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Tectonic Style Associated with the Doleritic Dykes of the Téra-Ayorou Pluton (Liptako, Western Niger)

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Abstract

The doleritic dykes present in the Téra-Ayorou pluton crosscut the basement of the Nigerien Liptako and are part of the system of intrusive mafic dykes in the Paleoproterozoic domain of the Léo-Man ridge. In the previous work, emphasis was placed on the petrology, geochemistry and geochronology of the Liptako doleritic dykes. This study aims to analyze the tectonic style of intrusive doleritic dykes in the Téra-Ayorou pluton. The characterization of the deformation which affected the doleritic dykes of the Téra-Ayorou pluton is important for the evaluation of their economic potential. To this end, measurements of tectonic structure planes were taken in the field, and samples were taken from the chilled margin and cores of dolerite dykes, before being processed in the laboratory. Analysis of the tectonic structures collected revealed a brittle tectonic pattern, characterizing a phase of deformation subdivided into two episodes D1 and D2. Episode D1, with its subvertically dipping normal faults and simple N70˚ - N110˚ fractures, is compatible with N-S extension. On the other hand, episode D2, which created shear corridors by reactivation of pre-existing fractures and oriented N150˚ - N170˚, is associated with a WSW-ENE extension. These results open up prospects for the exploration of gold, uranium mineralization and diamonds in the north-west of Niger.

Keywords

Dolerite Dykes, Associated Structures, Deformation Phases, North Liptako, Niger

1. Introduction

The dolerites of Téra-Ayorou (North Liptako), identified for the first time at Firgoun [1], appear in the form of dykes cutting the Yatakala series and the granites of West Niger [2]. Their behavior, with respect to the granitoids and the sedimentary cover, is thus that of an intrusion subsequent to the Liptako granites and prior to the Infracambrian sandstones of Firgoun [2]. For Ama Salah [3], then Baratoux *et al.* [4], the doleritic rocks of the Sirba belt rise in dykes grouped into bands of veins in N-S and NW-SE directions. More recent and detailed data on the Liptako doleritic dykes show that they are distributed in space in four random directions: WNW-ESE, NW-SE, E-W and N-S [5] [6]. Their petrography is restricted to an ophitic to subophitic or intergranular texture, or mineral associations including plagioclase, orthoclase, sanidine, pigeonite, augite, enstatite, biotite and edenite as well as chlorite and grains with a granophyric texture [2]-[6]. Geochemical analyses [5] [6] indicate that dykes oriented in WNW-ESE, NW-SE and E-W directions exhibit characteristics similar to intraplate tholeiitic basalts. On the other hand, the N-S oriented dykes, which cross the Sirba greenstone belt, are associated with an arc context [3] [6].

From these geodynamic facts, it appears that the WNW-ESE, NW-SE and E-W dykes are characterized by a source similar to the enriched basalts of mid-oceanic ridges, while the N-S direction dykes have an affinity of calc-alkaline basalts [6]. Thanks to the K/Ar and U/Pb dating carried out on the dykes of the Pluton of Téra-Ayorou, as well as those of the Sirba and Diagourou Darbani belts, the range of ages obtained are 896 Ma (K/Ar) for a N140˚ trending Kandadji dyke and varies between 1.37 and 1.01 Ga (K/Ar) for N20˚ trending dykes in the Sirba belt [3]. It is circa 1.91 Ga (U-Pb age) for the N010˚ dykes [4] and 1.788 Ga (U-Pb age) for the N00˚, N15˚ and N170˚ dykes [6]. The coupling of structural data with the U-Pb ages of the parallel NW-SE swarm of Essakane (1520 Ma) and the N-S swarm of Liptako (1788 Ma) suggests that the establishment of the Liptako dykes took place during the late-Eburnean (N-S dykes) and post-Birimian (NW-SE, WNW-ESE and E-W dykes) events [6]. In the genesis of the gold mineralization of the Nigerien Liptako, the NW-SE and NE-SW tectonic directions are today considered as shear corridors in which the major brittle deformation zones constitute the horizons carrying the highest grades [7] [8]. Despite this metallogenic interest, the doleritic dykes of Liptako, in particular those of the Téra-Ayorou pluton, have not been the subject of structural studies allowing us to understand the nature of the deformation they have undergone.

The objective of this work is to highlight, based on data collected in the field, the main structural characteristics present in the doleritic dykes crossing the Téra-Ayorou pluton (Liptako North). More specifically, it involves inventorying, describing and interpreting elements or geometric structures leading to the types of deformations undergone at different scales by the rocks constituting the Téra-Ayorou pluton and comparing the style of deformation with that observed in the West African Craton (WAC).

2. Geological Background

2.1. Geological Setting of Niger Liptako

The Niger Liptako corresponds to the western part of the Niger Republic (**Figure 1**)

[9]. Straddling the Niger River and the eastern border of Burkina Faso, the Niger Liptako represents the extreme NE part of the Baoulé-Mossi domain (**Figure 1**), which is the Paleoproterozoic part of the Man-Léo Dorsal [10].

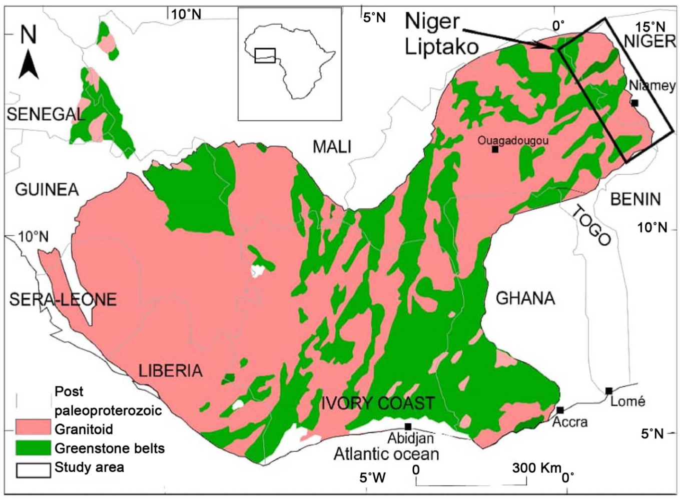


Figure 1. Simplified geological map of the Man-Léo Dorsal and the Niger Liptako area ([9]).

This crystalline and crystallophyllian basement of western Niger is made up of Birimian rocks structured in alternation of greenstone belts and granitoid plutons arranged generally NE-SW (**Figure 2**). Greenstone belts include basic rocks (basalts and gabbro), metamorphic rocks (amphibolites, schists, flints, epidotites, quartzites and garnetites) and volcanosediments (cinerites, volcanic breccia and tuffs) [11]. The granitoid plutons are made up of series of Tonalites, Trondhjemites, Granodiorites (TTG) and granites, diorites, monzonite, syenites, gneisses and migmatics [11]. These two categories of rocks are cut by quartz, quartzo-feldspathic and Birimian pegmatitic veins as well as post-Birimian doleritic dykes [5] [11] [12]. All of these rocks are covered by quartzitic sandstones and diamictites dating from the Infracambrian [13] [14] alternating with clayey and ferruginous oolitic sandstones of Oligocene age [15] as well as alluvium, colluvium and dunes of Quaternary age [2]. The Birimian rocks were structured during the Eburnean orogeny in the context of an island arc and/or volcanic arc, from a tholeiitic magma for the mafic rocks of the green belts and from a calc-alkaline magma for rocks of granitoid plutons [6] [16].

Structural studies have demonstrated that the Birimian rocks of Liptako were affected by four phases of deformation D1, D2, D3 to D4 in the Diagorou-Darbani belt [12], three phases of deformation D1, D2 and D3 in the Makalondi green belt [17], two deformation phases D1 and D2 in the granitoids and greenstone belts of Liptako [5] and a single phase in the Gorouol greenstone belt [16].

2.2. Geological Setting of Téra-Ayorou Pluton

The Téra-Ayorou pluton is located north of the Nigerien Liptako (**Figure 1**). More

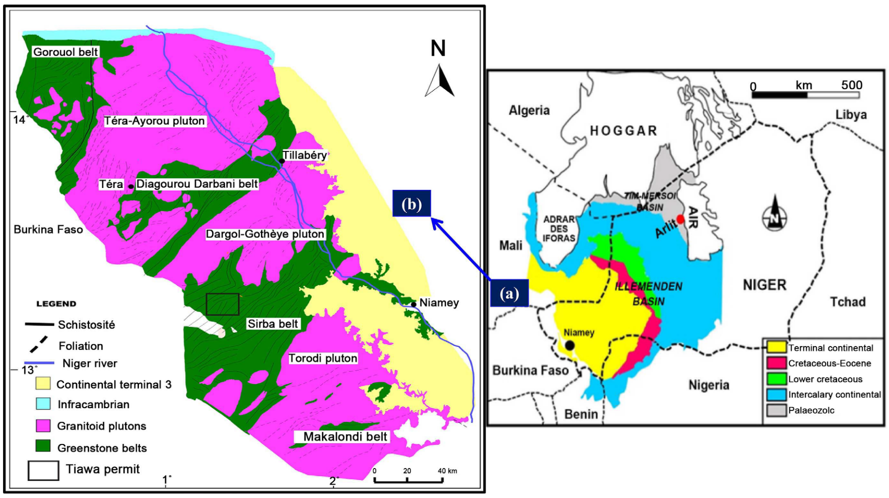
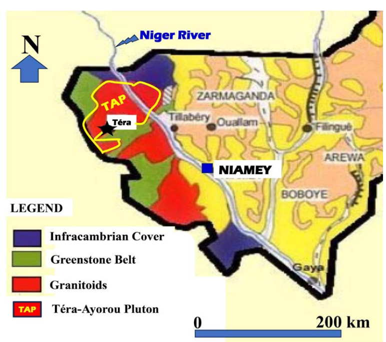


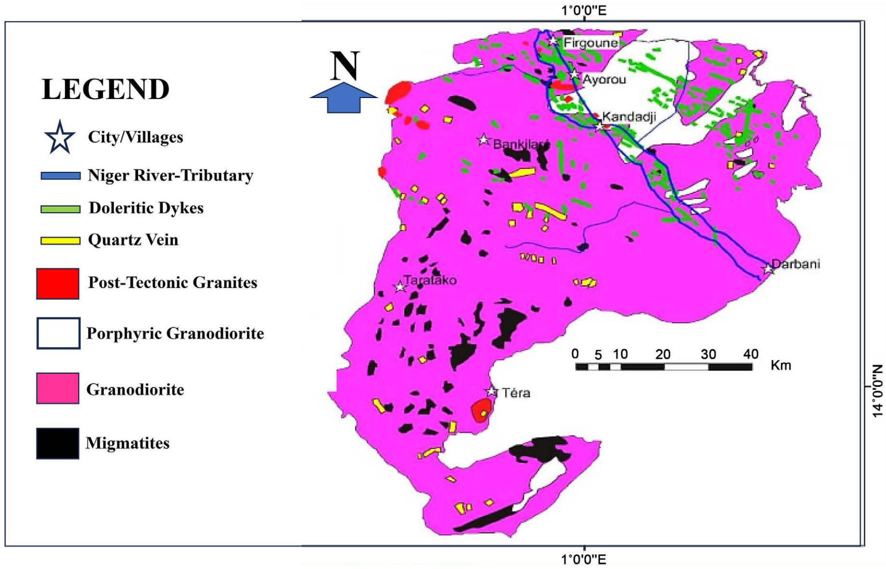
Figure 2. Location (a) and simplified geological map (b) of the Niger Liptako. The Téra-Ayorou pluton is located in the north between the greenstone belts of Goroual and Diagourou-Darbani (b) ([3] [8] [15], Modified). Arlit (a) and Tiawa permit (b) are respectively uranium and gold mining sites.

than 70% of the total volume of rocks forming this pluton are represented by foliated granodiorite [18] (**Figure 3**). Pons *et al.* [18] report that metamorphic foliation is characterized by a locally circular trajectory with an overall NE-SW direction. The foliated granodiorite is cut by a porphyritic granodiorite with large plagioclase crystals, a granite with synkinematic biotite or two post-kinematic micas, migmatitics, locally porphyritic quartzite diorites with large plagioclase and biotite crystals and quartz syenites [2] [5] [6] [8] [18] [19].

The ages of the granitoids of the Téra-Ayorou pluton were constrained between 2158 ± 9 Ma and 2000 ± 60 Ma [2] [20] [21]. The two sectors under study, Ayorou and Kandadji, are located to the northwest of this pluton (**Figure 3**). They are mainly characterized by the presence of post-Eburnean doleritic dykes oriented mainly in two subparallel directions WNW-ESE and NW-SE [2]-[4] [6]. The WNW-ESE oriented dykes represent approximately 80% of the total dyke volume, while the NW-SE oriented dykes account for approximately 15% to 20% [5]. It is over a kilometer distance that they intersect granodiorite and porphyritic granodiorite [5] (**Figure 3**).



(a)



(b)

Figure 3. (a) Western Niger simplified geological map ([2], modified) and (b) Geology of the Téra-Ayorou pluton sector.

3. Methodological Approach

The present study essentially involved a field component during which data collection was carried out [6]. The field work consisted of the inventory and description of tectonic structures in the Ayorou and Kandadji sectors (**Figure 3**).

In both sectors, measurements of the planes of the tectonic structures were obtained from the borders and cores of the doleritic dykes outcropping in relief relative to the surrounding rocks. Photographs of outcrops were taken in areas showing morphological characteristics or other structural orientations of the dykes.

Thin sections were made on the chilled margin and centers of the doleritic dykes and observed under a polarizing transmitted-light microscope to determine intracrystalline characteristics. From certain photos, structural diagrams were developed. Comparing structural diagrams with measurements of directions and structural plans can potentially make it possible to address stress fields. Subsequently, the stress fields are subjected to different comparisons in order to place them in the regional tectonic context and to specify the tectonic style of the deformation having affected the doleritic dykes of the Téra-Ayorou pluton.

4. Results

4.1. Petrography of Doleritic Dykes of the Téra-Ayorou Pluton

The doleritic dykes of the Téra-Ayorou pluton crop out from the granodioritic surrounding rock and are marked by frozen edges (**Figure 4**).

From a macroscopic point of view, it can be noted that the chilled margins (commonly called peripheries) are frequently characterized by fine grains and the cores of the dykes by fine to medium grains. For the central zones (or cores) of the dykes, we can also notice relatively uniform morphological characteristics.

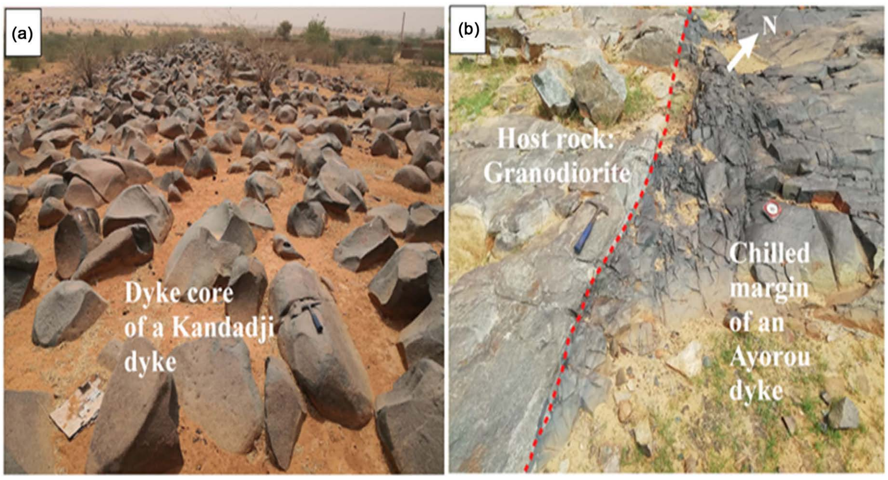


Figure 4. Photographs showing the appearance of the dykes at the outcrop (a) at the center of the N110˚ trending Kandadji dyke (70 m wide) and (b) at the chilled margin of N120˚ trending Ayorou dyke (65 m wide).

They are thus made up of chaotic rounded to sub-angular blocks (Figure 4(a)), the relief of which seems to be accentuated by fluvial erosion. These chaotic blocks show black or brown tints on the surface parts altered by water, while the fresh internal parts not affected by the alteration display a greenish-grey tone. The black or brown color of the altered surface parts corresponds to a layer of altered ferro-magnesian minerals. Microscopic observations of the cores and chilled margins of the dykes (Figure 5) in the study area confirm the macroscopic characteristics (fine grains at the dyke peripheries and medium to coarse grains at the dyke centers).

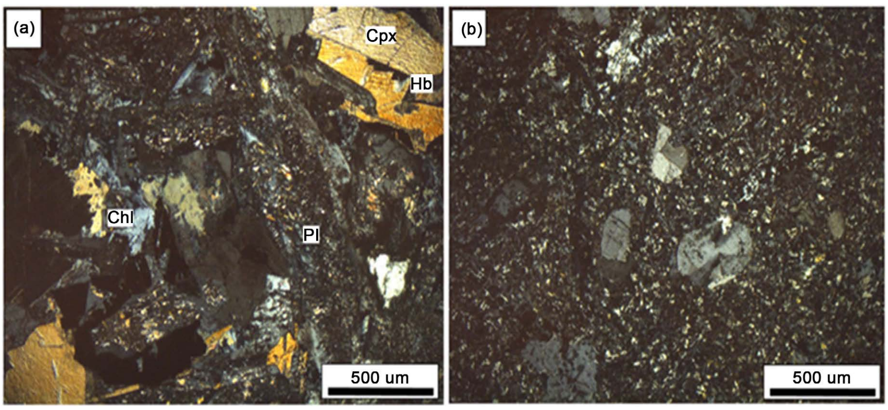


Figure 5. Microphotographs showing the texture and constitute minerals of the dolerites (a) at the N110˚ trending Kandadji dyke center and (b) at the N120˚ trending Ayorou dyke chilled margin. Pl: plagioclase; Cpx: clinopyroxene; Hb: hornblende; Chl: chlorite.

The microphotographs in Figure 5(a), corresponding to the N110˚ trending Kandadji dyke center, show that they are made up of plagioclase, pyroxene, hornblende and chlorite. Microscopic observations indicate no intracristalline deformation.

4.2. Main Types of Deformation Structures

Field observations, combined with photo interpretation, indicate that the tectonic elements are mainly simple fractures, shear fractures and normal faults. These tectonic elements are locally associated with structures of metamorphic and magmatic origin.

4.2.1. Structures of Tectonic Origin

Simple Fractures

They were observed in the central parts of the doleritic dykes at Kandadji and Ayorou (Figure 6).

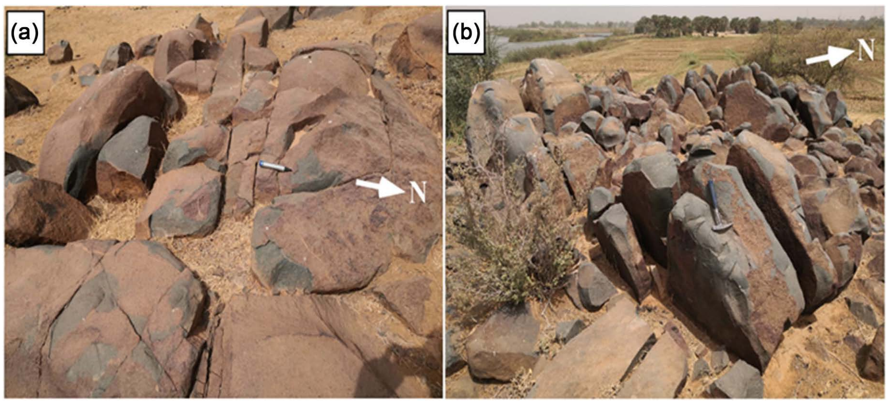


Figure 6. Photos showing quasi-parallel and repetitive fractures affecting the center of (a) the N110˚ oriented Kandadji dyke (70 m wide) and (b) the 120˚ oriented Ayorou dyke (30 m wide).

Generally speaking, for most of these central zones, the simple fractures would have functioned in quasi-parallel and repetitive discontinuities and whose orientation is between N110˚ and N120˚. Nevertheless, the irregularity or discontinuity of certain fractures as well as their appearance in small dimensions in places suggest that they are linked to the cooling of the magma or to meteoric alteration (Figure 6(a)). In the central areas of a doleritic dyke (30 m thick and approximately 700 m long), simple fractures form weakly straightened blocks over a multimetric distance (Figure 6(b)).

Normal Faults

Normal faults were observed at Kandadji at the frozen edge of a dyke oriented N110˚ (60 m wide) and to the west of Ayorou at the center of certain dykes oriented N120˚ (40 m wide and 1 km long). They appear in the form of locally conjugated microfaults delimiting a micrograben (Figure 7(a)) or striated micromirrors showing imprints of sliding of the subsidence compartment (Figure 7(b)). The planes delimiting the micrograben and those forming the mirror of the normal microfault indicate submeridian dips (N65˚ to N85˚ towards the SW or SE).

Strike-Slip Fractures

The strike-slip fractures were observed at the frozen margins of a Kandadji doleritic dyke 60 m wide and oriented N110˚ over a length of 2.5 km (Figure 8(a))

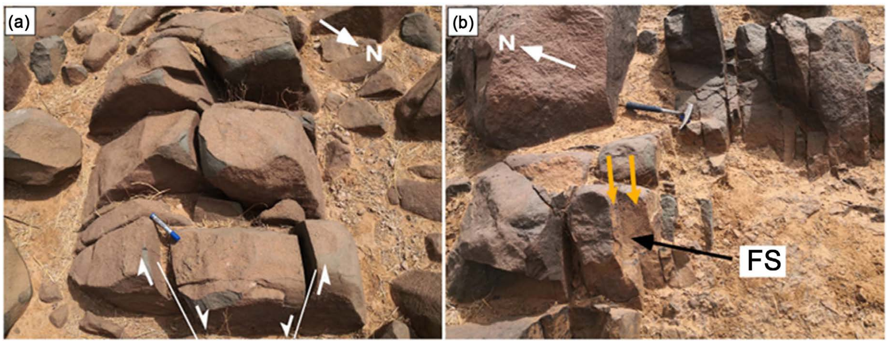


Figure 7. Photos showing (a) normal microfaults bounding a micro graben and (b) fluted striations (FS) on a normal fault mirror.

as well as on a Ayorou doleritic dyke oriented N110˚ (70 m wide and 700 km in length) (Figure 8(b)). These fractures are characterized by phases of fracturing following average directions N70˚ to N110˚ most often reactivated to the right or left by fractures covering directions N150˚ to N170˚ (Figure 8(a')) and Figure 8(b')). The edges of the dykes are thus cut into decimetric to centimeter sheets, which locally gives the edges a breccia appearance (Figure 8(a)). There are also good N-S brittle and elongated shear corridors in such fracture zones. Likewise, leucosomes (and therefore anatexis structures) are well expressed in the shear zones, particularly at the level of the surrounding granodiorite and at the contact of certain dykes (Figure 8(a')).

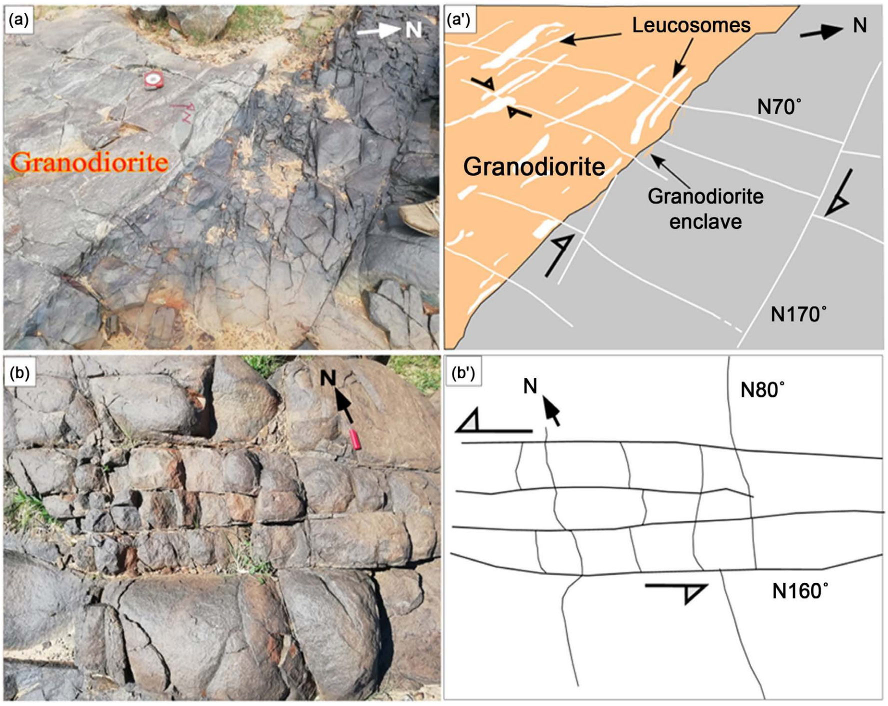


Figure 8. Shear corridor showing dextral or sinistral strike-slip fractures affecting the frozen edges ((a) and (a')) of a dyke oriented N120˚ (60 m wide) from Kandadji and ((b) and (b')) of a dyke oriented N110˚ (70 m wide) from Ayorou.

4.2.2. Structures of Magmatic Origin

Structures of magmatic origin were identified on the walls of doleritic dykes in the two study areas. They appear in the form of corded lavas and flow structures of linear or curvilinear shape, continuous or discontinuous, quasi-parallel or repetitive, divergent or secant (**Figure 9**).

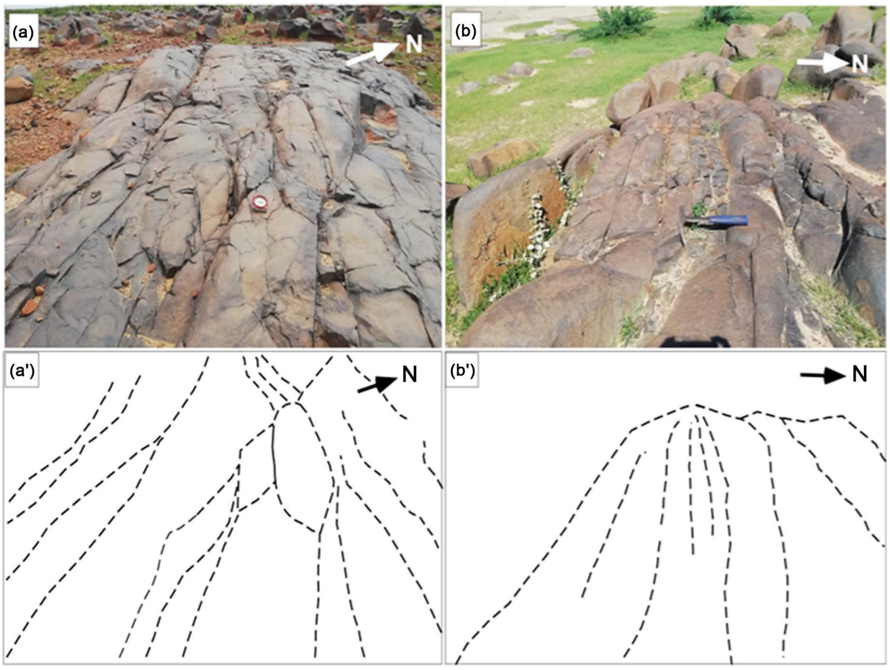


Figure 9. Fractures linked to magma cooling affecting the borders of (a) a doleritic dyke from Ayorou oriented N120˚ and (b) a doleritic dyke from Kandadji oriented N110˚. (a') and (b') Photo interpretation figures highlighting linear and curvilinear flow structures.

5. Discussion

The Kandadji-Ayorou sector, northwest of the Téra-Ayorou pluton (Liptako, Niger), includes a lithological ensemble formed essentially of granodiorites cut by doleritic dykes. The nature of the tectonic elements or tectonic deformation structures (normal faults and fractures ranging from simple to shearing or even strike-slip), revealed in this study, demonstrates that the tectonic style associated with the dolerite dykes of the Téra-Ayorou pluton corresponds to the style classic of brittle deformation. These fragile elements are associated with flow structures of linear or curvilinear shapes (**Figure 9**).

For Noura [6], the presence of flow structures is consistent with a basaltic magma of low viscosity. Furthermore, the curvilinear character (**Figure 9(a)**) of certain structures indicates that they were put in place during cooling, while the material was still plastic. The continuity of the fractures oriented N70˚ in the surrounding rocks (**Figure 7**) can give them a tectonic origin, unlike the strike-slip fractures oriented N150˚ - N170˚ which do not intersect the surrounding granodiorite, and for which a magmatic origin linked to cooling seems more appropriate. However, anatexis structures, such as leucosomes observed in the surrounding granodiorite and at contact with certain dykes (**Figure 7(b)**), underline the evolved character of metamorphism in contact with the surrounding rock.

Interpretation of the tectonic deformation structures and study of the overlapping relationships between the main orientations governing these structures lead us to divide this brittle deformation into two episodes D1 and D2. Episode D1 is oriented between N70˚ and N110˚, while episode D2 direction is N150˚ - N170˚. However, given the lack of structural data on the dolerite dykes of the Niger Liptako and the West African Craton, the interpretation in terms of the functioning of this phase of brittle deformation remains complicated. Nevertheless, the similarity of the structural measurements obtained on the Birimian and Infracambrian rocks of the Liptako basement [22] [23] makes it possible to compare the fractures of this study to fractures in directions N-S (N150˚ - N160˚), WNW-ESE (N90˚ - N110˚) and ENE-WSW (N60˚ - N80˚) highlighted in cratonic and mobile zones in West Africa [2] [7].

One of the most plausible interpretations is that of Noura [6] who mentions that these direction ranges would be compatible with a submeridian extension for episode D1, and would be compatible with a WSW-ENE extension for episode D2. Furthermore, the D1 episode of this study is comparable to the D1 brittle phase linked to N-S extension in the infracambrian sandstones of Karey Gorou [23], and to the D3 brittle phase responsible for E-W and N-S fractures in the belt of Makalondi [24].

The D1 episode is also comparable to the post-D4 brittle deformation responsible for the N80˚-trending normal faults and WNW-ESE (N100˚ - N110˚) fractures described by Soumaila [12] in the Diagorou-Darbani green belt. Likewise, the N150˚- N170˚ strike-slip fractures in this study are comparable to the dextral or sinistral submeridian separations described by Abdou *et al.* [25] in the Liptako dolerite dykes. Several authors [12] [18] [19] [26] relate the D3 and post-D4 phases affecting the Liptako basement to a post-Eburnean extension, or pan-African for authors such as Soumaila and Konaté [27], Hallarou [28], Garba Saley [24], Ahmed *et al.* [11] and Noura [6].

Associated with N-S elongation [24] [27], the D1 episode may also be related to pre-Panafrican rifting in crystalline and crystallophyllian rocks of the Damagaram province [29]. On the other hand, submeridian extension, described in Infracambrian sandstones, was associated by Affaton *et al.* [23] to the Mesoproterozoic opening of the Kibarian basins at around 1378 ± 36 Ma, while Alzouma Amadou *et al.* [14] and Ibrahim Maharou [12] would have attributed it to the opening of the Neoproterozoic basins between 870 Ma and 800 Ma. These different hypotheses underline the episodic nature of the functioning of Eburnean tectonics, in terms of transition from breaks to shear joints in the study area.

Based on the approximate age of 896 Ma obtained by Ama Salah [3] on a Kandadji dyke with an orientation of N140˚ and that the late dolerite veins are of variable ages (Mesoproterozoic to Jurassic) [30]-[33], one can say that certain dolerite dykes (intrusive in the submeridian faults) would be late and very little deformed

[6] [34]. It is therefore not surprising that most observations [34] [35] assume that the establishment of doleritic veins would play an important role in the redistribution of several mineralizations. Just as Dabo [34] reported gold mineralization in the Birimian formations of Frandi-Boboti (Kédougou-Kéniéba buttonhole, Senegal). Similarly, reinterpretation of aeromagnetic data validated by field work indicates that faults and pipes of diamondiferous kimberlites in the Kenieba region are often associated with dolerite dykes [36]. Geochemical studies carried out on the dolerite dykes of the Téra-Ayorou pluton [5] have indicated that they are characterized by significant uranium enrichment. Finally, it has been observed that most of the uranium mineralizations hosted by sandstones of the Iullemmeden basin are identified and characterized as associated with the E-W, N-S and WNW-ESE brittle fractures [15] [37] [38].

Consequently, it remains that post-Birimian events, linked to the establishment of doleritic veins, would play an important role in the reconcentration and enrichment of primary mineralizations both in the context of the Liptako Shield and at the level of the sedimentary basin. According to Noura *et al.* [5], this post-Eburnean event corresponds to fissural volcanism occurring in an extensive intraplate context [39], and the above-mentioned uranium enrichment could also be linked to the crustal contamination highlighted in the doleritic dykes of the West African Craton and elsewhere in the doleritic dykes of Cameroon and Chad [40].

6. Conclusion

The Liptako dolerite dykes are marked by a broken tectonic style, due to a single phase of deformation, which is subdivided into two episodes, namely D1 and D2. Event D1, which is governed by north-south extension, was recorded in the dyke centers in the form of normal faults and simple fractures. Event D2, which is also influenced by a West-South-West-East-North-East (WSW-ENE) extension, caused reactivation of fractures on the cooled edges of the dykes. Other fractures are associated with structures of magmatic and meteoric origin. The fractured style of deformation, the apparent change in the dimensions of the dykes and the fractures affecting them, and the absence of deformable structures indicate that these dykes borrowed pre-existing fractures during their emplacement, and were then influenced by extensive post-Birimian phases. The apparent change in dyke dimensions could be attributed to the pressure or volume of the magma during its ascent. It would be important to develop this work by integrating a geochronological approach using the U-Pb method, in order to accurately calculate this brittle deformation over time.

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Conflicts of Interest

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

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