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Research Article

# Sedimentological Analysis of the Facies from the Maastrichtian to Eocene Ages of the Ader Doutchi Sub-basin and Chronological Timing of the Different Fracturing Episodes

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## Abstract

The present study covered the Ader Doutchi sub-basin, corresponding to the south-eastern part of the Iullemmeden basin. The sediment fill of the Ader Doutchi sub-basin is made up of deposits from the Maastrichtian to Eocene ages. The objective of this study is to: (i) analyze the vertical sequence of facies, (ii) identify the main fractures, (iii) chronologically map the main fractures from field observations and (iv) Determine the time sequence of major fracking events. The methodology implemented is based on field and laboratory work. The field work consisted of the survey of lithostratigraphic sections, with sampling and structural measurements. The laboratory work is all about processing structural data using the Win-Tensor 5-8-9 program. The sedimentological analysis of Maastrichtian to Ypresian deposits (lower eocene) reveals two main facies: one clay and the other marno-limestone. The analysis of fractures in the studied formations highlights three episodes of fracturing, D1, D2 and D3, associated with the Maastrichtian, Paleogene and Ypresian age deposits.

## Keywords

Iullemmeden Basin, Ader Doutchi Sub-basin, Retrotectonic, Maastrichtian, Ypresian

## 1. Introduction

The Ader Doutchi sub-basin is located in central Niger. It represents the eastern part of the Iullemmeden Basin. The Ader Doutchi sub-basin has a monoclonal structure, with layers having very weak slopes of 1 to 2% towards the SW [7]. The Ader Doutchi sub-basin is affected by a fracture network. The network consists of several intersecting fracture families. The character-

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ization of this network involves a detailed survey of fracture geometry, identifying dominant families and their main orientation [17]. Apart from a few studies on fracking from satellite images taken in a disparate manner in the Iullemmeden basin, no study of deformation affecting Cretaceous-Eocene deposits has been undertaken in the Ader Doutchi sub-basin. To overcome these shortcomings, a retrotectonic approach, integrating structural analysis was implemented. The objective of this study is to establish a chronological chronology from field observations of the main fractures and to determine the succession in time of the main fracking episodes.

## 2. Geographical Setting and Geological Context

### 2.1. Geographic Setting

The Ader Doutchi sub-basin is divided between the regions of Tahoua, Maradi, Zinder and Agadez (Figure 1). It covers an area of around 160,000 km$^2$. Its relief is varied and rugged, characterised by plateaux and hills, with sandy glacis. These geomorphological formations create a diversity of microenvironments conducive to different agricultural activities [33]. The climate in the area is Sahelian, with a short rainy season from June to September and a long dry season from October to June, influencing soil formation and characteristics [2]. The area is crossed by ephemeral watercourses (koris), which play a crucial role in the irrigation of market garden crops [33]. The vegetation is adapted to the arid climatic conditions of the region, with drought-resistant plants predominating. It is grouped into two categories, that of the plateaux, comprising acacias (Acacias) and combrétacées (Combretum), to which are added the grasses in the herbaceous carpet, and that of the plains and valleys rich in Gao (Acacia albida) and Balanites aegyptiaca. To this must be added a significant band of grasses and Prosopis [27].

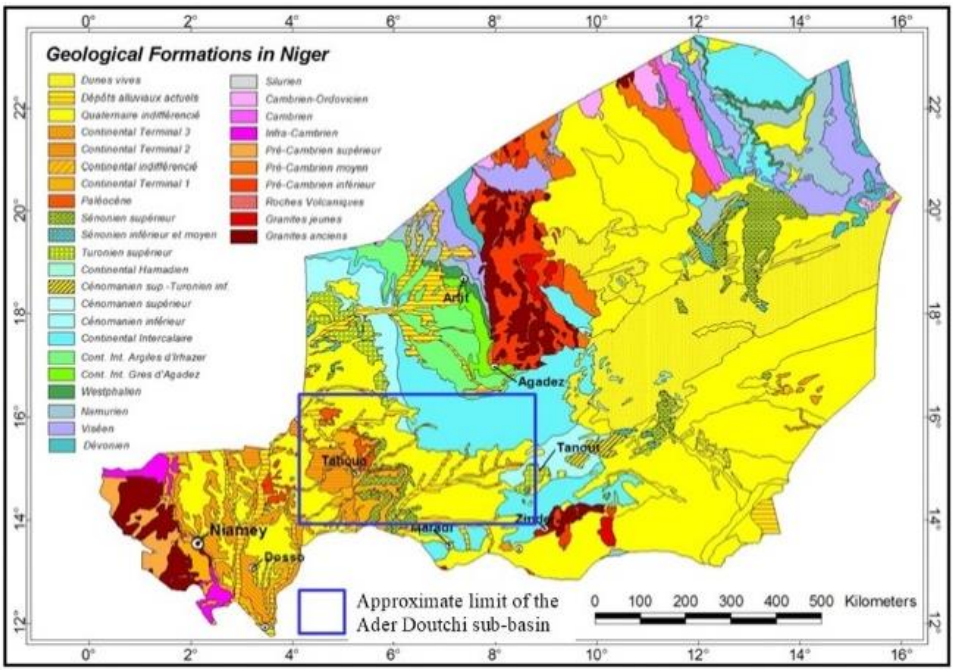


*Figure 1. Location of the Ader Doutchi sub-basin in Niger [11].*

### 2.2. Geological Setting

The Ader Doutchi sub-basin lies to the south-east of the Iullemmeden basin (Figure 1). The sedimentary fill is made up of deposits from the Intercalary Continental (CI), the Cretaceous, the Eocene and the Terminal Continental (Ct). This Ader Doutchi sub-basin corresponds to a synclise with a NW-S axis. It rests on the remobilised Birimian basement of the Aïr to the NE (Figure 1). It is continuous to the west with the Meso-Cenozoic formations of the Iullemmeden Basin, which abut the Birimian and Infracambrian terrains marking the eastern edge of the West African Craton (Figure 1). In the study area, three sedimentary formations characterise the Ader Doutchi sub-basin. At the base are the Alanbanya (Ibohamane sands, Bouza silts), Farin Doutchi and In Wagar formations, of Upper Cretaceous age (Figure 2), consisting mainly of unconsolidated sands and silts and clays containing a few banks of ferruginous oolites. These are topped by the Garadaoua formation of Palaeocene-Ypresian age, represented by more or less marly limestones framed by two levels of papyrus schists. The summit is covered by deposits of the

Ader Doutchi formation, rich in ferruginous materials (sandstones, siltstones, ooids) of Oligo-Miocene age [28] (Figure 2).

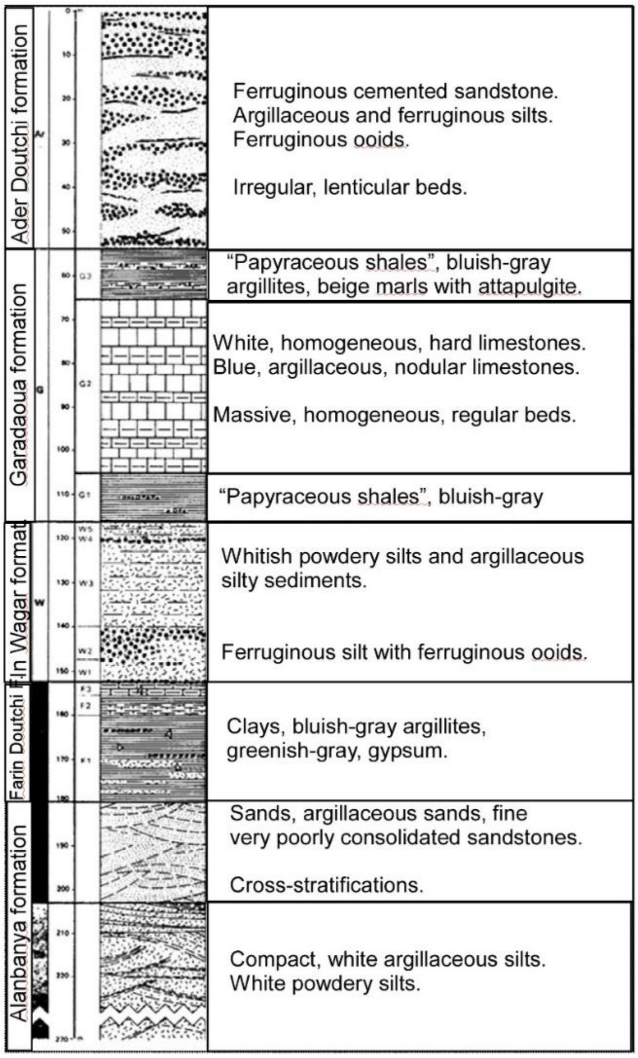


***Figure 2.*** *Coupe lithostratigraphique du sous-bassin de l'Ader Doutchi [16].*

## 3. Material and Methods

The compilation of available documents (articles, theses, reports, maps), relating to the geology of the Iullemmeden basin in general and that of the Ader Doutchi sub-basin in particular, has made it possible to take stock of knowledge of the geology of the region studied. The fieldwork consisted of surveying lithostratigraphic sections, together with sampling and structural measurements. A relative chronology was established by observing how the fractures intersected one another. In addition, the application of the retrotectonic method enabled the successive fracturing episodes to be calibrated chronologically. According to the retrotectonic approach, when three successive deformation episodes D1, D2 and D3 affect a region comprising three terrains, A (Maastrichtian), B (Palaeocene) and C (Ypresian), the older Maastrichtian terrains record all the deformations affecting the area concerned. The Paleocene terrain records only syn- and post-Paleocene deformation. The more recent Ypresian terrain records only the most recent episode of deformation. In the region studied, nearly 150 fracture planes of all categories were measured. For each fracture family, the selected planes were then processed using Win-Tensor 5-8-9 software (Delvaux, 2003) [3]. This approach made it possible to determine the succession in time of the different fractures.

## 4. Results

### 4.1. Sedimentological Analysis of Facies

The synthetic section of the south-western part of the Ader Doutchi sub-basin groups together the following three formations: In Wagar (W), Garadaoua and Ader Doutchi. The Maastrichtian formation of In Wagar (W), about 6m thick, comprises three units from base to top: W3, W4, W5. Unit W3 consists of four levels (Figure 3). The base level is represented by fine sandy beds with oblique arched or trough-shaped bedding passing vertically into massive sandy beds. The intermediate deposits of unit W3 are represented by fine whitish sands with undulating bedding, relayed at the top by bioturbated sandy banks with subhorizontal bedding. Unit W4 is approximately 10 m thick and comprises seven levels (Figure 3).

The base level is made up of fine beige clayey sandstones, vertically relayed by argillites then by silty argillites, surmounted by fine clayey sandstones with varying degrees of shale. The intermediate level of unit W4 is represented by fine clayey sandstones with calcareous concretions, surmounted by fine clayey sandstones of varying ferruginous content, with calcareous nodules. The top of unit W4 corresponds to medium clayey sandstones, more or less ferruginous. Unit W5 comprises three levels (Figure 3). The base level is made up of foliated, mottled silty mudstones. The intermediate level corresponds to more silty, mottled claystones. The top of unit W5 is represented by grey argillites with gypsum lenses. The Maastrichtian In Wagar formation is overlain by the Palaeocene-Ypresian Garadaoua formation. The latter is subdivided into four members. These are, from base to summit, the: Kao, Tamaské, Barmou and Keita. The four members of the Garadaoua formation have been subdivided into eight levels. The G1 member of Kao is made up of two levels. The base level is represented by yellowish marls, highly fossiliferous, including nautiluses, echinoids (genus Linthia), bivalves and gastropods. The upper level consists mainly of papyracene shales (Figure 3). The Tamaské Member (G2) comprises three limestone layers of varying thickness, forming cliffs with rectilinear edges coinciding with fault planes. The base level consists of fossiliferous limestones of varying clay content. The intermediate level of the G2 member is represented by massive limestones rich in fossils. The top of G2 corresponds to chalky and nodular limestones. The Barmou G3 member is represented by a level of papyraceous shales or cardboard shales. The Keita G4 member comprises two levels: the first is marly, sandstone with a conglomeratic tendency, and the second is made up of papyracate shales. The top of the Garadaoua section is overlain by the Ader Doutchi formation (Figure 3). The latter is essentially made up of bari-coloured argillites and clayey siltstones at the base. The Ader Doutchi formation has alternating irregular beds of kaolin claystone, more or less lateritic, and ferruginous oolites in the middle section, with ferruginous oolite sandstone at the top.

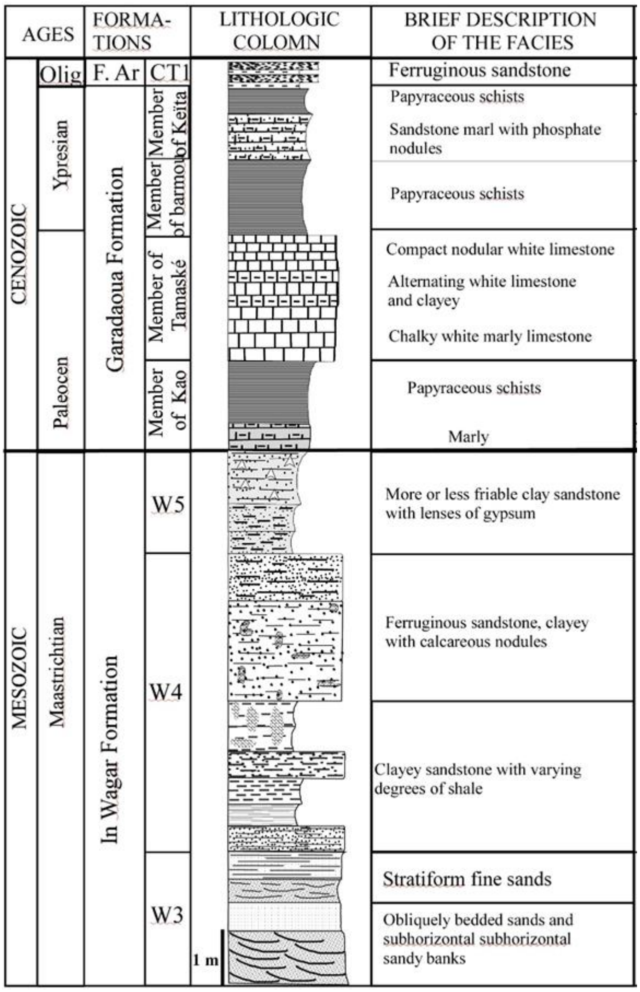


***Figure 3****. Synthetic lithostratigraphic section of the study area.*

## 4.2. Chronological Timing of the Major Fracture Families

In the Ader Doutchi sub-basin, the two flush formations studied are of Maastrichtian age (In Wagar), palaeocene-ypresian (Garadaoua) and were considered (Figures 3 and 4). The Maastrichtian terrains, which are the oldest, recorded all brittle deformations (F1, F2 and F3) affecting the study area (Figure 4 A, B and C), while the Paleocene terrains only recorded syn and post-Paleocene deformations (F2 and F3) (Figure 4 B and E). The most recent Ypres sites recorded only the last fracking episode (F3) (Figure 4 C and E). The first generation of F1 fracture has a direction between N80° and N110°. Second generation F2 fractures are oriented between N120° and N170° while the third generation F3 fractures are oriented between N40° and N70°. The Continental Terminal (Ct1) formation of ferruginous clay sandstone deposits surmounting the Ypresian terrain has a pleated structure (Figure 4D).

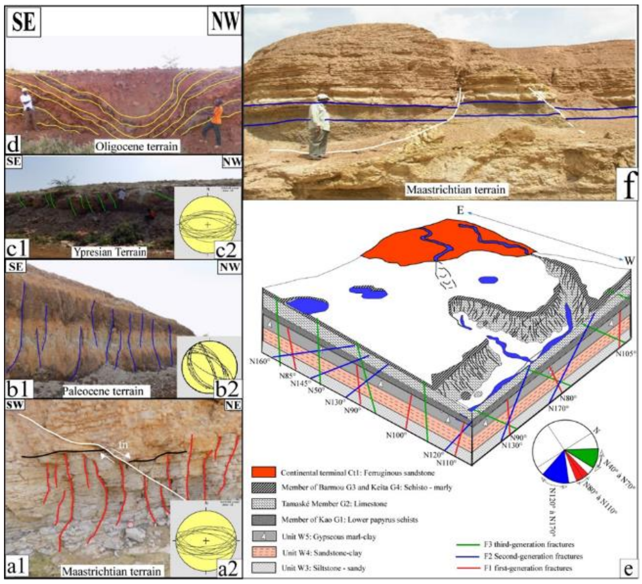


***Figure 4****. Synthetic diagram of the fracture network affecting the studied formations.*

a1) Nakoni clay deposit affected by first generation F1 fractures, a2) Stereographic projection of the first generation F1 fracture planes, fn) Generation F2 normal fault (N135°, 40°SW), b1) Garadaoua limestone deposits affected by second generation fractures F2, b2) Stereographic projection of the fracture planes of second generation F2, c1) Garadaoua marnocalcareous deposits affected by third generation fractures, c2) Stereographic projection of the fracture planes of the first generation F3, d) Continental Terminal 1 (Ct1) Pleated Oligocene-age Ferruginous Clay Sandstone Deposit e) Block diagram showing the different fracture f) Normal stripe faults seen on a Nakoni outcrop.

## 4.3. Analysis of Brittle Deformation in the Maastricht Nakoni Terrain

The Nakoni outcrop, of medium orientation SW-NE, is affected by two types of brittle deformation structures: fractures and faults. This outcrop is mainly composed of siltstones of Maastrichtian age in its basal part and ferruginous clay sandstone at the top. On this intensely fractured Nakoni outcrop, the retrotectonic approach was applied. Thus, three generations of fractures, successively F1, F2 and F3 were distinguished. The first generation of F1 fractures, N80 to

N110°, affecting only the Maastrichtian deposits, was linked to the extensive D1 deformation episode in the N-S direction (Figure 5 B). The second generation of F2 fractures from N120° to N170°, is well represented in the Paleocene and Maastrichtian terrains. The third generation F3, with orientation from N40° to N70°, affects both Maastrichtian, palaeocene and ypresian terrain (Figure 5 A). In the regional geodynamic context prevailing at that time, in accordance with data from [1], this phase was linked to extensive N-S movements related to the opening of the Atlantic. These observations are in line with the work of Dlala, M. in Tunisia [6]. Indeed, this author has highlighted an extensive N-S tectonic in the central part of the Tiouacha massif, at Kef el Kretma, in the marnocalctic nodular deposits of Campanian age to Maastrichtian, along a major ridge that rises to 1110 m.

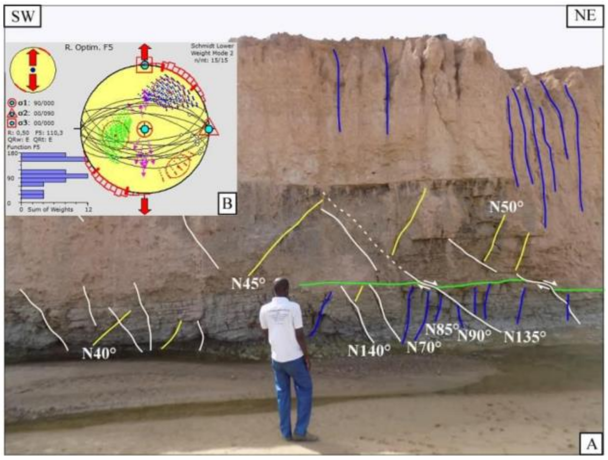


***Figure 5.*** *Fractures F1, F2 and F3 observed at the Nakoni outcrop.*

A: Network of fractures affecting the Maastricht argillites (blue: family F1; white: family F2 and yellow: family F3; fn: faults) B: Stereogramme showing a first phase of extensive deformation D1 marked by an elongation direction N0° C: Green line (boundary between silty argillites interstratified by ferruginous banks and more argilites interstratified by ferruginous banks).

## 4.4. Analysis of Brittle Deformation in the Palaeocene-ypresidan Soils of Garadaoua

Oriented NW-SE, this outcrop is marked by two families of fractures (F2 and F3), affecting the paleocene and ypresian terrains. These two fracture families are associated with episodes of compressive strain D2 and D3 (Figure 5).

### 4.4.1. Compression Strain Episode D2

The Maastrichtian distensive episode D1 is followed by a paleoocene D2 depressive episode (Figure 6 B). The latter affects clay-limestone formations established by the Maastrichtian transgressions T4 and palaeocene T5 [5]. Episode D2 is also associated with the formation of shear joints, which sometimes have re-played in stalling in connection with the reorientation of stresses. These joints are mainly observed in the Maastrichtian deposits. In the Paleocene limestone deposits, the F2 family is represented by the fractures inherited from the Maastrichtian distensif episode. These are the orientation fractures: (N120°, 72°SW), (N150°, 38°SW), (N160°, 85°ENE) (Figure 6A). These fractures are sealed by the marmo-calcareous deposits of the lower Eocene. The mean shortening direction from microtectonic analysis is N140° (Figure 6A). This phase D2 is comparable to that identified by [14] in the Tim Mersoï basin, corresponding to a N130° end-cretaceous décrochant compression. A comparable shortening direction (N140°) was obtained in the Taoudenni basin by [1], who linked it to an intra-eocene compressive episode. According to the same author, in the Iullemmeden basin, the manifestation of this intra-eocene compressive episode would be rather discreet.

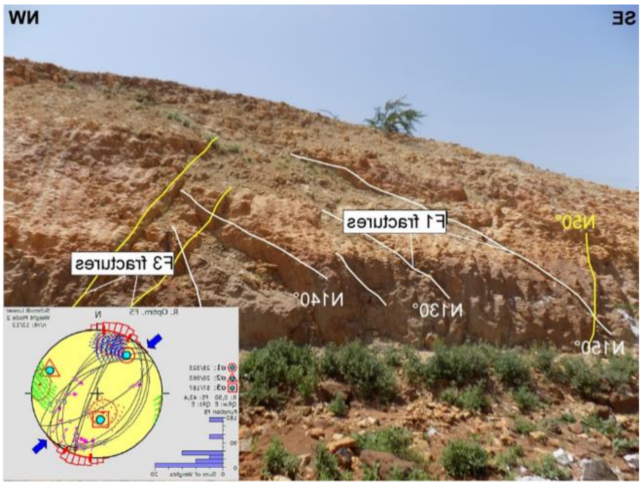

***Figure 6.*** *Fractures F2 and F3 observed at the Garadaoua outcrop.*

A: In white the fractures of the F2 family and in yellow the fractures of the F3 family. B: Stereogramme showing a second phase of compressive deformation D2 marked by a shortening direction N140°.

### 4.4.2. Compression Strain Episode D3

Episode D3 (Figure 7A) was identified in the Ypres-age marnocalctic deposits. In the underlying Paleocene and Maastrichtian deposits, F3 fractures overlap with those of F1 and F2 (Figures 6 and 7). Episode D3 is a compressive deformation with an average shortening direction of N150° (Figure 7B). This ypresciál compression deformation is comparable to that of N140 direction, as evidenced by [1] in the Néma-Nara region of Mali (Taoudenni basin). Indeed, in this region, [1] identified two suborthogonal shortening directions: one older N140° (presumed to be Palaeocene) and the other newer N30° presumably Ypresiean.

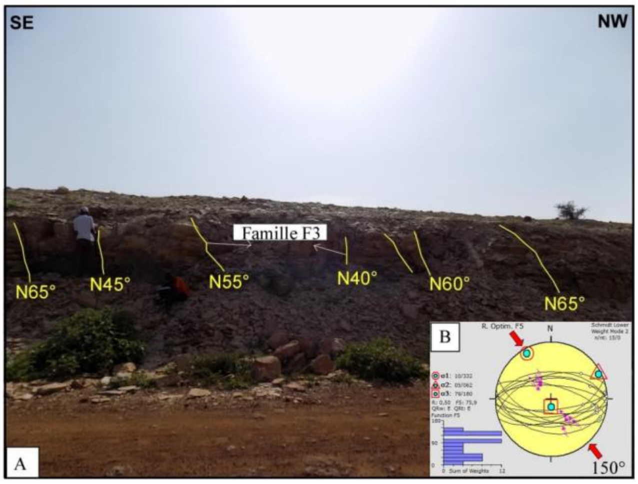


***Figure 7.*** *Fractures F3 observed at the Garadaoua outcrop.*

A: Network of fractures of the F3 family affecting the ypresclal marnocalcarian deposits. B: Stereogramme showing the third phase of compressive deformation D3 marked by a shortening direction N150 °(shortening axis shown in red).

## 5. Discussion

The tectonic history of the Ader Doutchi basin is closely linked to the geodynamic context of West and Central Africa from the Late Cretaceous to the Cenozoic. During the period from the Maastrichtian to the Yprescenian, the study area is affected by three episodes of deformation: an extensive episode D1 in the Maastrichtian, followed by a compressive episode D2 in the Paleocene, followed by a second compressive episode D3 in the Yprescenian (Figure 8).

### 5.1. Cretaceous Tectonic Distensive, Episode D1

Several basins of West and Central Africa were marked, from the Cretaceous to the Eocene, by tectonic activities either in extension for some, or in compression for others. In the Ader Doutchi sub-basin an episode of extensive D1 deformation of N-S direction was evidenced in silt-clay deposits of Maastrichtian age. Well-documented rifting and compression episodes in studies such as those by [32] and [18], illustrate the diversity of tectonic regimes that have influenced regional geology. In the Lower Cretaceous, the Tim Mersoi basin experienced a rifting episode marked by a significant rate of subsidence, reaching about 4.11 m/Ma. This phenomenon allowed the development of considerable sedimentary thicknesses in the axial zone of the DASA graben [32]. This extensive tectonic is corroborated by observations in the Téfidet Ditch, where an extension and transtension regime predominated, with an average extension direction of about N60 °[18]. These geological structures, including the NW-SE oriented normal faults, are evidence of an active tectonic environment that has favoured the formation of grabens in Niger and the upsetting of the Aïr fringes [12, 13]. Other basins such as Kandi and Sokoto, however, have been subjected to compressive forces. The direction of shortening between N130 °and N-S points to a tectonic transition influenced by the change in the pole of rotation of the African plate during the Cretaceous. This compression contributed to the formation of distinct geological structures, as indicated by the work of Guiraud and [14]. The tectonic activity in central Tunisia during the Aptian to the Campanian-Maastrichtian period also illustrates this duality between extension and compression. Distensive to décrochante distensive deformation is observed, with a direction of extension NNE-SSW to N-S [6]. This highlights the complex interaction between different tectonic regimes within African sedimentary basins. This tectonic diversity has not only shaped the geological landscape but also had significant implications for natural resources, including gypsum, limestone and phosphate deposits.

### 5.2. Paleocene Compressive Tectonics, Phase D2

The analysis of the compressive phase D2, as observed in the Paleogene limestone deposits of Garadaoua, highlights the tectonic dynamics that shaped the subbasin of the Ader Doutchi. The shortening direction, derived from microtectonic analyses of fracture planes, is oriented on average towards N140 °(NW-SE). This orientation indicates a reactivation of the previous structures under the effect of compressive forces, a phenomenon that was supported by the earlier work of [1] in the Iullemmeden basin. This NW-SE compressive tectonics, which began in the Late Cretaceous according to [14], has had a significant impact on the current geometry of the Tim Mersoi basin. This phase not only reactivated existing structures but also contributed to the formation of new tectonic deformations. The observations made in Algeria, notably in the Aurès by Laffitte (1939) [19, 10, 15]; and in Tunisia by [9] highlight that this NW-oriented compressionSE exercised a decisive control over the distribution of palaeogeographic domains (Figure 8). This suggests that the tectonic mechanisms are not limited to specific areas but extend over wider regions, thus influencing the morphology and stratigraphy of sedimentary basins.

### 5.3. Eocene Compression Tectonics, Phase D3

The D3 compressive tectonic event, oriented N150 ° and also NW-SE, was evidenced in the Ypresen age marnocalctic deposits of Garadaoua, located in the Keita sector. This compressive episode denotes the complexity of tectonic regimes affecting the sedimentary deposits of the Ader Doutchi sub-basin. In the Tefidet Ditch, this episode is associated with a Oligocene-Pliocene age postrift phase, as pointed out by [18], who observed a transtension-oriented extension regime around N70 °. This regime has mainly generated post-sedimentary faults and fractures, as well as alkaline volcanism, revealing dynamic geological activity during this period. West of the Iullemmeden basin in the Niamey region, work by [29] has linked this eocene compressive episode to a presumed post-oligocene compression phase of miocene age, oriented approximately N140°. According to these authors, this phase took place in a context of continuous convergence between the African and European tectonic plates, resulting in the reactivation of the inherited faults in the form of gaps, whether senestrous or dextrical, depending on their orientation in relation to the direction of shortening. [1] also linked this NW-SE compressive episode to the Pyrenean-Atlantean phase, resulting from the collision between the Africa and Europe plates. This NW-SE compression would have had significant consequences on the permanent withdrawal from the sea in the intracratonic basins of West Africa, as well as on a partial regression in the coastal basins.

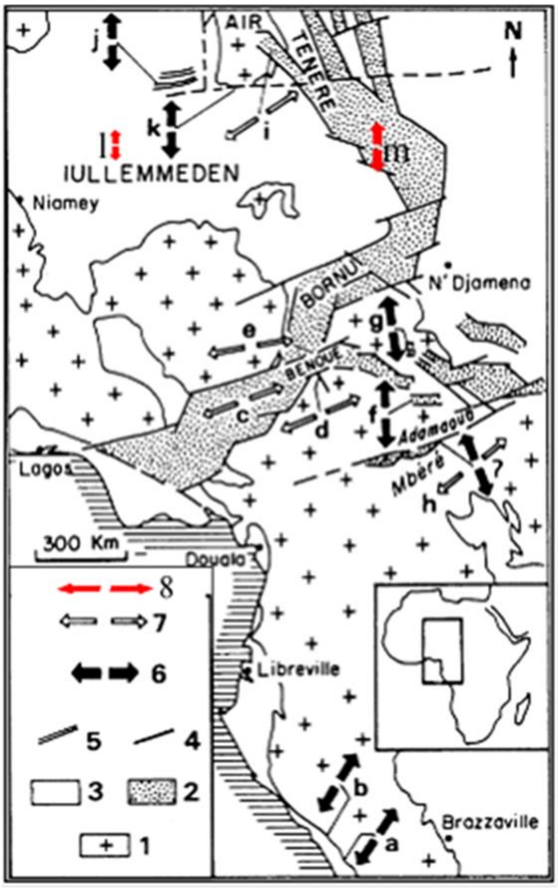


***Figure 8.*** *Paleoconstraints in the lower and upper Cretaceous, derived from microtectonic observations [13-20]. 1: Precambrian or paleozoic substrate; 2: Intracratonic basin subsiding in the lower Cretaceous 3: Meso-cenozoic basins; 4: Active faults in the lower Cretaceous; 5: Half-grabens beam; 6: Anté-Crested elongation directionaptian superior 7: Elongation direction at the upper Albian aptian; 8: Elongation direction at the upper Maastrichtian. a to m: microtectonic stations; a-b: Mayonne rim [23]; c: Moyenne Benoué [30]; d: Mika, Haute Benoué [26]; e: Kaltungo [22]; f: Koum [25]; g: Figuil [23]; h: Sud Adamaoua [8]; i: Nord Tefidet [12]; j: Tim Mersoï [21]; k: Taoussat [21]; l: Nakoni [20]; m: Termit-Agadem Ditch [31].*

## 6. Conclusion

The structural analysis of the Maastrichtian-Ypresiden formations in the Ader Doutchi sub-basin has revealed three distinct deformation episodes, designated D1, D2 and D3, corresponding respectively to the Maastrichtian, Paleocene and Ypresiden ages. The first episode, D1, is characterized by an extensive regime with an elongation oriented N0°. This episode was associated with a widespread subsidence in the West and Central African basins, concomitant to a major transgression observed at Libycoceras and Laffiteina. The compressive episodes D2 and D3, with shortening directions of N140° and N150°respectively, are interpreted as the consequences of the counterimpacts of the collision between the tectonic plates of Europe and Africa during the Paleogene period. These tectonic events illustrate not only the complex dynamics of the geological forces at work in this region, but also their significant impact on local stratigraphy. In short, this study strengthens our understanding of the tectonic processes that shaped the Ader Doutchi sub-basin. She highlights the importance of an integrated approach to geological deformation analysis, which could be beneficial for future research on geological resources in this region. The results also pave the way for further studies to explore in greater depth the geodynamic implications of these tectonic events on regional development.

## Abbreviations

| | |
|---|---|
| Ar | Ader Doutchi |
| CI | Continental Intercalaire |
| Ct | Continental Terminal |
| D | Deformation Episode |
| F | Fracture Family |
| G | Garadaoua Formation |
| ORSTOM | Overseas Scientific Research Office |
| W | In Wagar Training |

## Author Contributions

**Karimou Laouali Idi:** Conceptualization, Data curation, Formal Analysis, Investigation, Resources, Software, Validation, Writing-original draft, Writing-review & editing

**Habsatou Ousmane:** Writing-review & editing

**Ibrahim Abdou Ali:** Writing-review & editing

**Hassan Ibrahim Maharou:** Writing-review & editing

**Daouda Illia Allo:** Software

**Abdourazakou Maman Hassan:** Writing, editing and publishing, Software

**Moussa Konate:** Data curation, Methodology, Formal Analysis, Validation

## Conflicts of Interest

The authors declare no conflicts of interest.

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