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Kinematics Markers of the Oligocene Deformation of the Continental Terminal 3 (Ct³) in the Niamey Region (Southeastern Edge of the West African Craton)

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Abstract

This study focuses on kinematic markers of Oligocene deformation in the Continental Terminal 3 (Ct^3) formation in the Niamey region (southeastern edge of the West African Craton). Previous work on the analysis of Oligocene deformation markers in Ct^3 is fragmentary. The objective of this study is to identify synkinematic deformation structures in the Ct^3 deposits and to determine the geodynamic context responsible for these structures. To achieve these objectives, a methodological approach integrating structural geology based on measurements of deformation structures in the field and the processing of these measurements using the Win-Tenseur program (version 5.8.9) was used. The various deformation markers identified, namely curved mirrors, curved striations, undulating grooves, and crescent-shaped tear figures, show the synlithification character of the Oligocene deformation of the Ct^3. The analysis revealed two deformation phases that affected the terminal continental (Ct^3), designated D1a and D1b. The extensive phase D1a, with a N50˚ orientation, resulted from mantle dynamics, and phase D1b, with a N170˚ extension direction, resulted from an extensive episode within the compressive regime that occurred during the collision between Africa and Europe.

Keywords

Niamey Region, Oligocene, Continental Terminal 3, Mantle Dynamics, Deformation Markers

1. Introduction

The Continental terminal is the last continental detrital assemblage defined by

Kilian in 1931. According to Greigert (1966), it corresponds to the last episode of filling of the Iullemmeden basin, outcropping over more than 90,000 km^2 in Niger (Greigert & Pougnet, 1967). It refers to quartz-kaolinitic detrital formations with siderolithic facies (Greigert, 1966; Lang et al., 1986), characterized by iron mineralization represented by ferruginous oolites (Didier, 1969). Within this continental unit, Greigert (1966) and then Greigert & Pougnet (1967) distinguished three series, comprising, from base to summit: 1) the siderolithic series of Ader Doutchi or Ct1, 2) the clayey-sandy series with lignites or Ct^2, and 3) the Middle Niger clayey sandstone series or Ct^3. However, in the study area, only Continental Terminal 3 (Ct^3) is exposed. The latter consists of alternating clayey sandstone and ferruginous oolitic sandstone with hardened levels, more or less associated with termite tubes, resting on Infracambrian deposits and/or in major or fundamental unconformity on the Paleoproterozoic basement (Tessier, 1954; Ibrahim-Maharou & Konaté, 2018; Ousmane et al., 2020). Previous work on the analysis of Oligocene deformation markers in Ct^3 is fragmentary. Consequently, a detailed structural analysis remains to be done. The overall objective of this study is to search for markers of Oligocene deformation in the Ct^3 formation. Specifically, it aims to: 1) identify synkinematic deformation structures in the Ct^3 deposits and 2) determine the geodynamic context responsible for the formation of these structures.

2. Geological Context of the Study Area

From a geological point of view, the Niamey region straddles two major geological units (**Figure 1**): to the west, the Paleoproterozoic Liptako basement (2300 to 2000 Ma, Soumaila, 2000), belonging to the Birr domain of West Africa, and to the east, the Iullemmeden sedimentary basin, which is a vast Paleo-Mesocenozoic syncline. The Niger Liptako corresponds to the northeastern edge of the Man Ridge (Birimian domain of the Man Ridge) (Bessoles, 1977; Bessoles & Trompette, 1980; Deynoux, 1983; Soumaila, 2000; Soumaila et al., 2004; Soumaila & Konaté, 2005; Soumaila & Garba, 2006; Soumaila et al., 2008). To the north, the Niger Liptako is bounded by the Gourma Basin and to the southeast by the Volta Basin (**Figure 1**).

The Precambrian formations mark the eastern edge of the West African Craton. They outcrop discontinuously from north to south in the regions of Firgoun (Firgoun sandstone), Gassa (Gassa sandstone), Niamey (Niamey sandstone), and Kirtachi-Tamou (Kirtachi sandstone) (Machens, 1973). In the Niamey region, the outcropping formations of the Iullemmeden Basin are represented by Oligocene-Miocene deposits of the Continental Terminal 3 (Beauvais et al., 2008; Chardon et al., 2018; Issoufou-Fatiou, 2020) and Quaternary sediments (Ousmane et al., 2020).

2.1. Paleoproterozoic Formations

The Paleoproterozoic (Birimian) formations of the Liptako Nigerien consist of alternating green rocks (metabasalt, amphibolite, and ultramafic to mafic granular rocks) and granitoid plutons (Machens, 1973; Dupuis et al., 1991; Salah et al., 1996; Abdou et al., 1998; Soumaila, 2000; Garba-Saley et al., 2017; Hallarou et al., 2020). Granitoid plutons are composed mainly of granites, TTG (tonalite, trondhjemite, granodiorite), diorites, quartz diorites, monzonite, and locally syenite (Machens, 1973; Abdou et al., 1998; Soumaila, 2000; St-Julien, 1992; Soumaila & Konaté, 2005).

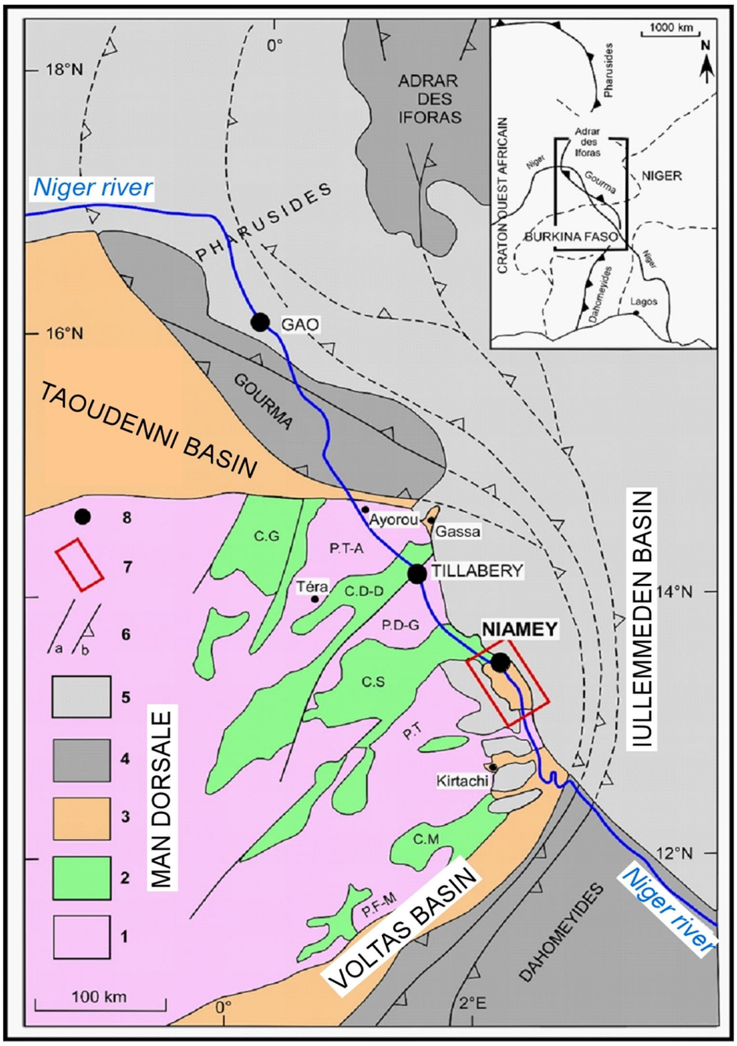

Figure 1. Location of the Niamey region within the Liptako structural framework (Affaton et al., 2000, modified). 1) Paleoproterozoic granito-gneissic massifs. 2) Paleoproterozoic schist belts. 3) Neoproterozoic and Paleozoic formations of the Taoudenni and Volta basins. 4) Formations involved in Pan-African orogenesis (600 Ma). 5) Mesozoic to Quaternary formations of the Iullemmeden basin. 6) Faults (a) and thrust planes of the Pan-African nappes (b). 7) Eastern and western branches of the green belt. 8) Niger River. 9) Cities.

2.2. Infracambrian Formations

In western Niger, Neoproterozoic formations mark the eastern edge of the West African Craton. They outcrop from north to south in the regions of Firgoun (Firgoun sandstone), Gassa (Gassa sandstone), Niamey (Niamey sandstone, the subject of this study), and Kirtachi (Kirtachi sandstone) (Machens, 1973). In Niamey, these formations are represented by quartzitic sandstones and conglomerates that lie in major unconformity on the Paleoproterozoic basement (Hamza-Mayaki et al., 2017; Ibrahim-Maharou & Konaté, 2018; Konaté et al., 2018).

2.3. Formations of Continental Terminal 3

Continental Terminal 3, the only part of Continental Terminal that outcrops in the Niamey region (Hamza-Mayaki et al., 2017; Ousmane et al., 2020), is an Oligocene to Miocene formation (Beauvais et al., 2008; Issoufou-Fatiou, 2020), consisting of alternating clayey sandstone and ferruginous oolitic sandstone with hardened layers, more or less associated with termite tubes (Tessier, 1954; Hamza-Mayaki et al., 2017; Ousmane et al., 2020). The Ct^3 rests on Neoproterozoic deposits with a gully unconformity and/or on the Paleoproterozoic basement with a major unconformity (Hamza-Mayaki et al., 2017; Ousmane et al., 2020; Ibrahim-Maharou & Konaté, 2018).

2.4. Surface Formations

The surface formations consist of alluvium, more or less reworked ferruginous lateritic deposits, dunes, and recent Quaternary terraces, which cover, depending on the area, the Continental Terminal 3 or the Paleoproterozoic basement (Greigert, 1966; Machens, 1973; Dubois, 1979; Hamza-Mayaki et al., 2017; Ousmane et al., 2020).

3. Location of the Study Area

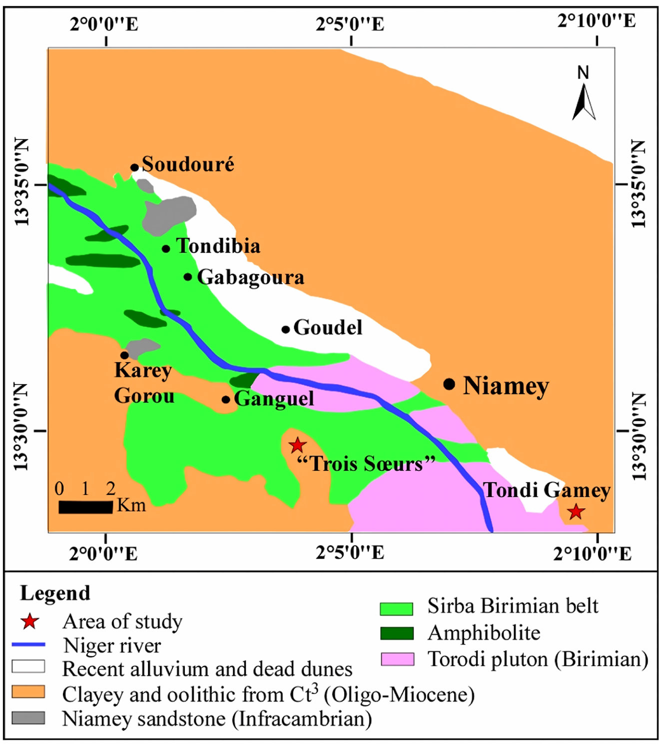

Figure 2. Location of study areas on the Liptako geological map extract (Machens, 1973).

The geological map produced by Machens (1973) was used to locate the outcrops in the study area. The GPS coordinates of these outcrops were projected onto Machens' geological map (1973), then onto a Google Earth image of the Niamey region. Machens' map (1973) was superimposed onto the Google Earth image of the Niamey region. This enabled the geological map of the study area to be updated. The areas covered by this study are located on the right and left banks of the Niger River (**Figure 2**). These are the "Trois Sœurs" and Tondi-Gamey areas, respectively.

4. Methodology

The methodological approach adopted is essentially based on field analyses and measurements of deformation structures. A total of 53 measurements were taken, including 37 in the Trois-Sœurs area and 16 in the Tondi-Gamey area. The results of these measurements are presented in **Table 1** and **Table 2**. In the absence of any cross-correlation between the various directions of normal microfaults, the directions are classified into two groups, F1 (N120˚ to N160˚) and F2 (N50˚ to N80˚), based on their strike and dip. Then these measurements were processed using the Win-Tenseur program (version 5.8.9) to calculate the stress tensors (σ1, σ2, σ3) (Delvaux, 2011, 2019). These stress tensors (σ1, σ2, σ3) are defined by three principal stress axes: maximum stress (σ1), intermediate stress (σ2), and minimum stress (σ3), and automatically calculated by the Win-Tenseur program. The Wallace-Boot hypothesis is used to theoretically predict slip directions based on known stresses, and also serves as the basis for paleostress inversion in the analysis of slip on fault systems (Lisle, 2013).

Table 1. Structural data of Trois Sœurs.

Structural data of Trois Sœurs		
Direction	Deep	Pitch
160	60W	60W
145	55W	60W
135	50W	60W
130	53W	60W
137	50W	60W
142	55W	60W
125	45W	60W
150	50W	60W
138	50W	60W
134	57W	60W
140	50W	60W
132	50W	60W
125	60N	65N
135	50N	70N
140	65N	60N

Continued

130	60N	70N
135	60N	65N
140	60N	70N
132	65N	65N
145	55N	65N
136	70N	65N
125	60N	65N
123	60N	60N
128	60N	60N
130	55N	60N
136	65N	70N
131	50N	60N
125	65N	65N
133	60N	63N
125	55N	60N
128	50N	60N
122	50N	65N
136	50N	65N
143	60N	65N
118	65N	65N
137	65N	65N
134	60N	65N
129	60N	65N

Table 2. Structural data of Tondi-Gamey.

Structural data of Tondi-Gamey		
Direction	Deep	Pitch
50	75S	65S
60	70S	60S
80	85S	70S
60	70S	75S
50	70S	60S
60	60S	75S
55	80S	85S
70	60S	70S
80	70S	80S
75	60S	70S
60	60S	60S
50	65S	80S
70	75S	80S
65	75S	60S
40	70S	70S
50	70S	60S

5. Results and Discussion

5.1. Deformation Structures Affecting the Deposits of Continental Terminal 3

The deformation of the Continental terminal 3 (Ct^3) deposits was analyzed in the Trois Sœurs and Tondi-Gamey areas. These deposits are affected by two types of deformation: synlithification and postlithification. This study focuses on the analysis of synlithification. Synlithification deformation occurs during the early stages of lithification, i.e., while the sediment is still soft and contains a high percentage of water (Guiraud & Séguret, 1986; Konaté, 1996). Post-lithification deformation is characterized by fractures and a brittle shear zone. This indicates the rigid nature of the material.

5.1.1. "Trois Sœurs" Area

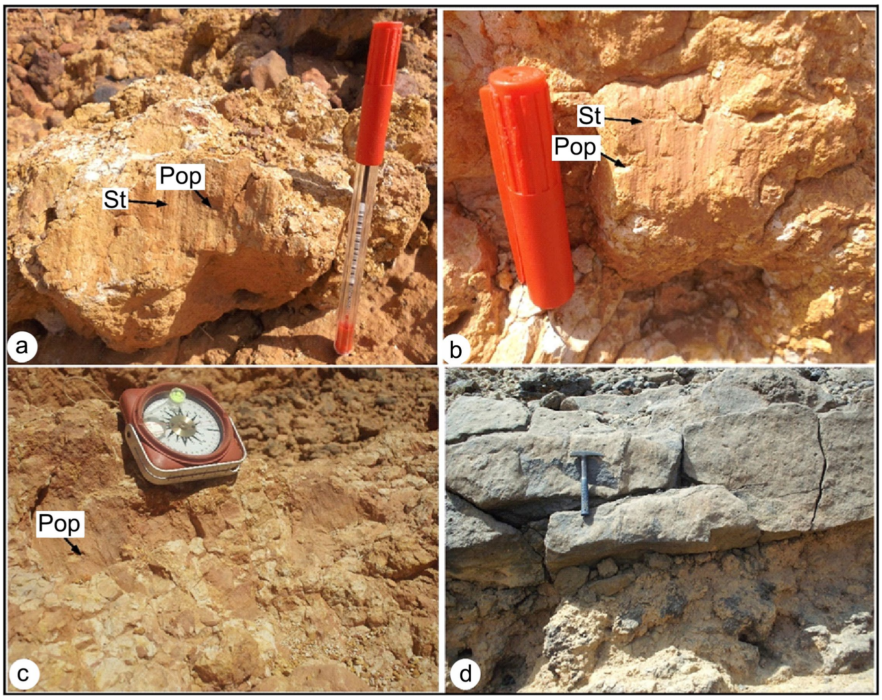

Figure 3. Normal microfault mirrors affecting ferruginous clayey sandstones of Ct^3. (a), (b), and (c): Normal microfault mirrors trending N110˚ to N140˚. (d): Normal microfault mirror trending N120˚ to N150˚. St: striation, Pop: pull-off pattern.

In the "Trois Sœurs" sector, curved to undulating microfault mirrors (F1) with a N110˚ to N140˚ orientation and a dip varying from 50˚ to 60˚ SW or NE affect both the sandstone-clay levels (**Figures 3(a)-(c)**) and the ferruginous levels. These mirrors have relatively curved striations, undulating grooves, and crescent-shaped tear marks, which are good indicators of the direction of movement (**Figure 3(d)**). These kinematic markers highlight normal faults consistent with high pitch values (50˚ and 70˚S or N). Similarly, the patina on the mirrors of these microfaults is the same color as the sediment, indicating that the tectonics are contemporary with the sedimentation. The curved mirrors indicate the high ductility of the material at the time of deformation. These observations confirm the synsedimentary nature of these normal microfaults. Due to their macroscopic characteristics, these normal microfaults are clearly distinct from classic brittle microfaults (Petit et al., 1983) and show strong similarities with synlithification microfaults (Petit & Laville, 1987) affecting loose sediments with a certain water content.

5.1.2. Tondi-Gamey Sector

In the Tondi-Gamey sector, microfault mirrors (F2) with a N50˚ to N80˚ orientation and a 60˚ to 80˚ SE dip were also identified in more clayey sediments (**Figures 4(a)-(d)**). These microfault mirrors are relatively curved and feature tectoglyphs marked by relatively curved striations, more or less undulating grooves, and tear marks (**Figures 4(a)-(d)**). Traces left by striating objects and tear marks indicate normal faults.

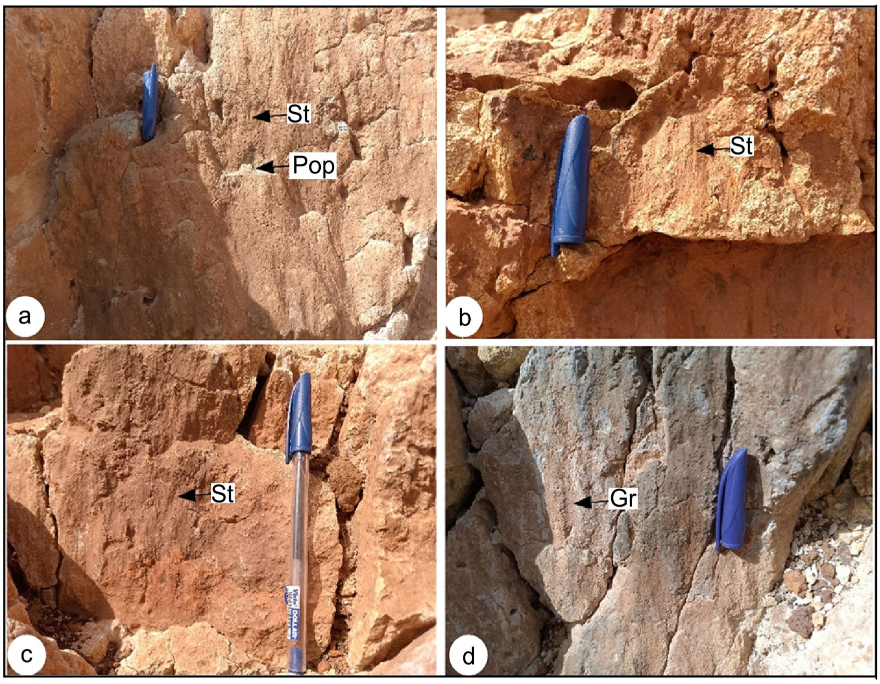

Figure 4. Normal microfault mirrors affecting the sandy clays of Ct[3]. (a)-(d): Normal microfault mirror with a direction of N50˚ to N80˚. St: striation, Pop: pull-off pattern. Gr: groove.

5.2. Determination of Paleostress States

5.2.1. "Trois Sœurs" Sector

Normal microfault planes with N110˚ to N140˚ orientation and 50˚ to 60˚SW dip were projected using the Win-Tenseur program (Delvaux, 2011, 2019). The stereodiagrams obtained indicate a σ3 stress direction varying from N50˚ to N55˚ (**Figure 5(a)**), with an average σ3 stress direction of N50˚ (**Figure 5(b)**). This family of normal microfault planes (F1) defines a first phase of extensive deformation D1a with an average extension direction of N50˚, dating from the Oligocene epoch.

5.2.2. Tondi-Gamey Sector

The normal microfault planes of the F2 family, oriented N50˚ to N80˚ with dips of 60˚ to 80˚SW, were projected using the Win-Tenseur program (Delvaux, 2011, 2019). The results of the projection of the normal microfault planes family (F2) show an average extension direction of N170˚ (**Figure 5(c)**). This extensive direction with an average orientation of N170˚ defines a second phase of extensive deformation D1b (Oligo-Miocene) epoch.

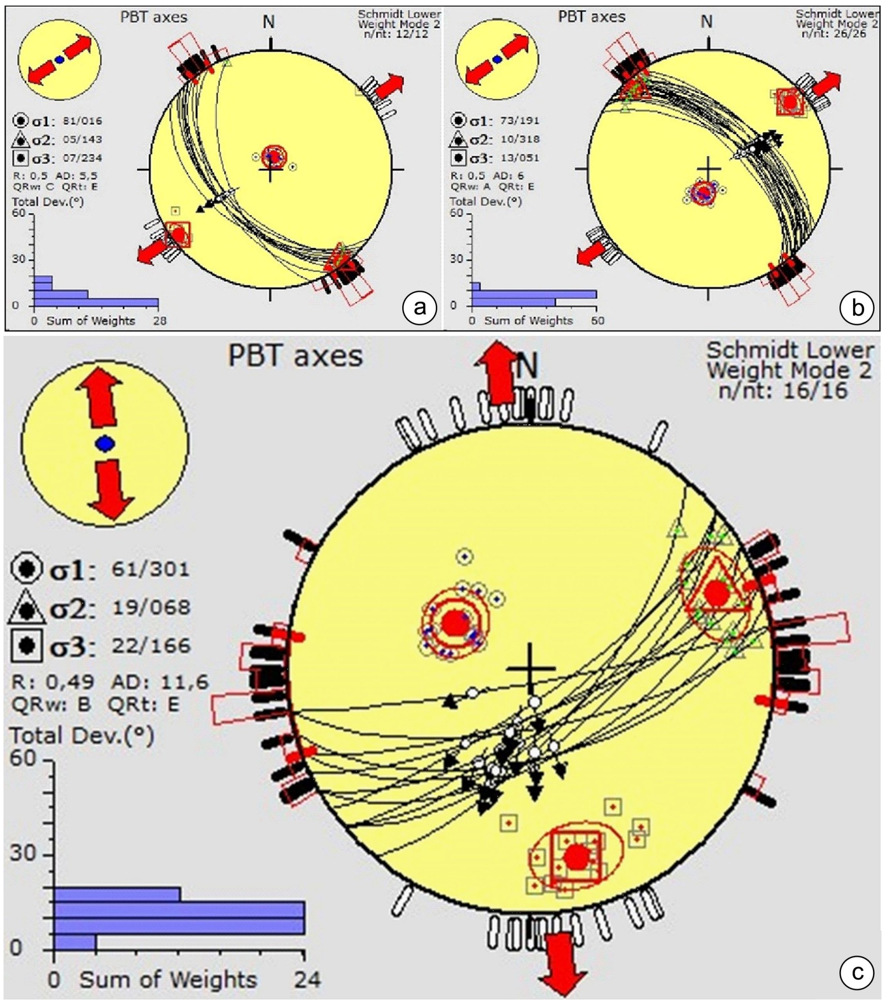

Figure 5. Results of processing the population of synsedimentary normal microfault planes. (a) and (b): The stereodiagram of microfault planes at the "Trois Sœurs" station shows an overall extension direction of N50˚ (NE-SW). (c): The stereodiagram of normal microfault planes at the Tondi-Gamey station indicates an extension direction of N170˚ (NNW-SSE).

6. Structural Summary

The two phases of extensive deformation highlighted during this study are summarized in **Figure 6**. The first deformation phase D1a has an extension direction of N50˚, and the second deformation phase D1b has an extension direction of N170˚.

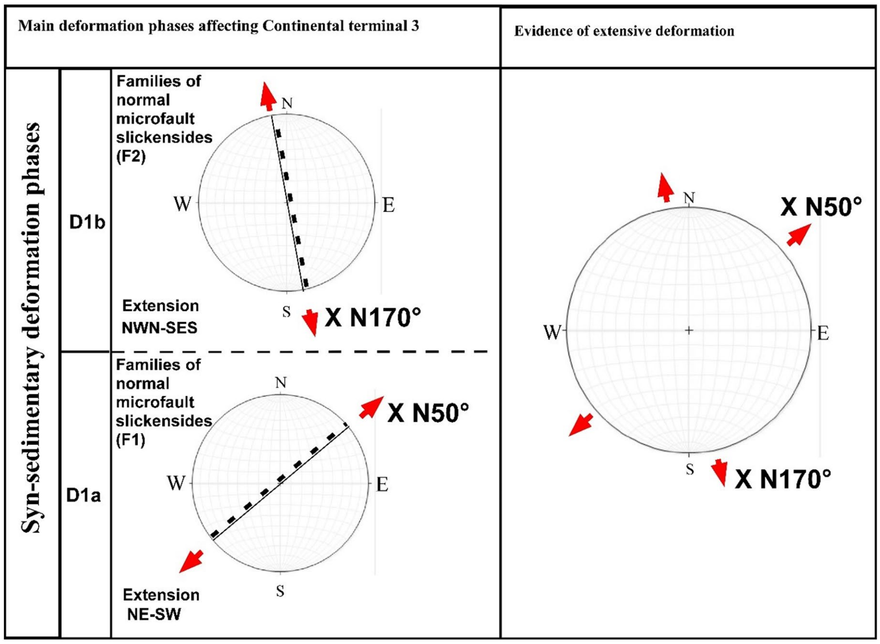

Figure 6. Summary showing the two extensive deformation phases D1a and D1b during the Oligocene to Miocene period.

7. Discussion

The deposits of Continental terminal 3 (Ct^3) in the Niamey region are affected by a phase of extensive synsedimentary deformation, marked by mirrors of normal microfaults oriented N110˚ to N140˚ and N50˚ to N80˚ with dips of 60˚ to 80˚ towards the SW or NE. These normal microfault planes are compatible with the respective extension directions N50˚ (NE-SW) and N170˚ (NNW-SSE). The N50˚ extension direction noted as D1a (**Figure 6**), highlighted in the Ct^3 deposits in the Niamey region, is comparable to the N50˚ to N80˚ extension direction obtained by Ousmane et al. (2020). Comparable results were obtained in northeastern Tunisia by Ben-Ayed (1986), Zouari (1995), and Hezzi (2014). These authors highlighted an extension in the N30˚ to N50˚ direction during the Oligocene, responsible for the formation of Oligocene grabens, which can be correlated with those observed in the Niamey region in this study. Ben-Ayed (1986) and Chihi (1995) suggest that during the Oligocene period, a distensive phase prevailed in Tunisia. A similar observation was made on the scale of the Arabian platform by Fournier (2011). The latter suggests that the E-W to NW-SE orientation of the grabens and associated normal faults is linked to regional extension in a N-S to NE-SW direction. By analogy, the N50˚ to N80˚ direction of the normal microfault mirrors, highlighted in the Tondi-Gamey sector, is compatible with the N170˚ (NNW-SSE) extension direction. However, this N170˚ extension direction, noted as D1b (**Figure 6**), was not highlighted by Ousmane et al. (2020) in the Niamey region. In the Oligocene-Miocene basins of Somalia, the same NNW-SSE directions of normal faults were described by Abbate et al. (1986). In the Termit basin in Niger, a phase of extensive deformation (NNW-SSE) identical to that obtained in the present study was highlighted by Genik (1992). This author linked this phase of deformation to an Oligocene-Miocene (Neogene to present) extension. In Eritrea, an N170˚ extension direction was identified in the Antalo limestones (Adeilo sector) by Sagri et al. (1998). This N170˚ extension direction correlates with the N160˚ deformation phase described by Huchon & Khanbari (2003) in the basins of the northern margin of the Gulf of Aden (Yemen). These authors linked this N160˚ extension direction to the late Oligocene-Miocene deformation phase. In the eastern portion of the Gulf of Aden rift, at the conjugate margins of Oman and Socotra, two phases of extensive deformation, D1 (N20˚) and D2 (N150˚), were identified by Fournier (2011). Similarly, at the margin of Yemen, two phases of Oligocene-Miocene extensional deformation, D1 (N20˚) and D2 (N160˚), were also described by Huchon & Khanbari (2003). These two phases of deformation are comparable to the results obtained in the present study. To explain the prevalence of this Oligocene distension on an African scale, Burke (1996) suggests that the African plate became immobile relative to the mantle from the Oligocene onwards (Burke & Gunnell, 2008;), whose mantle fluid circulations would have had a major impact on the development of Africa's topography. These topographic bulges (the Hoggar, the Aïr, the Iforas, the Tibesti) formed in association with a major episode of volcanism in Africa since 35 Ma (Rougier, 2012). This Oligocene distension on an African scale is associated with the opening of several basins, including the East African Rift, resulting from mantle dynamics. Indeed, the East African Rift is closely associated with magmatism and mantle fluid circulation during this Oligocene period (Ebinger & Sleep, 1998; Braun, 2010; Allen, 2011; Moucha & Forte, 2011). Furthermore, several authors (Huchon & Khanbari, 2003; Fournier, 2011; Ousmane et al., 2020) have interpreted this NE-SW (N50˚) extension direction as being the first phase of Oligocene deformation, resulting from mantle dynamics. Meanwhile, the overall NNW-SSE (N170˚) extension direction is linked to the second phase of Oligocene-Miocene deformation (Huchon & Khanbari, 2003). These authors linked this D2 deformation phase to the westward propagation of the Gulf of Aden oceanic rift. According to Rachdi et al. (1997), there were two episodes of extensive deformation during the Oligocene-Miocene within the general compressive regime caused by the collision between Africa and Eurasia. This event could be the origin of the tectonic structures characterizing the late D1b deformation phase with a N170˚ (NNW-SSW) direction, which was highlighted by the present study.

8. Conclusion

This study shows that the Oligocene-Miocene deposits of Ct^3 recorded two major phases of extensive deformation in the tectonic history of West Africa during the Cenozoic era. The first extensive Oligocene phase D1a, oriented N50˚, appears to have been closely controlled by the mantle dynamics of the time, giving West Africa a dome and basin structure. This structure appears to be associated with ascending and descending mantle currents. In the study area, these descending mantle movements are contemporary with the last episode of filling of the Iullemmeden basin, promoting the reactivation of most of the NW-SE-oriented faults. The second phase of deformation D1b, oriented N170˚, also extensive, is thought to be linked to an extensive episode within the compressive regime that occurred during the collision between Africa and Europe.

Conflicts of Interest

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

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