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Origins of the Ruiniform Character of the Sandstones of the upper Member of the Dindefelo Formation, Madina Kouta Basin (Kédougou, Senegal, West Africa)

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Abstract

The Dindefelo Formation, from the Madina Kouta basin in Senegal, is dated to the Tonian (1000 - 750 Ma). It comprises three members: silty clays, associated with fine quartz sandstones and intraformational conglomerates (DF1); clayey sandstone banks with clay-silty interbancs (DF2) and plurimetric banks, separated by clay-sandstone flats called ruiniform sandstones (DF3). Based on careful observations of sedimentary figures and petrographic analyses, here we examine the main processes that are at the origin of the ruiniform appearance of DF3. Of the three members of the Dindefelo Formation, DF3 has the highest mineralogical and petrographic maturity, and the highest density of sedimentary and tectonic structures. Forms present, include symmetrical, asymmetric, linguoid, interference ripples, dunes, bars, and anti-dunes. Tidal structures, desiccation cracks, hardened surfaces, bioturbations, and microbial mats are very abundant. This Formation is also characterized by a dense network of NNW-SSE, NE-SW and ENE-WSW oriented discontinuities that are more apparent on DF3 due to its characteristics. Under the combined action of these different synsedimentary and post-sedimentary processes, the sandstones are cut into plates, slabs, and parallelepiped blocks, giving rise to a ruiniform landscape in the form of giant teeth and mass landslides caused by a strong instability of the flanks. The originality of this model lies in the role played by sedimentary and tectonic structures.

Keywords

Petrography, Sedimentary Figures, Fracturing, Ruiniform Landscape, Landslides

1. Introduction

Ruiniform reliefs are frequently described in literature. They have different names depending on the locality, can be found in various lithologies with various processes, under a wide range of climates.

According to Migoń et al. (2017), the term "ruiniform reliefs" has not been formally defined and is used rather intuitively by geomorphologists, primarily to describe dispersals of highly weathered rock outcrops of moderate height. These outcrops are found on various continents and in various locations and are considered by Adamovič et al. (2006) to be erosional landforms that produce rock shapes reminiscent of ruins, based on anthropocentric interpretations.

The most famous are cited in the sandstone districts of the Czech Republic in Central Europe (Adamovič et al., 2006), on the limestone plateaus of southern Spain (Durán et al., 2005), in the Canyonlands National Park in Utah, USA (Lohman, 1974; Dixon, 2010), on the summit surfaces of quartzite mesas in Venezuela (Piccini & Mecchia, 2009; Wray, 2010), in the Carboniferous sandstones of Vila Velha in the Paraná Basin in southern Brazil (Melo & Coimbra, 1996), or in the sandstone and limestone soils of northern Australia (Young, 1986; Grimes, 2012). In Africa, literature is less extensive but there is no shortage of models. These include: the chaotic relief, ruiniform in places, bordering Mount Cameroon (Tchawa, 2012), the ruiniform reliefs of the Aledjo Mountains in northern Togo (Da Costa et al., 2018), the "Sindou needles" in southwestern Burkina Faso (Kouakep Chimi, 2022-2023), the upper member of the Dindéfélo Formation in the Madina Kouta basin (Deynoux et al., 1993; Youm et al., 2018; Youm, 2019). The term was first used in this basin by geologists from COGEMA (Adeguelou & Fall, 1979) to designate the middle part of the "Lower Sandstones or Sandstones of the Ségou Cliff" described by Bassot (1966).

While the lithologies adapted to the development of this type of morphology are sedimentary rocks (sandstone and limestone in particular), other categories of rocks can also support this type of relief. Their sculpture is linked to the interaction of Multiple factors, including: the changing attributes of sedimentary rocks (texture, cementation, sedimentary structures), tectonic and non-tectonic fractures, physical, chemical, and biological weathering (Melo & Coimbra, 1996). The combination of sufficient rock resistance to support steep rock faces and the presence of discontinuities is the basic prerequisites (Migoń et al., 2017).

The resulting shapes are varied and sometimes have bizarre names: fairy chimneys, woodpeckers, needles, mushrooms, sphinxes, ... They are often included in Geoparks such as Bohemia Paradise in the Czech Republic (Adamovič et al., 2006), Dunhuang Yardangs and Hexigten in China (Migoń et al., 2017).

In this work, we examine the main processes that are at the origin of the ruiniform appearance of the sandstones of the Upper Member of the Dindefelo Formation. The study is based on field observations (sedimentary figures and fracturing) and petrographic analyses.

2. Geological Context of the Madina Kouta Basin

The sedimentary cover of West Africa is distributed in several extensive basins of Mesoproterozoic to Paleozoic age (Villeneuve & Rocha Araujo, 1984) including the Madina Kouta basin, a southwestern extension of the Taoudéni basin. It covers an area of 30,000 km^2 and extends to the NE of Guinea Conakry and a thin strip to the SE of Senegal (**Figure 1**). In recent years, we have been interested in our research in the Senegalese part of the country, which includes two Supergroups: Ségou-Madina Kouta and Mali or Mauritanides. The deposits of the Madina Kouta basin are formed by alternations of detrital facies, sandstone-silty, sometimes carbonates, dated from the end of the Mesoproterozoic to the Neoproterozoic (Delor et al., 2010) (**Figure 1**).

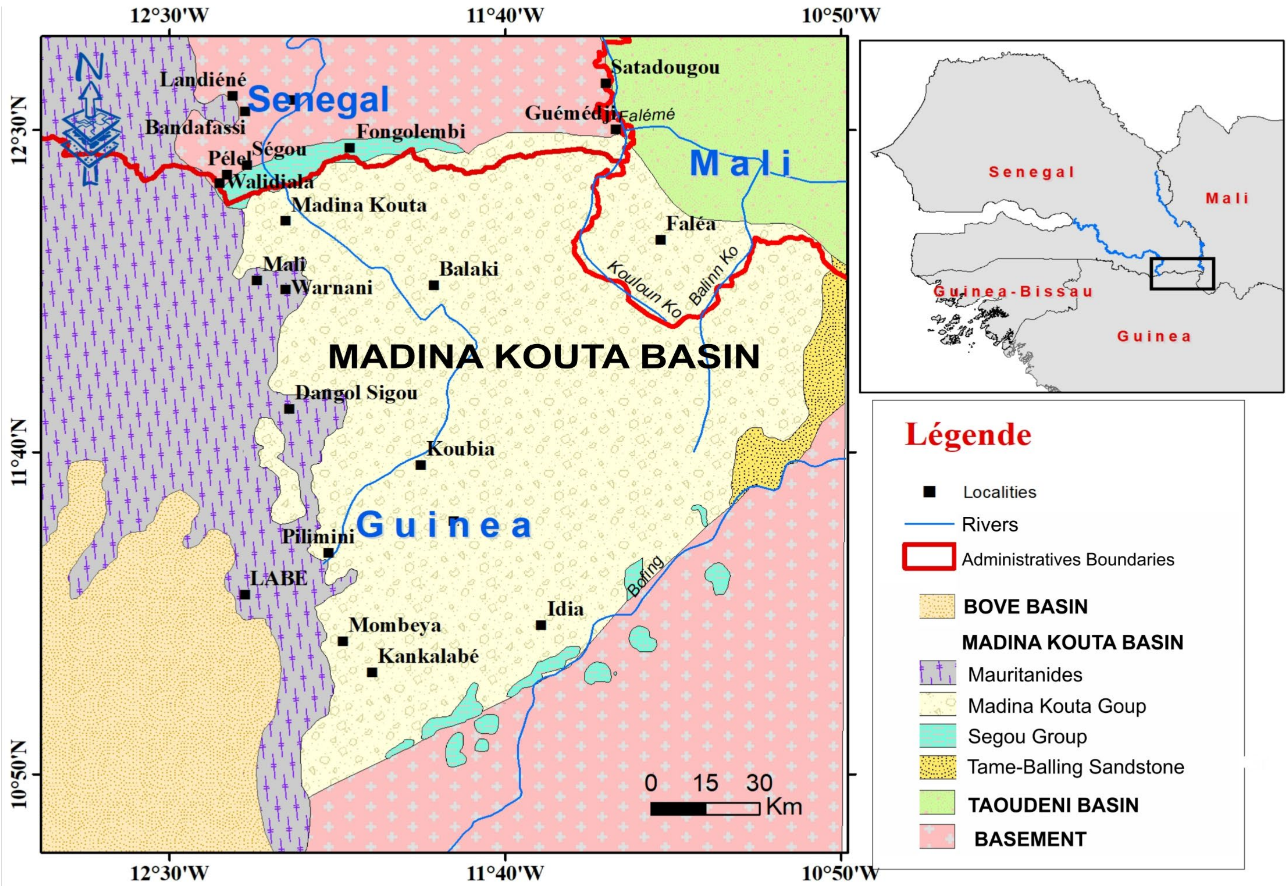

Figure 1. Geological map of the Madina Kouta Basin (modified, after Deynoux et al., 1993).

2.1. The Ségou Madina-Kouta Supergroup

There are two groups: the Ségou group and the Madina Kouta group (**Figure 2**). The Segou Group rests unconformably on the Birimian bedrock and extends along a line from Fongolembi to Pelel Kindessa. It forms most of the Meso-Neoproterozoic sedimentary cover in Senegalese territory. It is subdivided by Deynoux et al. (1993) into two formations: a basic conglomerate discordant on the basement, surmounted by sandstones, oolitic limestones (F. de Pélel) and decimetric to plurimetric

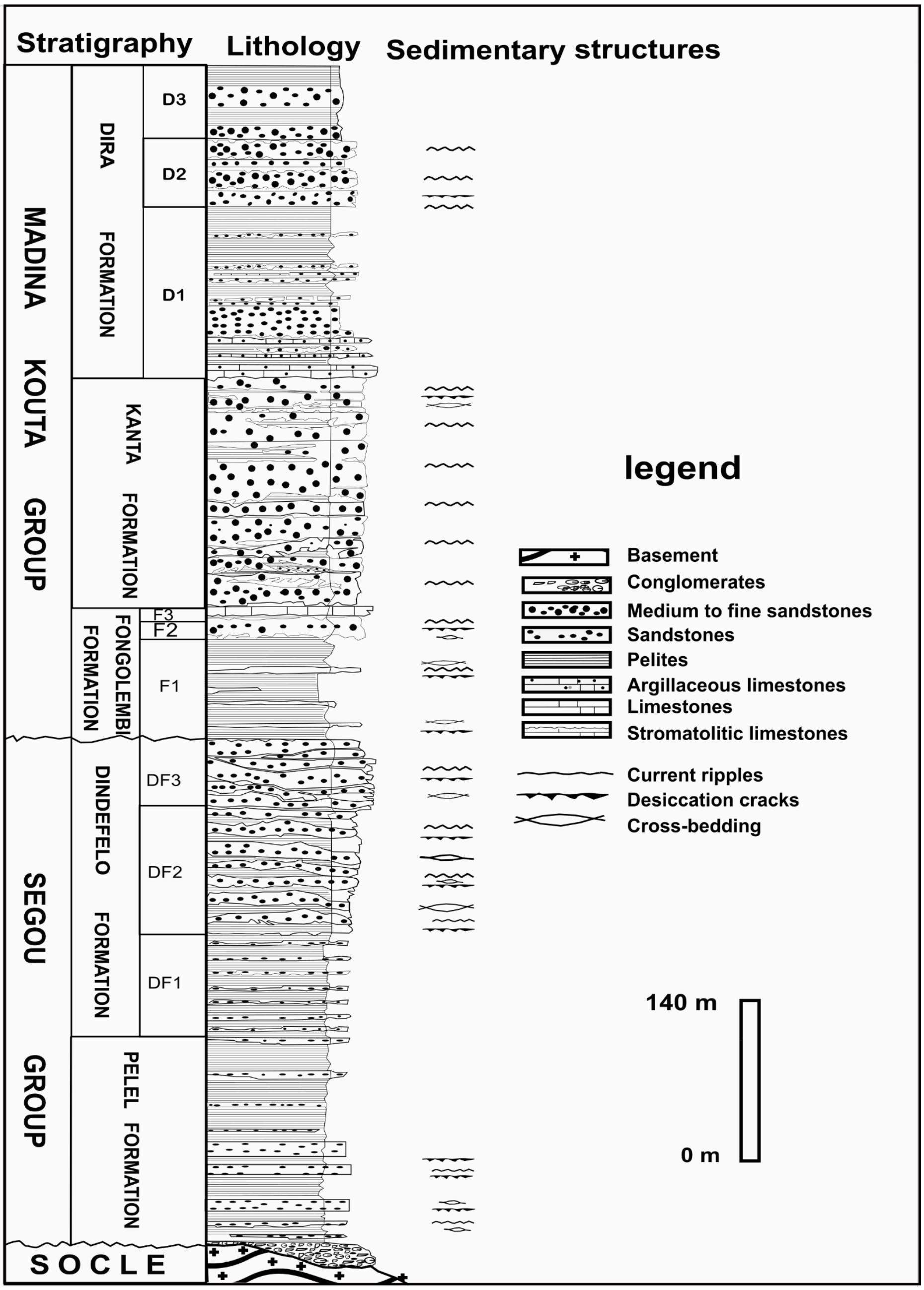

Figure 2. Synthetic lithostratigraphic section of the Ségou Madina Kouta Supergroup (modified, after Deynoux et al., 1993).

sandstone bars alternating with thin clay-silty interbancs (F. de Dindéfélo). Delor et al. (2010) described the basic conglomerate in detail and made a third formation, the Kafori formation. Madina Kouta's Group is transgressive on the Segou Group and sometimes discordant on the base. It is only observed on the Fongolembi plateau and on the border with Guinea south of Ségou. It is made up of three Formations: (i) the Fongolembi Formation consisting of fine clay-silty sandstone topped by an alternating silt-sandstone; (ii) the Kanta Formation, consisting of fine to medium silty sandstones with intersecting oblique stratifications;

(iii) the Dira Formation consisting of siltstones, calcareous sandstones and coarse yellow sandstones with silty intercalations followed by fine sandstones and purple siltstones.

2.2. The Mali or Mauritanids Supergroup

It was divided by Culver and Hunt (1991) into two formations: the Hassana Diallo Formation, which contains the members of Pelel and Diagoma, all glacial origin, and the Nandoumari Formation, which includes the members of Tanagué, Bowal and Fougon, all probable marine origin. This lithostratigraphic division was taken up by Delor et al. (2010) who distinguished two groups (i) the Walidiala Group, which begins with an alternation of sandstone and pelitic (F. de Walidiala 1) topped by massive tillites and laminated tillites with dropstones, capped by calcareous silt-sandstone argillites in centimetric wafers (F. de Walidiala 2) and quartz arenites with convoluted beddings (F. de Walidiala 3); (ii) the Mali Group subdivided into three formations: the Mali Limestone Dolomite Formation 1, the Mali Chert Formation 2 and the Mali Purple Pelite Formation 3. The recent work of Youm (2019) and Youm & Sow (2025) has led to the proposal of a new division in the Walidiala Group with two formations instead of three: the Walidiala Formation 1, alternating massive tillite and laminated silty clay with dropstones, and the Walidiala 2 Formation consisting of quartz arenites in channels. This work has also proposed two (2) formations in the Mali Group: The Formation of dolomitic limestones and calcareous dolomites with celestine and barite (M1) sometimes evaporitic and the purple pelitic-cherts Formation (M2). The continuity of these formations in the Landiene and Bandafassi sectors has been proven by the work of Youm & Sow (2025).

3. Materials and Methods

The present work was conducted following several field missions that allowed us to make detailed observations on the lithology and sedimentary figures and structures. On each facies, samples were taken and brought to the laboratory for mineralogical and petrographic analyses. The thin sections for the petrographic study were established at the Faculty of Sciences of the Chouaïb Doukkali University in El Jadida (Morocco). The observation of the slides as well as the photos were taken with a microscopic binocular Leica DM 750 P, equipped with an ICC 50 HD type camera at the Institut Fondamentale d'Afrique Noir (IFAN) of the Cheikh Anta Diop University in Dakar. Regarding fracturing, field observations were supplemented by the work of Sarr et al. (2012), who used both field observations and microscopic studies.

4. Lithostratigraphy of the Dindefelo Formation

The Dindéfélo Formation is easily recognizable on the ground since it forms the cliff arming the main escarpment bordering the Birimian peneplain to the south. It is discordant on the formations of Kafori and Pelel and sometimes even on the base. In the Dimboli sector, Deynoux et al. (1993) estimated its thickness to be 80 m and divided it into three members (DF1, DF2 and DF3) while Delor et al. (2010) identified two sets (one lower and one upper). Youm (2019) retained the division of Deynoux et al. (1993) and provided additional data on lithostratigraphy. He thus highlighted the existence of feldspathic conglomerates and microconglomerates at the base of the Dindéfélo Formation in the Dindéfélo, Yamoussa and Tépéré sectors. Hardened informational and surface breccias, tectonic breccias in ruiniform sandstones, evidence of tectonic activities and emersion phases are also identified. He also linked the sandstone/pelite alternations at the base of the hills between the villages of Tépéré and Dindéfélo to the Dindéfélo Formation. Thus, following the work of Deynoux et al. (1993) and Youm (2019), we retain three members in the Dindéfélo formation: Df1, Df2 and Df3.

4.1. DF1

It shows from bottom to top three types of facies: silty clay and purple greywackes, sometimes cornified with centimetric to metric levels of fine white to pinkish sandstone (**Figure 3(A)**); a clear alternation of clay and sandstone with a predominance of sandstones towards the summit where they amalgamate, showing levels of interbedded intraformational conglomerates. The sandstone facies consist of

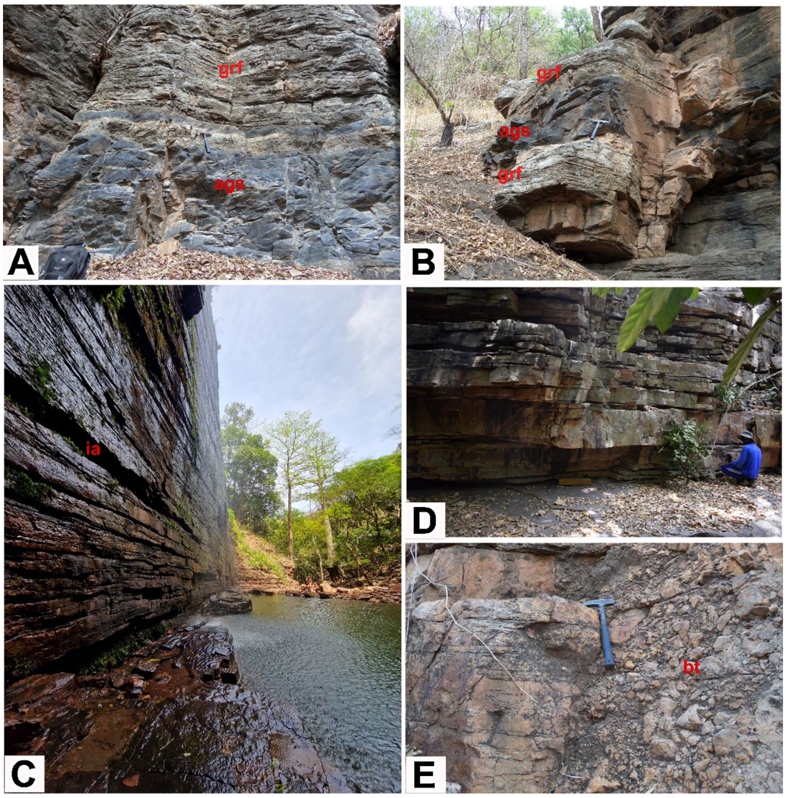

Figure 3. Silty clay and purple greywackes with intercalations of fine sandstone levels of DF1 (A-B), fine clayey sandstone with clayey interbeds of DF2 (C); Quartz sandstone with clay-sandstone interbeds, from DF3 (D); monogenic tectonic breccias of DF3 (E); ia = clayey intercalations; ags = Silty clays, grf = Fine sandstones; bt = tectonic breccias.

10 to 30 cm beds of white or pink quartz sandstone or friable brown to pink clayey sandstones (Figure 3(A) & Figure 3(B)). It is common to find in these fine facies centimetric pastes of very coarse to microconglomerate sandstones. Intraformational conglomerate levels are 3 to 5 m thick. These are breccias with granular support and contain intraclasts made up of large quartz grains, centimetric to decimetric sandstone fragments, caught in a dark sandstone-microconglomerate matrix rich in volcanic material and a ferruginous cement.

4.2. DF2

It is made up of decimetric to metric beds of friable medium clayey sandstone, mauve, purple, or pinkish white, interspersed with centimetric and decimetric beds of pelites and argillites. The clay interbeds are strongly eroded and leave spaces between the sandstone banks constituting zones of weakness (Figure 3(C)), creating favorable conditions for differential erosion characteristic of the sandstones of the Dindefelo Formation.

4.3. DF3

It outcrops spectacularly at the top of the hills, all along the Senegalese Guinean border, from Tépéré to Pelel where it disappears completely. On the ground, the whole of Member 3 is structured in tiers made up of plurimetric sandstone units separated by centimetric clay-sandstone flats (Figure 3(D)). There are also monogenic breccias pockets (Figure 3(E)). From the base to the top, the sandstone banks increase in thickness and granulometry, to the detriment of the soft clay-sandstone beds. These banks are easily recognizable by their very characteristic conjugate fractures giving rise to a ruiniform landscape (Figures 4(A)-(D)). The

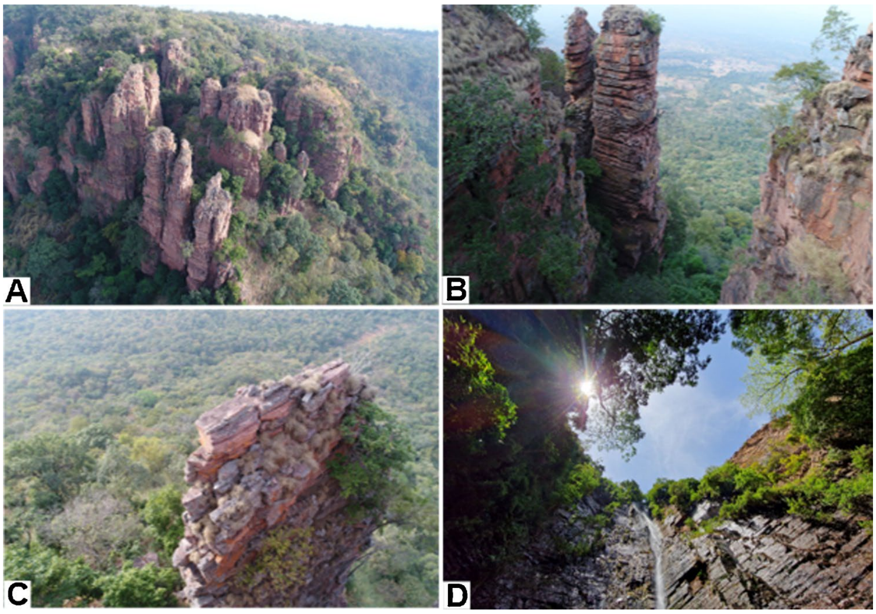

Figure 4. Overview of the ruiniform sandstones of DF3: Multi-metric ruiniform sandstone of the Dents de Dandé (A-B); General view of the strongly fractured ruiniform sandstones, of the Dindéfélo waterfall (C-D).

monogenic breccias associated with the sandstones are very localized and very resistant; their lithoclasts, very angular and small, are made up of fragments of quartzite sandstone observed north-east of Ségou and east of Dindéfélo where they are quite often located along small faults.

5. Etude Pétrographique

5.1. DF1

The purple and greywacke silty clay in places of DF1 are made up of small mono- and polycrystalline angular quartz with ferruginous cement sandstone infiltrations (**Figure 5(A)**). The sandstones, fine to very fine, have a pelitic matrix and a ferruginous cement; their classification is poor and their porosity extremely high (**Figure 5(B)**).

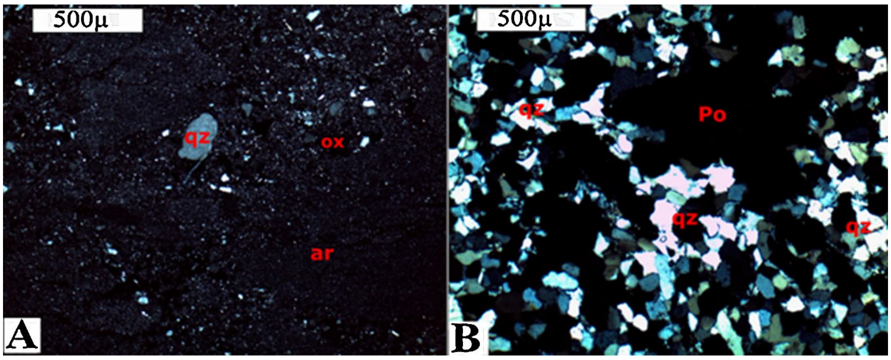

Figure 5. Microscopy of the DF1 facies: Purple silty claystones with infiltrations of coarse material and ferruginous cement (A); Exceptionally fine and very porous quartz arenites (B). ar: claystone; ox: iron oxide; Po: porosity; qz: quartz.

5.2. DF2

Petrographically, the figurative elements of the DF2 clay sandstones are made up of quartz grains with alternating very fine-grained beds and fine-to-medium-grained beds (**Figure 6(A)**): i) the fine-grained beds are made up of angular elements of the size of very fine arenites, not joined, bound together by a very ferruginous cement; (ii) coarse-grained beds consist of fine to medium-sized, rounded to subangular, cracked and heavily worn quartz grains, bound together by a matrix of very fine quartz grains. They are sometimes joined and often interlocked, with undulating extinction and sometimes feeding. In the rock, there are also a few rare plagioclases. Glauconia and iron oxides are well represented in some slides. It is a quartzo-silty arenite, with glauconia and high porosity and iron oxide film.

5.3. DF3

DF3 sandstones are fine to medium-fine quartzite sandstones, well sorted, hard, with smooth breaks, whitish pinks. They are made up of angular to subangular grains of mono- and polycrystalline quartz with undulating extinction, intimately welded, scratched, serrated, and meshed (**Figure 6(B)**). The matrix is very scarce, and the cement is siliceous and ferruginous. These banks are easily recognizable by their very characteristic conjugate fractures giving rise to a ruiniform landscape (Figure 4(C) & Figure 4(D)). It is therefore a sandstone with good mineralogical and petrographic maturity.

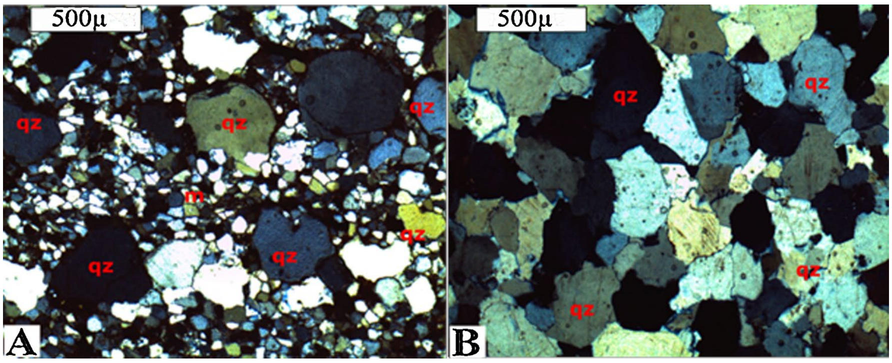

Figure 6. Microscopy of DF2 sandstones showing alternating very Joined fine-grained beds and fine- to medium-grained beds (A) and fine- to medium-grained quartzics arenites of DF3 (B); qz: quartz; m = Matrix.

6. Analysis of Sedimentary Structures and Figures

6.1. DF1

Examination of the sedimentary structures internal to the DF 1 sandstone bars shows undulating beddings, very frequent HCS, flat fine laminations, oblique and intersecting laminations, very frequent herringbones towards the top, flaser-beddings, surfaces with asymmetric current ripples and waves at the top of the banks, and a discreet normal grading. The argillites at the top of fine sandstone beds exhibit parallel laminations and are often heavily eroded.

6.2. DF2

Within the clayey sandstones of DF2 we find parallel stratifications on a large scale, oblique laminations, sometimes intersecting on a large scale, herringbones at the base, flaser beddings and undulating beddings, but also load figures at the base of the beds. On the surface of the banks, there are asymmetric current ripples, desiccation cracks but also bioturbations. All these structures could be referred to as a nipple intersecting stratification zone or HCS.

6.3. DF3

The quartzite sandstones of DF3 are rich in sedimentary structures and figures, marked by tidal bundles which are very abundant. The present forms include symmetrical, asymmetrical ripple *marks* (Figure 7(A) & Figure 7(B)), linguoïds, ripples, sometimes climbing ripples (climbing ripples stratification) as well as imprints of current ripples (Figure 7(C) & Figure 7(D)). There are also many bioturbations (Figure 8(A) & Figure 8(B) and microbial mats. Wrinkles as well as desiccation cracks (Figures 8(C)-(E)) and hardened surfaces are very frequent

Figure 7. Sedimentary structures and figures associated with DF2: Wave Ride (A-B); Fossilized Ripples and Ripple Prints (C-D). (C) for Youm et al. (2018).

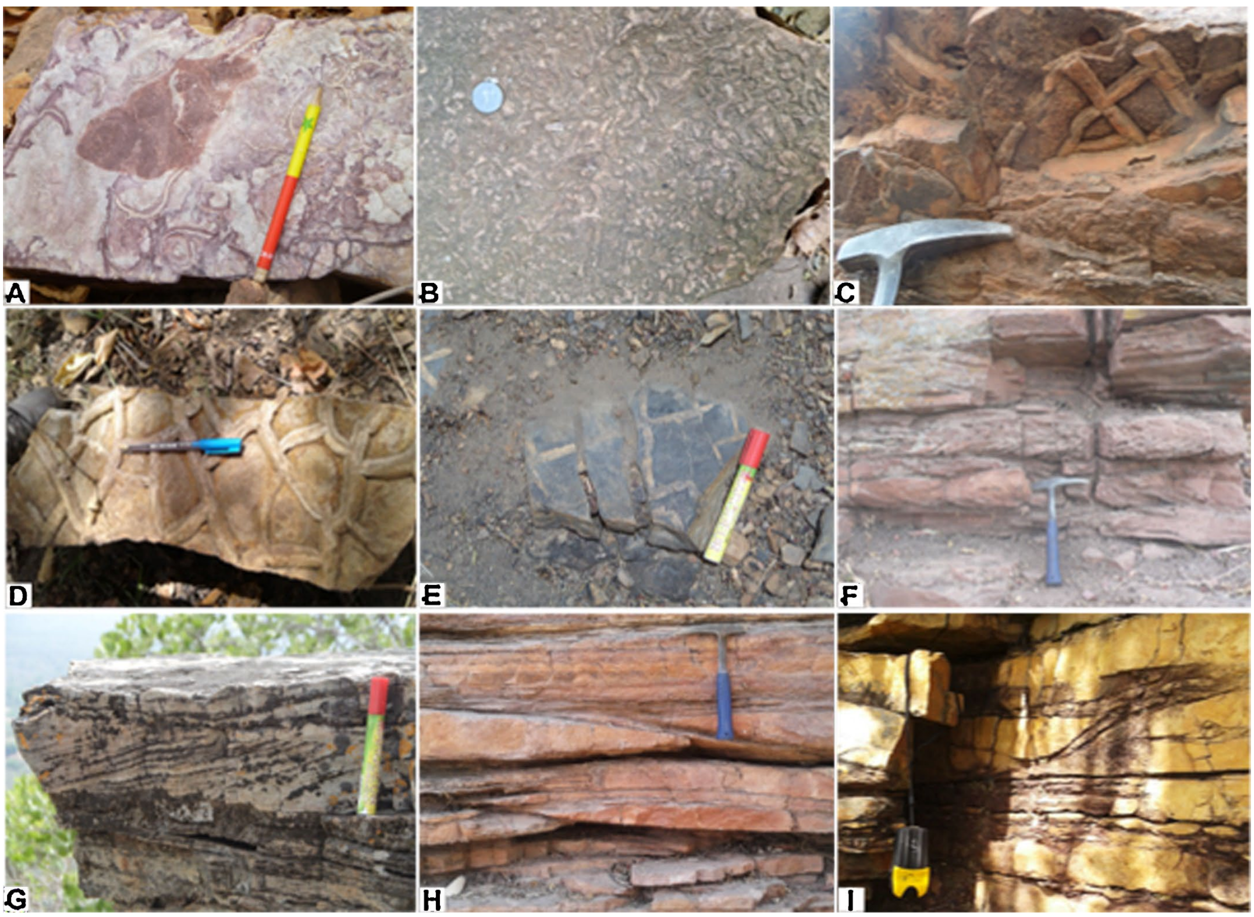

Figure 8. Sedimentary structures and figures associated with DF3: Bioturbations not known (A-B); Desiccation slots (C-E); Herringbones structures (F); tidal dunes and anti-dunes (G-H); tidalites and tidal gutters (I). (H) for Youm et al. (2018).

and better expressed than in the other limbs, unlike fishbone structures (**Figure 8(F)**). As bedding, DF3 exhibits large-scale parallel stratifications, intersecting, sometimes arcuate oblique stratifications, flaser-beddings, HCS, sandbars, dunes, anti-dunes (**Figures 8(G)-(H)**) and tidalites and tidal gutters (I). The basal surfaces of the sandstones are erosive and irregular with load imprints of centimeter depth, erosion gutters of centimeter to decimeter depth. Many hard ground surfaces covered with lateritic crusts are found at different altitudes.

7. Study of Fracturing

It was conducted in detail by Sarr et al. (2012) in the Ségou sector. Their work led to the conclusion that the sandstones and pelites in the area are crossed by discontinuities and micro-discontinuities forming three main families. These families are oriented NNW-SSE, NE-SW and ENE-WSW. They are represented by cracks and faults. These directions are comparable to those described by Mall et al. (2019) in the Birimian basement of the Kédougou Kéniéba buttonhole where the NE-SW directions remain the most representative with more than 20% of the total lineaments, followed by the NNW-SSE direction. The authors emphasize that the preponderance of the NE-SW direction is due to the major NE-SW faults, including the regional tectonic accident called MTZ (Main Transcurency Zone). Our field measurements in the framework of the lineament analysis have made it possible to distinguish in order of length, frequency and decreasing importance the following major directions: NE-SW, WNW-ESE, ENE-WSW, NNE-SSW. Another minor N-S direction can be seen on the directional rosette with a more accentuated density towards the Pelel Kindessa area where the most spectacular structures such as the Dande teeth are located.

8. Discussion: Relationships between Fracturing, Petrography and Sedimentary Figures

The three families of discontinuity (Sarr et al., 2012) confirmed by our field measurements affect all three members of the Dindéfélo Formation but their visibility varies according to the lithological nature (argillites or sandstones), the sedimentary figures and structures present, and the petrographic and mineralogical maturity. Thus DF3, which has the lowest clay content, the highest density of sedimentary figures and structures as well as bioturbations (**Figure 7** and **Figure 8**) and the highest petrographic and mineralogical maturity (**Figure 5** and **Figure 6**), better visualizes these ruined deformations. In the last terms of DF3, the sandstone banks are cut into plates, slabs and parallelepiped blocks (**Figure 3(D)**, **Figure 3(E)** and **Figure 4**), giving rise to a ruiniform landscape with mounds in the shape of giant teeth that can exceed 20 m in height all along the Senegalese-Guinean border, the most spectacular of which are the "Dandé teeth" (**Figure 4**) which attract the curiosity of many tourists. These different syn and post-sedimentary processes also lead to a strong instability on the cliff sides, causing mass landslides that can sometimes be observed more than a kilometer away.

Ruiniform reliefs on sandstone have been studied in several areas: sandstones of the Czech Republic in Central Europe (Adamovič et al. 2006); Carboniferous sandstones of Vila Velha in the Paraná Basin in southern Brazil (Melo and Coimbra, 1996); and ruiniform sandstones of the Sindou Member of the Kawara-Sindou Formation in southwestern Burkina Faso (Kouakep Chimi, 2022-2023). The processes involved in their formation necessarily implicate rock texture and cementation, tectonics, and erosion. Compared to these areas, the ruiniform sandstones of the Dindéfélo Formation are distinguished by the role played by sedimentary structures (current ripples and desiccation cracks), which are particularly striking in this member. These sedimentary structures, located at the level of sedimentary discontinuities, constitute zones of weakness which promote the dismantling of the structures formed and the formation, at the foot of the hill, of scree which covers the ground up to more than 100 meters from the outcrop.

9. Conclusion

The ruiniform sandstones of Dindéfélo have several models, the most remarkable of which are mounds in the shape of giant teeth and mass landslides caused by a strong instability of the flanks. This instability results from the combined action of synsedimentary processes (sedimentary figures and structures, mineralogy) and post-sedimentary processes (petrography, tectonics); these processes are more accentuated within DF3 than DF2 and DF1. The originality of this model lies in the role played by sedimentary structures, in particular current ripples, and desiccation cracks. These phenomena have resulted in magnificent ruiniform landscapes (Dande teeth, waterfalls, gorges, etc.) thus participating in the local economy through the enhancement of Senegal's geosites through geotourism.

Conflicts of Interest

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

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