, especially associated with NE-SW fracturing, are largely abundant on Landsat 8 images. With their sigmoidal, elongated, discontinuous signatures describing a sliding movement, these quartz veins indicate a shear zone context. The presence of large-amplitude plicative structures oriented N100-110 and the crenulation schistosity of N125˚E direction highlight the existence of a late regional tightening or shortening oriented N-S or NNE-SSW after the Eburnean cycle.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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